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REVIEW

How to ventilate obstructive and asthmatic patients

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Abstract

Exacerbations are part of the natural history of chronic obstructive pulmonary disease and asthma. Severe exacerbations can cause acute respiratory failure, which may ultimately require mechanical ventilation. This review summarizes practical ventilator strategies for the management of patients with obstructive airway disease. Such strategies include non-invasive mechanical ventilation to prevent intubation, invasive mechanical ventilation, from the time of intubation to weaning, and strategies intended to prevent post-extubation acute respiratory failure. The role of tracheostomy, the long-term prognosis, and potential future adjunctive strategies are also discussed. Finally, the physiological background that underlies these strategies is detailed.

Keywords: Mechanical ventilation, Chronic obstructive pulmonary disease, Asthma, Intrisic positive end-expiratory pressure (PEEP), Non-invasive ventilation, Weaning

Introduction

Respiratory failure from acute exacerbations of chronic obstructive pulmonary disease (COPD) or severe asthma is characterized by acute worsening of respiratory symptoms associated with the development of severe airflow limitation, gas trapping, dynamic hyperinflation and intrinsic positive end-expiratory pressure (PEEPi). In the most severe cases, these exacerbations may cause acute respiratory failure, which may require mechanical ventilation. This review focuses on strategies for ventilation and describes the physiological background that underlies them. Even though the pathogenesis and clinical course of asthma and COPD differ, ventilator support management of the two conditions is similar in various respects.

Acute respiratory failure in COPD and asthma: the magnitude of the problem

COPD exacerbations are common and have important clinical consequences, including an acute decline in quality of life, temporary or permanent reduction in lung function and exercise capacity, hospitalization, and increased mortality. They also have a major economic impact. According to cohort studies that enrolled unselected critically ill patients receiving mechanical ventilation (invasive or non-invasive) for more than 12 h [1], the proportion of patients managed for COPD exacerbation decreased from 10% in 1998 to 7% in 2016 (Fig. 1). This trend paralleled an increased rate of non-invasive ventilation (NIV) use as first ventilatory support following intensive care unit (ICU) admission (from 16% in 1998 to 51% in 2017). Simultaneously, overall mortality decreased (Fig. 1).

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Severe asthma exacerbation causing respiratory failure may lead to major mechanical ventilation-associated complications (e.g., barotrauma, cardiovascular collapse, atelectasis, and pneumonia) that can impact on morbidity and mortality. Severe asthma exacerbation accounts for approximately 1% of mechanically ventilated patients admitted to the ICU [1]. NIV use in these patients increased from 3% in 1998 to 34% in 2016 [2].

Take-home message

This review summarizes practical ventilator strategies to manage patients with asthma and chronic obstructive pulmonary disease (COPD). The causes, impact and management of dynamic hyperinflation are discussed, as well as heart–lung interaction. We underline the importance of non-invasive ventilation to prevent intubation. We provide key messages regarding ventilator settings in intubated patients. Future adjunctive strategies are discussed.

Respiratory system mechanics and gas exchange

In terms of respiratory system mechanics, asthma and COPD are characterized by the development of dynamic hyperinflation, defined as increased relaxation volume of the respiratory system at the end of a tidal expiration. In healthy subjects, the end-expiratory alveolar and airway pressures are zero relative to the atmosphere, and pleural pressure is negative. In the presence of dynamic hyperinflation, the alveolar pressure remains positive throughout expiration, leading to the development of auto-positive end-expiratory pressure (auto-PEEP), also termed intrinsic PEEP or PEEPi [3] (Fig. 2).

In COPD, PEEPi is primarily caused by expiratory flow limitation, a complex phenomenon that is due to reduced lung recoil pressure (emphysema) leading to small airway collapse that increases airway resistance (see [4] for an extensive description). It is exacerbated by shortened expiratory time, due to increased respiratory rate, and increased tidal volume, the latter being, in general, a consequence of an augmentation of respiratory drive (and therefore a higher volume to exhale) [5]. The consequences of dynamic hyperinflation depend on whether patients are passively ventilated or triggering their ventilator. In passively ventilated patients, dynamic hyperinflation increases delivered mechanical power [6] with its associated risk of barotrauma and hemodynamic compromise [7]. In patients triggering their ventilator, initiation of inspiratory flow requires inspiratory force to overcome PEEPi [8], which translates into increased inspiratory effort during the triggering phase. Ultimately, this increased effort may fail to trigger the ventilator, leading to ineffective triggering, one of the most frequent dyssynchronies [5]. In terms of gas exchange, patients with COPD have complex patterns of V/Q distributions: low V/Q regions that remain perfused, high V/Q regions, and mixed patterns. COPD patients often exhibit small amounts of shunt (typically less than 10% of cardiac output) [9].

Severe asthma exacerbation is characterized by a major increase in airway resistance due to bronchospasm, airway inflammation, and mucus. Expiratory flow is dramatically reduced with resultant major dynamic hyperinflation [10]. This leads to an increased risk of barotrauma and hemodynamic compromise. Hypoxemia in asthma is characterized by the presence of low V/Q units; hypoxemia is usually attenuated by compensatory redistribution of blood flow mediated by hypoxic vasoconstriction and changes in cardiac output [9, 11]. It has been described that in asthma patients, hypercapnia is mainly due to increased dead space ventilation caused by alveolar overdistension [11, 12]. However, this mechanism has not been proved [9].

Heart–lung interactions in the mechanically ventilated COPD patient

The pathophysiological changes in the pulmonary system may have adverse effects on cardiac function.

COPD is associated with pulmonary hypertension, increased pulmonary vascular resistance, right ventricle dilatation, and right ventricle hypertrophy. Both left ventricle systolic and left ventricle diastolic functions are often impaired in COPD patients. Among 148 patients admitted to the ICU for severe COPD exacerbation, 31% had an exacerbation that was definitely associated with left-heart dysfunction [13]. These cardiac alterations are caused by dynamic hyperinflation and the large swings in negative intrathoracic pressure developed by the respiratory muscles to overcome the inspiratory elastic threshold caused by PEEPi and increased airway resistance. Dynamic hyperinflation is more detrimental to left ventricle hemodynamics than large swings in negative intrathoracic pressure [14]. Direct ventricular interaction and significant septal flattening appear to be responsible for reduced left ventricle end-diastolic volume and stroke volume [15]. Dynamic hyperinflation worsens the increase in right ventricular impedance (afterload effect), while large negative intrathoracic pressure swings increase the venous return to the right ventricle (preload effect). Both favor direct ventricular interaction with leftward shift of the septum.

