Ventilatory support in the intensive care unit

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Abstract

This article focuses on the functional features of positive-pressure ventilators, the modes of invasive and non-invasive mechanical ventilation, and the main ventilator settings. It also highlights the potential complications of mechanical ventilation, the basic principles of weaning, and the pathophysiological basis of patient-ventilator dyssynchrony.

Keywords Complications; modes of mechanical ventilation; patient-ventilator dyssynchrony; ventilator settings; weaning

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Learning objectives

After reading this article, you should be able to:

- describe the physiological basis of mechanical ventilation and the functional features of positive-pressure ventilators
- describe the basic modes of mechanical ventilation and how to set the ventilator in different modes
- describe the basic principles of weaning from mechanical ventilation
- list the most severe complications of mechanical ventilation

Basic features of positive-pressure ventilators

The main purposes of instituting mechanical ventilation are[1] to decrease the work of breathing,[2] to support gas exchange and[3] to buy time for other innervations to reverse or treat the cause of respiratory failure.

The ideal ventilator would require:

- a leak-proof connection between the ventilator and the patient
- a signal to initiate an inspiration
- variables regulating the amount of air to be provided during inspiration
- a signal to terminate inspiration
- a regulated pressurized air/oxygen blender.

The signal to start inspiration, that is, the delivery of air/oxygen with positive pressure, is termed **triggering variable**; the determinant of the amount of air/oxygen to be provided during inspiration is termed **control variable**; the signal to end inspiration is termed **cycling off variable**.

The triggering variables found in ICU ventilators are:

- **Time**: when the ventilator breathing frequency is set by the operator (controlled modes), a breath is initiated at regular intervals (every x sec, where $x = 60$/breathing frequency).
- **Pressure**: the inspiration begins when the patient's effort decreases the pressure in the circuit by an operator-defined level.
- **Flow**: a continuous flow is established in the circuit (bias flow), and the inspiration begins when the patient's effort decreases the flow measured at the expiratory controller by an operator-defined level.
- **Flow waveform**: software computes a signal that is a 'shadow' of the expiratory flow signal with some delay, and when patient's actual expiratory flow crosses the 'shadow signal', inspiration starts. Flow waveform as a trigger variable is currently used only in non-invasive ventilators.
- **Electrical activity of the diaphragm**: a nasogastric tube equipped with a sensor for the electrical activity produced by diaphragmatic contraction provides a signal for the initiation of inspiration in the mode of ventilation called neurally-adjusted ventilatory assist (NAVA).

Once triggered, the ventilator must 'know' how to deliver the pressure, and this is determined by the **control variable**. The control variables available in ICU ventilators are:

- **Volume**: the operator defines the volume of oxygenated air to be delivered in each breath, and the profile of the flow −time relationship.
- **Pressure**: the operator sets the positive pressure that will be applied in the circuit during inspiration.
- **Electrical activity of the diaphragm**: the operator sets the ratio of pressure with the diaphragmatic electrical activity signal (measured by the dedicated sensor as described above). This mode of pressure delivery is used in NAVA.
- **Instantaneous flow and volume** generated by the patient's effort: the ventilator delivers pressure, which is proportional to the pressure generated by the patient expressed as the instantaneous flow and volume, the operator defines the proportionality. This mode of pressure delivery is used in the mode of ventilation called Proportional Assist Ventilation (PAV).

Modern ventilators use software to combine the basic control variables, so that the operator may define a target for ventilation, (either tidal volume or minute ventilation). The ventilator adjusts the delivered pressure to achieve the set target taking into account the patient's contribution in each breath.

The signal to the ventilator to terminate the mechanical inspiration and allow passive expiration is the cycling off variable. The cycling off variables used in ICU ventilators are:

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- **Time**: the operator defines the duration of inspiration. Time is used as cycling off variable when it is also selected as the triggering variable. The modes where the operator defines the respiratory rate and its timing are called 'controlled' modes. In most ventilators, time as cycling off criterion is also used in assisted modes of mechanical ventilation as a safety feature when the duration of inspiratory flow is considerably long (i.e. $>$ 3 sec).
- **Flow**: the inspiration ends when the inspiratory flow has decreased to a fixed value or operator-defined (featured in new generation ventilators) percentage of its peak value.
- **Pressure**: when airway pressure increases above a predefined threshold (1–3 cmH_2O), the pressure delivery by the ventilator stops. This cycling off criterion (not adjustable by the operator) is usually present as a safety feature, along with the flow criterion.
- **Electrical activity of the diaphragm**: the operator defines the decrease of diaphragmatic activity to signal the end of inspiration.