Application of external PEEP up to values approaching PEEPi does not result in hemodynamic impairment in COPD [4]. Higher PEEP levels reduce cardiac index [16]. However, the effects of external PEEP on lung mechanics and hemodynamics depend on many factors, such as airway characteristics, lung volumes, intravascular

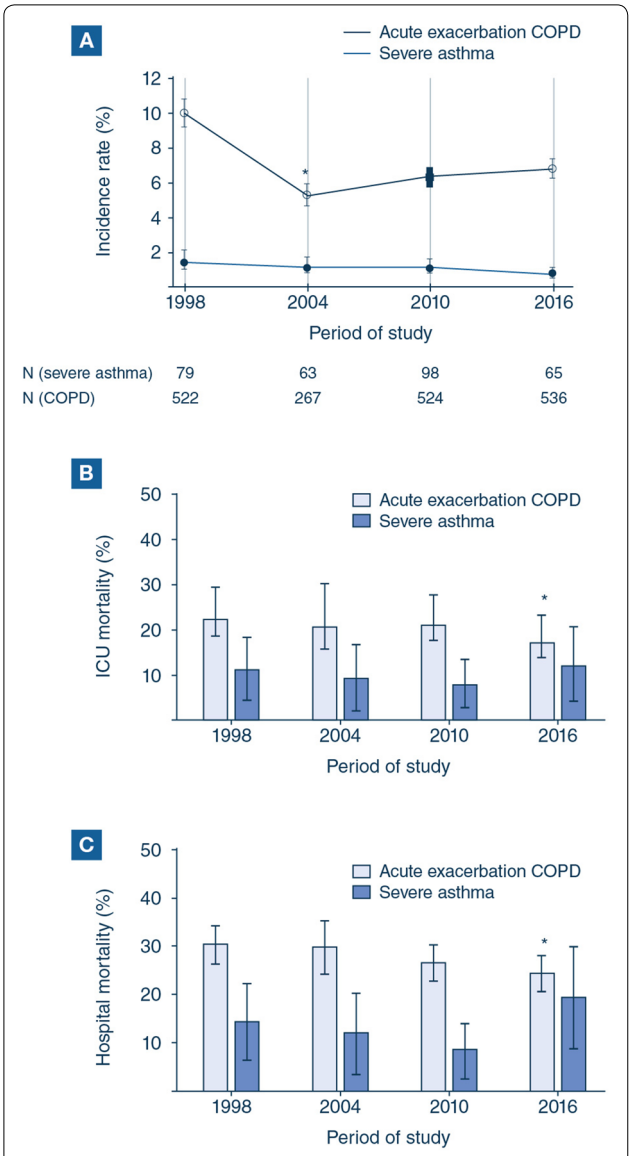

Fig. 1 Rates of acute chronic obstructive pulmonary disease (COPD) exacerbation and severe asthma exacerbation among patients mechanically ventilated for acute respiratory failure (panel **A**) and evolution of ICU mortality (panel **B**) and hospital mortality (panel **C**) over time in these two populations. *$p < 0.001$ compared to period 1998

volume status, vasomotor tone, etc., making the individual patient's response difficult to predict [17].

Finally, patients with COPD are at increased risk of difficult weaning, and are susceptible to developing weaning-induced pulmonary edema in particular [18]. Diuretics and nitroglycerin are efficient in treating weaning-induced pulmonary edema in selected COPD patients [19, 20].

In patients with severe asthma, similar heart–lung interactions are observed. Because of the presence of an extremely severe hyperinflation, they may develop severe hypotension [21].

Non-invasive ventilation in COPD over the decades

Delivering mechanical ventilation without intubation in patients with CO_2 retention was attempted during the 1960s [22], but without becoming widely accepted; intubation with invasive mechanical ventilation remained the rule for patients admitted for respiratory failure.

In the late 1980s, several groups treated patients with chronic or acute-on-chronic hypercapnic respiratory failure with a face mask [23–26]. The success was largely due to combining physiological assessment of the mechanisms of respiratory failure (including respiratory muscle function [26]) with new technologies (pressure support ventilation [27]). In the early 1990s several studies demonstrated the efficacy of positive pressure ventilation usually delivered with pressure support ventilation and PEEP [28, 29]. It is remarkable that some of the best results were obtained without any PEEP [26], highlighting the importance of pressure delivered during inspiration. Randomized clinical trials showed that the intubation rate was dramatically reduced, resulting in improved outcomes, with fewer complications related to invasive mechanical ventilation and improved hospital survival [30–32] (Fig. 3).

Implementing NIV into practice took more than a decade [33] but NIV became the benchmark for treating acute respiratory failure due to severe COPD exacerbation, bringing about a steady decrease in mortality over time [33]. Concomitantly, the risk of mortality increased in patients transitioned from NIV to invasive mechanical ventilation. However, it is of note that COPD patients who failed NIV and were subsequently intubated were not at higher risk of mortality than those intubated as a first-line respiratory support [30, 33]. Technological improvements continued, stimulated by the need for efficient techniques in the hospital and by the extensive use of home NIV, which required more comfortable and user-friendly equipment [34]. Automated management of leaks progressively became the rule and ICU ventilators eventually became as efficient as dedicated ventilators in compensating for leaks and reducing patient-ventilator dyssynchronies [35, 36].

NIV is sometimes proposed as a ceiling of ventilator assistance care [37–39]. A multicenter French study showed that patients with "do-not-intubate" orders who were managed with NIV had good quality of life 6 months after discharge; caregivers of patients treated with NIV had similar stress and anxiety levels to those of caregivers of patients with no limitation on therapy

[39]. Because NIV relieves dyspnea [40], the technique has also been used to relieve dyspnea in dying patients receiving palliative care [41], although this approach has not gained widespread use.

In severe asthma exacerbation, retrospective studies have suggested that cautious use of NIV was associated with improved outcome [42]. However, no high-quality randomized controlled trial has highlighted benefits of NIV in severe asthma exacerbation, and the level of risk may be very high in cases of respiratory failure. As a consequence, guidelines do not recommend NIV in severe asthma exacerbation [43, 44].