Modes of mechanical ventilation

Non-invasive mechanical ventilation (NIMV)

NIMV refers to positive-pressure ventilation delivered through the physiological airway using a non-invasive interface (nasal mask, facemask). The use of NIMV is associated with decreased need for endotracheal intubation and sedation, reduction in ICU length of stay and mortality, as well as decreased rate of ICU-related infections. Not all patients with respiratory failure are eligible for NIMV. Contraindications for the use of NIMV include cardiac or respiratory arrest, inability to keep a patent airway and to manage secretions, anatomical abnormalities (facial or upper airway trauma, surgery), intractable emesis or GI bleeding and severe haemodynamic instability.

Application of NIMV as first initial ventilation support has been proven to be effective in patients with acute exacerbation of COPD and hypercapnic acidosis, pulmonary edema and post-operative respiratory failure (either as preventive or curative approach). In patients with de novo respiratory failure or ARDS (especially in moderate and severe disease), a high rate of NIMV failure has been reported associated with increased mortality.

Close monitoring of the patient is required in the first 1–2 hours following initiation of NIMV for early recognition of signs of NIMV failure. Various risks have been associated with NIMV failure including disease severity, comorbidities, shock, impaired level of consciousness, severe acidosis and failure to improve after 1–2 hours of NIMV. Criteria for initiation and termination of NIMV are presented in Box 1.

NIMV can be delivered using either NIMV-dedicated devices or ICU ventilators. Currently two main modes of NIMV are used: continuous positive airway pressure (CPAP) and bilevel positive airway pressure (BiPAP). CPAP is mainly used in patients with variable airway obstruction (obstructive sleep apnoea syndrome). CPAP has also been used in patients with hypoxaemic respiratory failure due to cardiogenic pulmonary oedema. BiPAP delivers both inspiratory positive airway pressure (IPAP) and expiratory positive airway pressure (EPAP). It is the preferred initial mode in hypercapnic respiratory failure (e.g. in COPD patients).

Criteria for initiation and termination of NIMV

Criteria for initiation of NIMV

- Absence of contraindications
- Increased dyspnoea (moderate to severe)
- Tachypnoea (>24 breaths/min in obstructive and >30 in restrictive disease)
- Signs of increased work of breathing, use of accessory muscles, abdominal paradox
- Acute or acute on chronic respiratory failure (COPD) $PaCO_2 > 6$ kPa (45 mmHg)
- H^+ 50 nmol (PH< 7.35)
- Hypoxaemia not corrected by oxygen therapy alone (use with caution)
- PO_2/FiO_2< 40kPa (300 mmHg)

Criteria for termination of NIMV

- Haemodynamic instability
- Decrease level of consciousness
- Increase $[H^+]$ and $PaCO_2$
- Worsening PaO_2
- Tachypnoea >30 b/min
- Severe dyspnoea
- Signs of increase work of breathing
- Inability to clear secretions
- Agitation or intolerance to NIV with progressive respiratory failure

Box 1

Invasive mechanical ventilation

In mechanically ventilated patients, the total pressure applied to the respiratory system at time t ($P_{TOT(t)}$) is the sum of the pressure generated from respiratory muscles (Pmus(t)) and the pressure provided from the ventilator (Paw(t)).

According to the equation of motion, $P_{TOT(t)}$ is dissipated to overcome the resistive pressure (Pres(t) = V'(t)xRrs) and elastic recoil pressure (Pel(t) = ΔV(t)xErs) of the respiratory system, determining the volume time profile as follows:

$$P_{TOT(t)} = Pmus(t) + Paw(t) = Pres(t) + Pel(t) = V(t)xRrs + \Delta V(t)xErs$$

(Rrs: respiratory system resistance; Ers: respiratory system elastance.)

Applying the equation of motion helps the physician to comprehend the physiological basis of different modes of mechanical ventilation.