Management of invasive ventilation

Invasive ventilation is indicated in patients suffering a respiratory arrest, for instance, or who have failed NIV

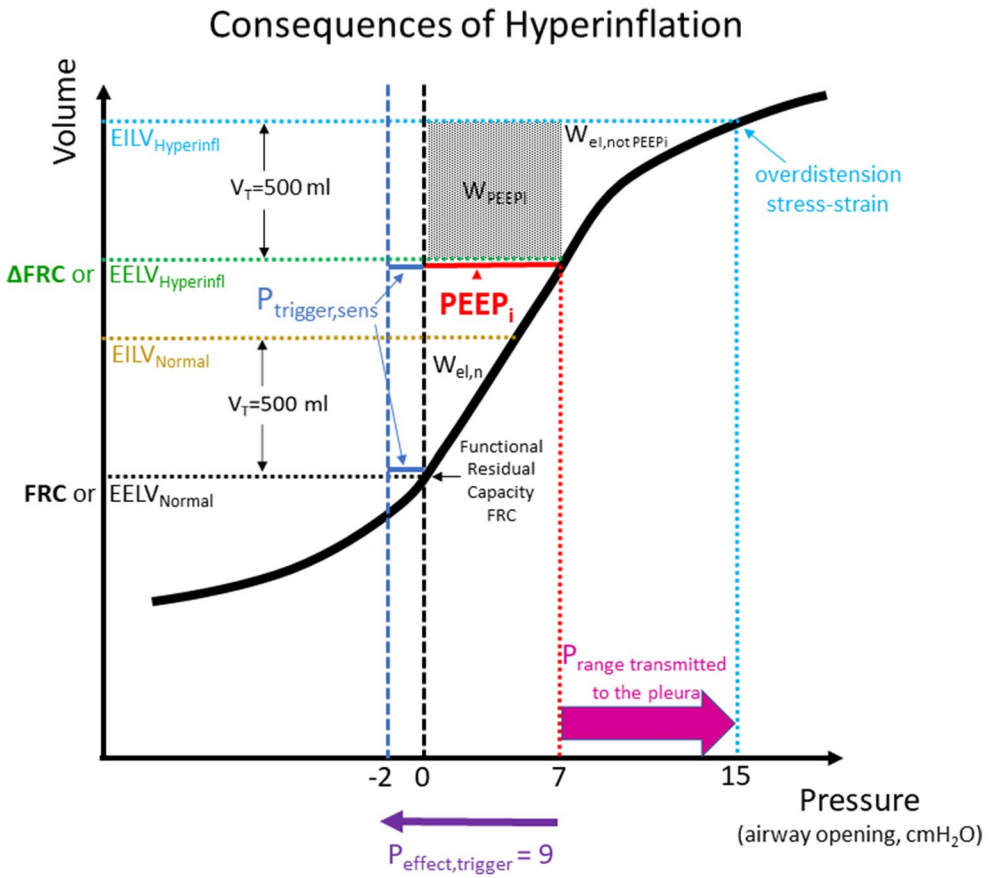

Fig. 2 Pressure–volume (P–V) relationship of the respiratory system when pressure is measured at the airway opening. In normal subjects, the end-expiratory lung volume ($EELV_{Normal}$) is the relaxation volume of the respiratory system or functional residual capacity (FRC), where no inward or outward recoil pressure exists (the pressure of the respiratory system is 0 cmH_2O relative to the atmosphere). To trigger the ventilator, the patient's inspiratory muscles have to develop an inspiratory effort ≥ the trigger threshold set on the ventilator (2 cmH_2O in the example). A tidal breath of 500 ml delivered by the ventilator will increase the volume of the respiratory system to its end-inspiratory lung volume ($EILV_{Normal}$). The normal elastic work of breathing ($W_{el,n}$) represented by the triangular area is not excessive. In hyperinflated COPD or asthma patients, the end-expiratory lung volume ($EELV_{Hyperinfl}$) is greater than the respiratory system relaxation volume, increasing ΔFRC (Δ denoting the increase in volume from the normal FRC); at this increased volume, an inward recoil pressure exists (the pressure of the respiratory system is 7 cmH_2O relative to the atmosphere). This pressure is called the intrinsic positive end-expiratory pressure (PEEPi). (This pressure is usually measured by the end-expiratory occlusion method with the patient relaxed). To trigger the ventilator, the patient's inspiratory muscles first have to develop an inspiratory effort to overcome the positive inward recoil of the respiratory system present at the end of expiration (7 cmH_2O, PEEPi) and then the trigger threshold set on the ventilator (2 cmH_2O in the example). The pressure required to effectively trigger the ventilator ($P_{effect,trigger} = 7 + 2 = 9$ cmH_2O in the example). If they fail to generate this amount (9 cmH_2O), an ineffective triggering effort ensues, which does not trigger the ventilator. A similar tidal breath of 500 ml delivered by the ventilator will increase the volume of the respiratory system to its new end-inspiratory lung volume ($EILV_{hyperinfl}$), where there is risk of overdistension (stress and strain of the lung) with its potentially injurious sequalae (this is the plateau pressure if measured by the end-inspiratory occlusion method with the patient relaxed). The elastic work of breathing is mainly attributed to PEEPi (square shaded area, W_{PEEPi}) and is greatly increased leading to increased delivered mechanical power

for any reason, including persistent clinical signs of increased work of breathing. As previously explained (see above section "Respiratory system mechanics and gas exchange"), acute exacerbations of COPD are characterized by dynamic hyperinflation leading to development of PEEPi. The presence of dynamic hyperinflation and PEEPi should be considered if expiratory flow does not cease at end-expiration (Fig. 4). With controlled mechanical ventilation, total PEEP is measured during end-expiratory occlusion. The reference standard technique for quantifying dynamic hyperinflation is measurement of end-inspiratory lung volume [45]. As this is cumbersome in clinical practice, end-inspiratory plateau pressure (Pplat) during controlled mechanical ventilation is a reasonable, albeit less sensitive, surrogate for monitoring hyperinflation [45]. Pplat is measured with end-inspiratory occlusion for ± 3 s. Peak pressure is not a reliable measure for hyperinflation.

It is important to stress that in the early phase of mechanical ventilation, the primary goal in these patients is not to normalize blood gases, but to prevent complications due to hyperinflation while maintaining a pH of around 7.25–7.30 [46].