Controlled modes: in the controlled modes of mechanical ventilation, Pmus is zero and thus the only pressure which is dissipated to overcome Rrs and Ers is the pressure provided by the ventilator Accordingly, the equation of motion is modified as follow:

$$P_{TOT(t)} = Paw(t) = Pres(t) + Pel(t) = V(t)xRrs + \Delta V(t)xErs.$$

Depending on the variable that controls pressure delivery, the modes are defined as volume or pressure controlled.

In volume control mode (VC), (also called volume limited) the variable that controls pressure delivery is the preset flow and volume. Applying the equation of motion implies that the pressure provided by the ventilator depends on the elastance and resistance of the respiratory system and the predefined flow or volume. For example, a high Paw may be a consequence of high tidal volume, a high peak flow, decreased elasticity (e.g. ARDS pulmonary fibrosis) or increased airway resistance (e.g. obstructive lung disease).

In VC mode, the physician has to set the tidal volume (VT), the flow pattern (square/decelerating), the respiratory rate, the PEEP and the FiO_2. The minute ventilation (MV), is determined entirely by the set respiratory rate and VT. The peak flow is either preset or indirectly determined by the respiratory rate, the inspiratory time, and the inspiratory to expiratory (I:E) ratio.

In pressure control mode (PC), the variable that controls the pressure delivery is the pressure (the independent variable in the equation of motion). Consequently, the instant flow and volume is variable and determined by the preset pressure and the mechanical properties of the respiratory system. For example, the VT will be low when the set inspiratory pressure level is low and/or the airway resistance are high. PC mode requires the physician to set the airway pressure, the respiratory rate and the (I:E) ratio, the PEEP, and the FiO_2.

Setting the ventilator in controlled modes: During ventilation in controlled modes, the application of PEEP and FiO_2 should be set to target a certain SpO_2. FiO_2 should be set to the lowest value required to achieve the target oxygenation (SpO_2 of 92%–96% in the majority of patients) to avoid either hypoxaemia or hyperoxia-related complications.

PEEP titration is important to improve V/Q mismatch through the opening and maintaining patent alveoli which tend to close during tidal breathing. Thus, PEEP titration depends on the mechanical properties of the respiratory system and selection of a given PEEP relies on recruitability of the lung. In the majority of patients without severe obstructive lung disease, airflow limitation and the absence of intrinsic PEEP (PEEPi), a minimum initial PEEP of 5 cmH_2O is used. In ARDS, individualization of PEEP is suggested to optimize compliance and minimize driving pressure (ΔP, the difference between end-inspiratory airway pressure and PEEP). In selected patients, such as those with suspected low chest wall compliance or severe ARDS, trans-pulmonary pressure at end expiration (PLexp, the difference between Paw and the oesophageal pressure, Peos) can be used to ensure the adequate PEEP level (Box 2).

Selecting the optimum tidal volume in patients during controlled modes is crucial for achieving the best clinical outcome. VT should be set in a range between 6 and 8 ml/kg IBW. However, in patients with flow limitation, as patients with obstructive lung diseases, it often becomes necessary to limit VT, even below 6 ml/kg and accept a higher than normal $PaCO_2$ (permissive hypercapnia) to minimize dynamic hyperinflation and intrinsic PEEP (PEEPi). In patients with ARDS, setting the VT $\leq$6 ml/kg IBW is considered the cornerstone of protective mechanical ventilation. Further VT adjustment targeting to different physiological determinants that have been proven to prevent ventilator-induced lung injury are presented in Box 2. When hypercapnia is excessive for the desired VT, measures to decrease circuit dead space (i.e. use humidifiers instead of heat and moisture exchanger) and CO_2 production (i.e. temperature control) or novel adjunctive therapies (e.g. extracorporeal CO_2 removal) should be considered.

In patients ventilated in PC, the inspiratory time will determine the tidal volume for a given inspiratory pressure. Therefore, a change in tidal volume can be made by changing either inspiratory pressure or time.

Setting the respiratory rate (RR) complementary to selected VT aims to reach the minute ventilation, which will achieve the target for $PaCO_2$. RR setting also aims to achieve the preferred I:E ratio and/or the inspiratory plateau time (applied in VC). Applying inspiratory plateau time provides an additional time of lung inflation and is the desired setting in ARDS. On the contrary in COPD patients, reducing inspiratory plateau time represents one of the principal ventilator strategies aiming to decrease dynamic hyperinflation – for the same RR, the expiratory time increases, leading to a higher rate of lung emptying.