Many ventilator modes are used in intubated patients with COPD; however, it is not known whether one is superior to another. A common ventilator mode is volume assist-control ventilation. With volume assist-control ventilation, the inspiratory flow waveform can be set in the square pattern to facilitate monitoring of mechanics. To limit hyperinflation, minute ventilation is minimized, and sufficient time is allowed for expiration [45]. As a reasonable starting point, use of a moderate tidal volume, of around 6–8 ml/Kg, and a respiratory rate of 12/min, with constant inspiratory flow delivered at 60–90 l/min, has been proposed [47]. It has been proposed to keep the inspiration-to-expiration ratio low, e.g., 1:4. If, with these ventilator settings, Pplat is not too high (e.g., < 28 cmH_2O), the respiratory rate can be increased to improve gas exchange. If Pplat is high (e.g. > 28 cmH_2O), minute ventilation could be reduced by limiting tidal volume and/or respiratory rate in patients with PEEPi. Increasing expiration time at similar minute ventilation (e.g. by increasing inspiratory airflow thus decreasing inspiratory time with constant respiratory rate and tidal volume) has a much smaller effect on hyperinflation [45].

Selecting appropriate PEEP in acute COPD exacerbation may be complex and depends on whether or not the patient triggers her/his ventilator. In general, at the early phase of intubation, patients do not trigger their ventilator. In theory, zero PEEP would be optimal in these COPD patients with "pure" high airway resistance, as PEEP reduces expiratory driving pressure and is therefore expected to increase hyperinflation. However, the physiology appears more complex, with three possible effects of PEEP on hyperinflation [48]: (1) in patients with pure expiratory flow limitation, there is no change in hyperinflation (assessed by Pplat and by changes in end-expiratory lung volume) during progressive increase in PEEP until a threshold is reached; (2) any increase in PEEP increases Pplat and end-expiratory lung volume, and (3) a "paradoxical response" occurs, whereby increases in PEEP decrease Pplat and end-expiratory lung volume. A paradoxical response may be expected in patients with expiratory flow limitation and highly heterogeneous lungs [7, 49]. At the bedside, the effect of PEEP on hyperinflation is unpredictable [48], and it is therefore advised to measure Pplat while cautiously titrating PEEP. PEEP titration should be immediately stopped if Pplat increases [12].

In passively ventilated patients with expiratory flow limitation, the addition of external PEEP does not change either the degree of hyperinflation or the total PEEP until it approximates 80% of the original PEEPi. As soon as the patient is able to trigger the ventilator, moderate external PEEP is added to counterbalance PEEPi and hence to reduce the effort needed to trigger the ventilator and improve patient-ventilator interaction [50]. It is of note that patients with COPD are susceptible to ventilator-induced hyperinflation and dyssynchronies such as ineffective triggering (also called ineffective efforts or wasted efforts, Fig. 5) [50]. Because PEEPi increases the effort required to trigger the ventilator, a weak respiratory effort may fail to trigger it [51]. Ineffective triggering is associated with a less sensitive inspiratory trigger, a higher level of pressure support, a higher tidal volume, and a higher pH [50]. In patients with a high prevalence of ineffective triggering, markedly reducing pressure support or inspiratory duration to reach a tidal volume of about 6 ml/Kg predicted body weight was found to eliminate ineffective triggering in two-thirds of patients [52]. When pressure support is used, the pressure support level should not be set too high, to limit tidal volume (to around 6–8 ml/Kg) and subsequent dynamic hyperinflation [52]. Shortening insufflation time by decreasing the level of the expiratory trigger (also called cycling-off) may also help to reduce dynamic hyperinflation [52].

In severe asthma exacerbation, invasive mechanical ventilation is associated with an increased risk of complications and significant mortality [53]. Post-intubation hypotension is common, due to major lung hyperinflation, hypovolemia and sedation. Therefore, the indication for intubation should be limited to patients in life-threatening conditions (respiratory arrest, bradypnea, altered consciousness, patients totally exhausted and/or with severe and

worsening hypercapnia or major respiratory distress despite adequate medical treatment). Because of the major increase in expiratory resistance due to airway obstruction related to edema and bronchospasm, pulmonary hyperinflation might be extremely high in asthmatics. The key ventilatory strategy is to minimize hyperinflation, which is best achieved by reducing minute ventilation and lengthening expiratory time (low tidal volume, low respiratory rate [45] and high inspiratory airflow rate with the objective of targeting an inspiratory-to-expiratory time of 1:4 to 1:6). A low level of external PEEP (≤ 5 cmH_2O) is recommended by some authors, although this strategy is disputed [54]. The degree of hyperinflation must be closely monitored (using end-inspiratory and end-expiratory holds) with the aim of limiting Pplat and obtaining the lowest possible total PEEP [53]. As in COPD, using a volumetric mode with square wave airflow delivery allows easier monitoring. As an effect of major reduction of minute ventilation, $PaCO_2$ might increase dramatically [46]; reduction of $PaCO_2$ is very much a secondary goal.

Weaning from mechanical ventilation

Readiness to wean needs to be screened on a daily basis according to guidelines (Fig. 3) [55]. In ready-to-wean patients, a spontaneous breathing trial is performed, with either T-tube or pressure support ventilation [56]. In patients who tolerate the spontaneous breathing trial, it is possible to proceed with extubation.

In COPD patients, prophylactic post-extubation NIV and use of high-flow nasal cannula both decrease the occurrence of acute respiratory failure and subsequent reintubation (Fig. 3) [57, 58]. The addition of NIV sessions to high-flow nasal cannula use seems to be more efficient for preventing reintubation than use of high-flow nasal cannula alone [59]. Finally, NIV can also hasten weaning in COPD patients who repeatedly fail spontaneous breathing trials [60].

In a series of 208 patients intubated for hypercapnic respiratory failure, 4.4% required ventilation via tracheostomy at discharge [61]. The decision to opt for tracheostomy is made on the basis of considerations about, for example, the risks of the procedure versus its anticipated but unproven benefits [62]. In the difficult-to-wean patient, possible tracheostomy should be

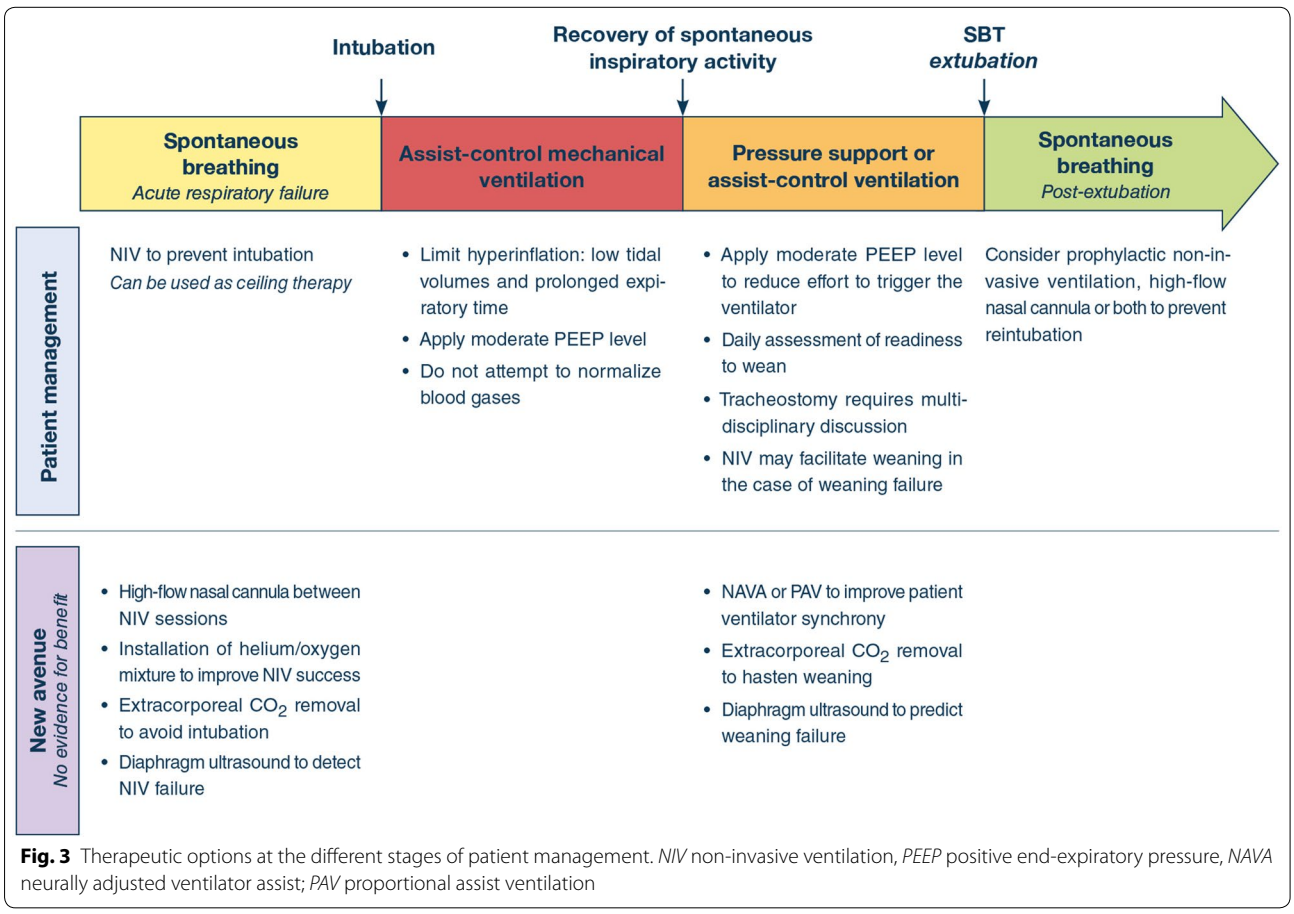

Fig. 3 Therapeutic options at the different stages of patient management. *NIV* non-invasive ventilation, *PEEP* positive end-expiratory pressure, *NAVA* neurally adjusted ventilator assist; *PAV* proportional assist ventilation

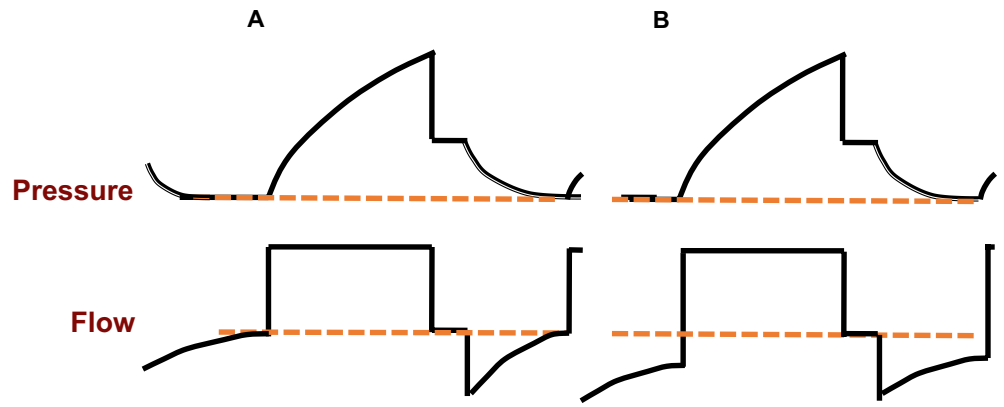

Fig. 4 Schematic representation of pressure and flow recordings in two mechanically ventilated patients. In a healthy subject (panel **A**) expiratory flow ceases at end-expiration, ruling out dynamic hyperinflation. In a COPD patient (panel **B**), expiratory flow does not cease at end-expiration, which suggests dynamic hyperinflation and intrinsic positive end-expiratory pressure (PEEPi)

the subject of a multidisciplinary discussion [63]. The patient and his or her family must be informed that tracheostomy does not alter the prognosis of the causal disease. Although tracheostomy can improve comfort [64], it may unduly prolong suffering associated with the underlying illness. In a context of chronic respiratory failure, these ethical considerations must be carefully thought through and discussed with the patient and his or her family before performing a tracheostomy.

Long-term outcome

In a small series of patients with COPD requiring prolonged mechanical ventilation (> 21 days), 2-year survival was 40% (68% in patients weaned from the ventilator and 22% in those not weaned) [65]. In another cohort of patients (59% with COPD) requiring prolonged ventilation at a weaning center, 1-year survival was 49% [66].