Assisted modes of ventilation

Pressure support ventilation (PSV) is the most commonly used mode of assisted ventilation in clinical practice. With this mode the ventilator, once triggered, provides a pre-set level of constant pressure which is independent of the patient's effort.

According to the equation of motion (see above), this pressure is added to Pmus and as a result the patient's effort is amplified. During the inflation phase a regulatory mechanism maintains the proper flow necessary to achieve the appropriate preset pressure

Strategies to prevent ventilator-induced lung injury

Ventilation strategies

- Ventilation strategies to protect from excessive stress and strain
  - VT to target a predicted ideal body weight (IBW) of approximately 6 ml/kg
  - VT adjusted to reduce dynamic strain (VT/FRC)
  - VT adjusted to achieve a $\Delta P < 14$ cmH_2O
  - Pplat <28 cmH_2O
  - End-inspiratory transpulmonary pressure <24 cmH_2O
- Ventilator strategies to reduce lung inhomogeneity
  - PEEP to target an end-expiratory transpulmonary pressure of 0–10 cmH_2O
  - Lung recruitment manoeuvres
- Non-ventilator strategies to protect from VILI
- Prone positioning
- Neuromuscular blockade
- Extracorporeal dioxide removal ($ECCO_2R$) and the extracorporeal membrane oxygenation (ECMO)

VT, tidal volume; IBW, ideal body weight; ΔP, driving pressure = Pplat – PEEP; Pplat, end-inspiratory pressure; PEEP, positive end-expiratory pressure

Box 2

which is kept constant until expiration occurs. The rate of pressurization to preset pressure — referred as rising time — is adjustable and influences the peak inspiratory flow as well as the duration of mechanical inspiration. Cycling off occurs when a predefined criterion is met (see above). In PSV the ventilator settings required for the proper function of the ventilator include PEEP and FiO_2, the level of assist, the triggering and cycling off variable and threshold, and the rising time.

As with controlled modes, both PEEP and FiO_2 are set to target adequate oxygenation. A minimum level of 5 cmH_2O PEEP is suggested for preventing atelectasis even in patients with previously normal respiratory mechanics. In patients with dynamic hyperinflation, application of PEEP aims to improve ventilator performance at triggering (by counterbalancing PEEPi). External PEEP at about 80% of PEEPi has been shown to substantially decrease inspiratory elastic workload at triggering without further increasing in dynamic hyperinflation.

During PSV VT is variable, and depends on the preset pressure level, respiratory system mechanics and inspiratory muscle effort. As a starting point, PS level is set to target a VT of 6–8 ml/kg IBW although individualization of the PS level is of importance in avoiding the delivery of either excessive or insufficient VT. Excessive level of assist (higher than patient's needs) is associated with patient–ventilator dyssynchrony at expiration (delayed opening of the expiratory valve) and induces respiratory alkalosis. In patients with a pre-existing low respiratory drive (i.e. metabolic alkalosis and sedation), excessive levels of assist promotes periodic breathing. Furthermore, in patients with obstructive lung diseases, it may lead to high tidal volume and dynamic hyperinflation leading to triggering delay and ineffective efforts (Figure 1a). On the other hand, when the level of assist is insufficient for the patient's demands, vigorous inspiratory efforts may result in patient–ventilator asynchrony (in the form of double triggering or breath stacking) (Figure 1b).

Furthermore, the mismatch between a patient's ventilation demands and ventilator assistance may be associated with patient discomfort and increased work of breathing.

Setting the triggering and cycling off criteria as well the rising time is individualized, targeting the synchronization of the mechanical breath with the patient's inspiratory effort in terms of timing (matching between mechanical and neural inspiratory time). Patient–ventilator dyssynchrony is a common phenomenon during PSV (and other conventional modes of assisted mechanical ventilation) and has been shown to affect patient outcome adversely. Different forms of patient–ventilator dyssynchrony, their predisposing factors and the possible interventions for eliminating or reducing them are summarized in Table 1.