A prospective longitudinal study investigated the effect of prolonged mechanical ventilation on survival and quality of life in 315 patients with various causes of respiratory failure (95 had COPD as primary or secondary cause of respiratory failure) [67, 68]. Among the patients who survived to discharge from the weaning facility, 54% were detached from the ventilator and 30% were still attached to the ventilator at the time of discharge from the facility. The 1-year survival was 63% for ventilator-detached patients and 22% for the ventilator-attached patients. Survival was not influenced by the underlying cause of respiratory failure, including COPD [68]. By 12 months, the SF36 physical-summary score and mental-summary score returned to pre-illness values, and 85% of patients indicated their willingness to undergo ventilation again [68, 69].

Do particular features emerge in middle-income countries?

The burden of COPD and asthma is disproportionally high in low-resource countries due to high indoor/outdoor air pollution (smoking, exposure to coal indoors and to dust in the workplace) [70, 71]. The death toll from chronic respiratory diseases is a real challenge to the public health systems in developing countries, since the highest risk of dying from non-communicable disease is observed in low- and middle-income countries [72].

In addition, in most low- and middle-income countries, ICUs are scarce, and resources are limited. The availability of invasive mechanical ventilation, in particular, is limited, and its use is associated with a high risk of mortality, especially from ventilator-associated pneumonia [73–75]. As in high-income countries, NIV should be preferred to invasive ventilation, particularly in cases of COPD exacerbation. A recent meta-analysis summarizing experience of NIV in these countries reported a moderate risk of mortality in adults (16%), and a mean NIV failure rate of 28.5% in adults in this population [73]. For COPD exacerbation, the use of NIV as the primary ventilatory mode increased from a rate of 29% in 2000 to 97% in 2012 [76]. This change was associated with gradual falls in the rates of NIV failure (learning curve), ventilator-associated pneumonia, and concurrent use of antibiotics [76]. These data suggest that guidelines regarding the preferential use of NIV therapy are not specific to high-income countries and should also be applied to low- and middle-income countries.

New avenues of research

NIV has well-known drawbacks. Patient tolerance may be poor due to patient discomfort, dyspnea, skin damage, and claustrophobia [40]. Furthermore, caregiver skill

is important to the success of this technique. High-flow nasal cannula may be an alternative method [77, 78]. In a recent study conducted in 12 hypercapnic COPD patients with mild to moderate exacerbation who had initially required NIV, applying high-flow nasal cannula at 30 l/min for a short duration reduced inspiratory effort, and resulted in an effect similar to that of NIV delivered at moderate levels of pressure support [78]. In addition, high-flow nasal cannula is a more comfortable technique than NIV [79, 80].

Given the fact that approximately 15% of COPD patients fail NIV, attempts have been made to improve the efficacy of NIV. These attempts include inhalation of helium and oxygen gas mixtures, which requires a complex setting and a specific ventilator. Because of its low density compared with air, helium/oxygen markedly enhanced the ability of NIV to reduce patients' effort and to improve gas exchange [81]. However, despite some improvement of several physiological variables, randomized controlled trials did not show a clinical benefit (i.e., reduction in intubation rate or mortality) [82, 83] with the use of helium/oxygen mixture. The relatively low rate of intubation already achieved with NIV alone may explain the lack of benefit with helium/oxygen mixture.

More recently, extracorporeal CO_2 removal has been considered as a possible adjunct to NIV to avoid intubation in patients not responding to NIV [84]. Combining NIV with direct removal of CO_2 is postulated to improve

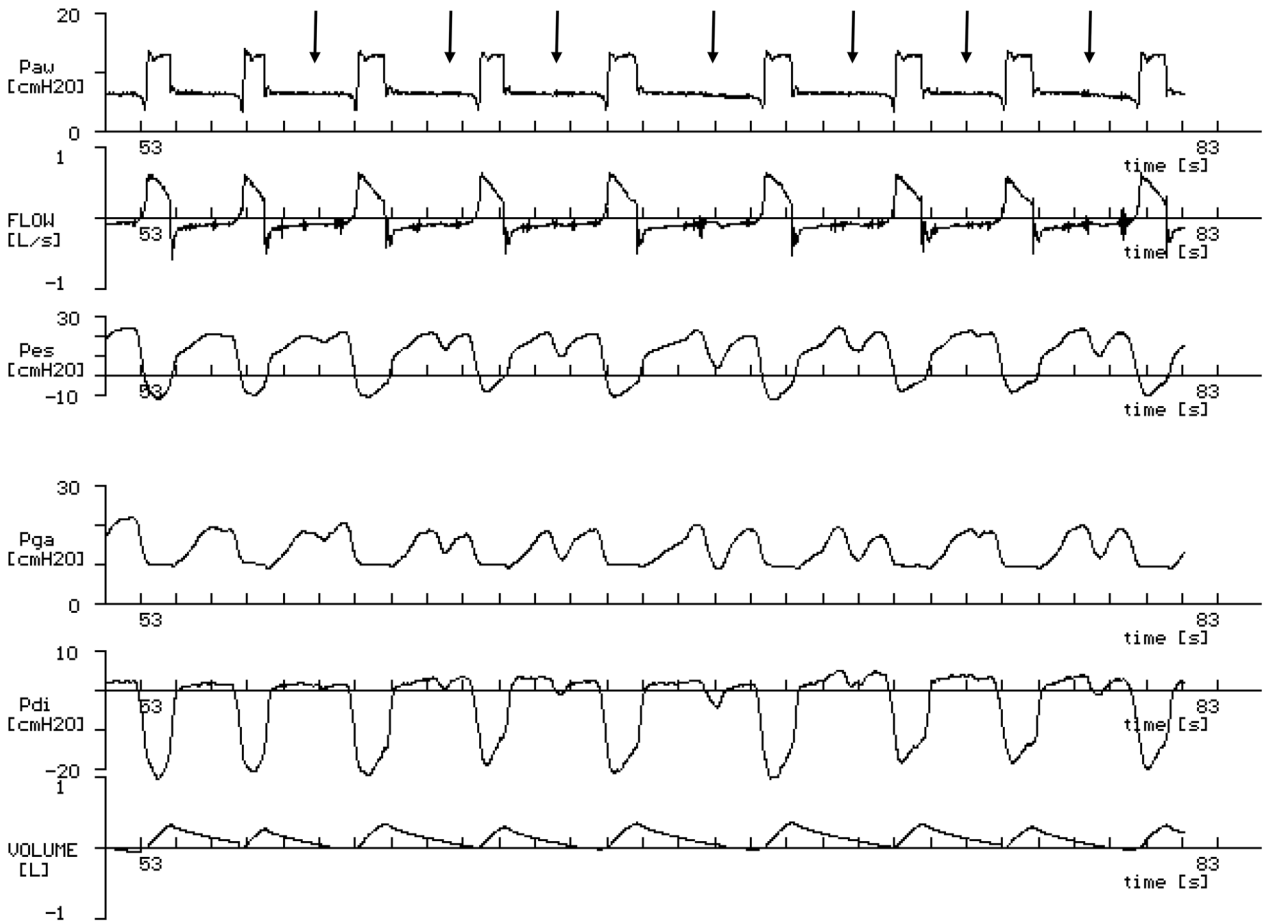

Fig. 5 Tracings (from top to bottom) of airway pressure (Paw), airflow (Flow), esophageal pressure (Pes), gastric pressure (Pga), transdiaphragmatic pressure (Pdi) and tidal volume (VOLUME) in a chronic obstructive pulmonary disease (COPD) patient exhibiting significant respiratory muscle effort during an episode of acute respiratory failure—due to a congestive heart failure during weaning—while mechanically ventilated with positive end-expiratory pressure (PEEP) of 6 cmH_2O and a pressure support level of 8 cmH_2O. This patient shows dynamic hyperinflation (average corrected intrinsic PEEPi 8 cmH_2O), and major recruitment of expiratory muscles (as reflected by the raising Pga during expiration). Of note, the presence of numerous ineffective triggering efforts indicated by the arrows (ventilator respiratory rate is about 18 breaths/min and the patient's respiratory rate is about 28 breaths/min). From Cabello B, Mancebo J (2003) Withdrawal from mechanical ventilation in patients with COPD: the issue of congestive heart failure. In: Vincent J-L (ed) Yearbook of intensive care and emergency medicine. Springer-Verlag, Berlin, Heidelberg, pp 295–301

alveolar ventilation and reduce the respiratory muscle workload. Extracorporeal CO_2 removal can also be used to accelerate weaning from endotracheal intubation as it may prevent ineffective shallow-breathing patterns and reduce inspiratory work by maintaining stable $PaCO_2$ levels during unsupported breathing [85]. Although these devices eliminate carbon dioxide efficiently, experimental evidence of their effectiveness in patients with COPD is limited. Demonstrating benefits in COPD will be challenging because of complications associated with extracorporeal CO_2 removal [86].

Another strategy to improve the prognosis of COPD patients is to optimize patient-ventilator interaction. Contrary to what occurs with pressure support ventilation, proportional modes of ventilation assist the patient by delivering a level of assistance that is proportional to his/her inspiratory effort [87]. There are two proportional modes: neurally adjusted ventilatory assist (NAVA) and proportional assist ventilation (PAV). NAVA is a mode that triggers, cycles and regulates inspiratory airflow based on the diaphragmatic electromyography signal. There is no influence of PEEPi during the ventilator assistance, since it starts with the patient's own breathing effort; furthermore, thanks to better patient-ventilator interaction, there should be no effect of leaks during NIV [88–90]. Several studies have shown that NAVA improves patient-ventilator interaction, diaphragm efficiency and patient comfort, as compared with pressure support ventilation [91]. However, no clear clinical advantage of NAVA over PAV has been demonstrated, although NAVA might be beneficial in difficult weaning [91, 92]. With PAV, the inspiratory assist is proportional to the activity of the inspiratory muscles, which is calculated from the measured flow and volumes using the equation of motion of the respiratory system [87]. PAV protects against high tidal volume and subsequent dynamic hyperinflation [93]. The use of PAV is associated with a shorter weaning time compared with pressure support ventilation [94].

A striking feature of patients treated with NIV or invasive ventilation is the high rate of ICU or hospital readmissions [95]. At least 50% of patients surviving an ICU stay will be readmitted within a year, and this percentage can reach 80% in some studies. Two factors may explain this high rate. First, patients may continue to need ventilation at home [96], but this practice has not been developed widely. Recent trials of home NIV for patients surviving an ICU admission suggest important potential benefits [34]. Second, many of these patients have untreated or undiagnosed comorbidities, especially sleep-related breathing disorders and cardiac dysfunction [97, 98]. New approaches are needed to reduce this high readmission rate.

Ultrasound can be used to evaluate respiratory muscle function and help manage mechanically ventilated patients [99], as it can give a gross estimation of diaphragm function [100]. In patients presenting with acute exacerbations of COPD in the emergency room, diaphragm dysfunction was associated with NIV failure [101], but these results have not been prospectively validated. Diaphragm dysfunction is also associated with a higher risk of weaning failure [102, 103]. Ultrasound can also be used to examine extra-diaphragmatic inspiratory muscle function, focusing on the intercostal parasternal muscle for example [104] (Fig. 6). Increased parasternal intercostal activity is associated with diaphragm dysfunction and weaning failure [104]. Ultrasound can also be applied to image the lungs in COPD, and may be useful in differentiating causes of acute dyspnea in these patients [105]. It can also help in identifying pneumothorax, pleural effusion, consolidation or cardiogenic edema. Whether such ultrasound imaging of the respiratory muscles improves patient outcomes remains to be determined. In addition, training and skills are required to ensure safe and worthwhile implementation.

Summary

Mechanical ventilation is the cornerstone of the management of COPD and asthma patients presenting with life-threatening respiratory failure. Although NIV prevents the majority of patients with COPD exacerbation from subsequently needing invasive ventilation, future efforts should focus on improving the efficacy of NIV and on evaluation of the high-flow nasal cannula technique. Invasive mechanical ventilation is reserved for patients who fail NIV and are subsequently intubated. The major goal during invasive mechanical ventilation is to limit hyperinflation; this is achieved through reduced minute ventilation, low tidal volumes and prolonged expiratory time. Normalization of blood gas is a secondary therapeutic goal. A low level of external PEEP may be applied to patients triggering their ventilator. Mechanical ventilation of asthma patients follows the same rules except that the use of NIV is not presently recommended despite promising recent data. Weaning should be performed as expeditiously as possible with a daily screening test followed by a trial of spontaneous breathing. In selected patients, prophylactic post-extubation NIV prevents post-extubation acute respiratory failure and subsequent reintubation. High-flow nasal cannula seems as efficient as NIV to prevent reintubation and the combination of NIV and high-flow nasal cannula may be even more efficient. Finally, tracheostomy should be the subject of a multidisciplinary discussion.

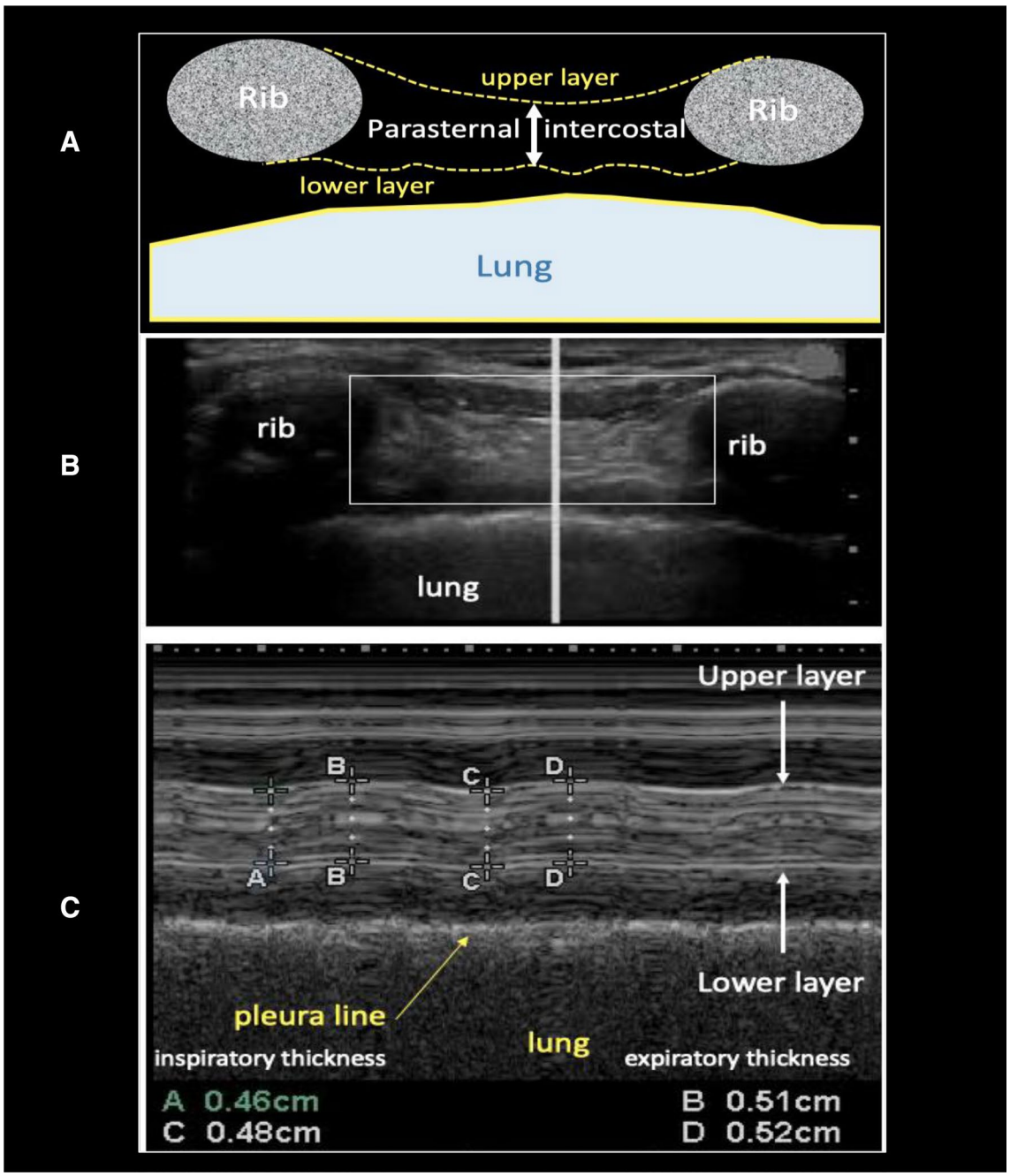

Fig. 6 Schematic representation (**A**) and ultrasound images of the parasternal intercostal muscle with B mode (**B**) and time motion mode allowing measurement of inspiratory and expiratory thickness (**C**)

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Compliance with ethical standards

Conflicts of interest

AD reports personal fees from Medtronic, grants, personal fees and non-financial support from Philips, personal fees from Baxter, personal fees from Hamilton, personal fees and non-financial support from Fisher & Paykel, grants from French Ministry of Health, personal fees from Getinge, grants and personal fees from Respinor, grants and non-financial support from Lungpacer, outside the submitted work. LB conducts an investigator-initiated trial on PAV+ (NCT02447692) funded by the Canadian Institute for Health Research and a partnership with Medtronic Covidien; his laboratory also receives grants and non-financial support from Fisher & Paykel, non-financial support from Air Liquide Medical System, non-financial support from Philips, non-financial support from Sentec, other from General Electric (patent). MD reports personal fees from Lungpacer Med Inc, grants from French Ministry of Heath outside the submitted work. LH reports a research grant paid to institution from Liberate Medical (USA) and speakers fee from Getinge Critical Care. AJ reports grant from the National Institute of Health (RO1-NR016055). FL reports research grants from the National Institutes of Health, VA Research Service, Liberate Medical LLC, and the National Science Foundation, all outside the submitted work. AM-D reports research grants from Fischer Paykel, Baxter, Philips, Ferring and GSK; participation to advisory board for Air Liquide, Baxter, and Amomed, lectures for Getingue and Addmedica. SN report advisory board for Philips and Breas and speaking fee from Resmed Italy outside the submitted work. OP reports no conflict of interest. LO-B reports no conflict of interest. LP reports lecture fees from Hamilton Medical and Getinge and personal fees from Löwenstein, all outside the submitted work. TV reports no conflict of interest. JM reports personal fees from Faron, personal fees from Medtronic, personal fees from Janssen, grants from Covidien (Medtronic) and CIHR, and reimboursement of travel and hotel expenses to attend a meeting from IMT Medical, all outside the submitted work.

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