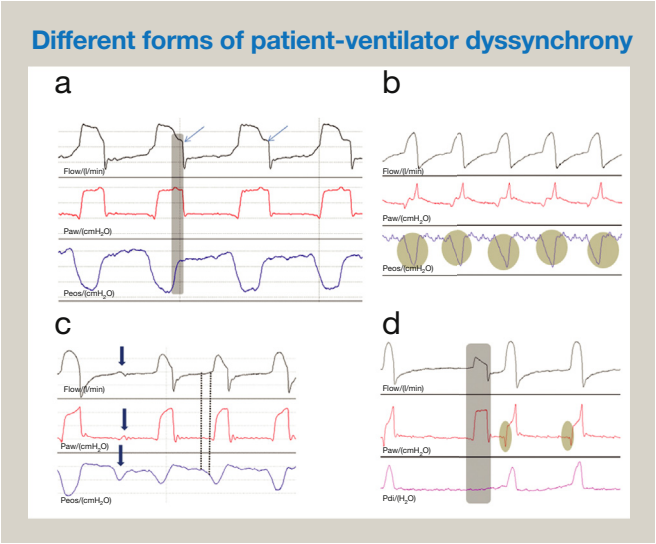

Figure 1 Different forms of patient-ventilator dyssynchrony. **(a)** Flow, airway pressure (Paw) and oesophageal pressure (Pes) waveforms in a patient ventilated on PSV at **high assist level** indicated by the square-shaped Paw and the sharp decrease in inspiratory flow to cycling off (arrows). There is also significant **cycling off delay** (grey shaded area). Note that Pes increase rapidly, but mechanical inflation continues into neural expiration. **(b)** Flow, Paw, and Pes waveforms in a patient on PSV with **low ventilator assist**. Notice the vigorous contraction of inspiratory muscles (deep decrease in Pes, green shaded area) during the mechanical inspiration. Observe that inspiratory flow is rounded and that there is a substantial decrease of Paw from the expected square-shaped form during inspiration. **(c) Ineffective effort and triggering delay.** Paw, flow, and Pes waveforms in a COPD patient ventilated on PSV. The second Pes (represents inspiratory effort) is not followed by a mechanical breath indicating an ineffective effort during expiration. It is manifested by a slight decrease in Paw and simultaneous decrease in expiratory flow (blue arrows). Notice also that in every mechanical breath, there is a time lag between the start of neural inspiration (first dotted line) and the start of mechanical inspiration (second dotted line) defined as triggering delay. **(d) Autotriggering.** Flow, Paw and diaphragmatic pressure (Pdi) waveforms of a patient ventilated on PSV. As indicated by the absence of Pdi increase, there is no inspiratory effort before the second mechanical breath (autotriggered breath, grey shaded area). Notice that compared to patient triggered breaths, where a decrease in Paw is observed before the start of mechanical inflation (green shaded areas), there is no distortion in the Paw and flow-time curve in the autotriggered breath. Moreover, the shape of the inspiratory flow-time curve is different compared to that of patient-triggered breaths.

Proportional modes of assisted mechanical ventilation: In the last two decades new forms of assisted ventilator modes have been introduced that utilize the patients' inspiratory effort to deliver inspiratory pressure offering several physiological advantages, compared with the conventional modes of assisted MV.

Proportional assist ventilation with load-adjusted gain factors (PAV+) is a patient's effort driven ventilator modality. With this mode the ventilator provides pressure proportionally to patients instant flow and volume and thus proportionally to elastic and resistive workload.

An algorithm permits the calculation of the elasticity (Ers) and resistance (Rrs) of the respiratory system in a semi-continuous fashion. This allows appropriate adjustment the flow and volume gain factors. What is set by the caregiver is the level of unloading, defined as gain and expressed as the percentage of the Ers and Rrs of the respiratory system. PAV+ decreases the triggering delay and the likelihood of ineffective efforts and expiratory asynchrony, increase sleep efficiency, and promotes breathing stability. Furthermore, PAV+ permits the continuous monitoring of respiratory system mechanics. On the

Interventions to eliminate or reduce patient-ventilator dyssynchrony

Phase	Type of asynchrony	Definition	Causes	Ventilator waveform Characteristics	Suggested Interventions
Triggering phase	**Triggering delay**	Increase in time lag between initiation of inspiratory muscle effort and ventilator triggering	- DH -High triggering threshold -High ventilator assist -Low respiratory drive	Abrupt increase in inspiratory flow and/or an abrupt decrease in expiratory flow and small decrease in Paw are not followed by ventilator triggering	*Interventions to increase respiratory drive* -Decrease assist level - Decrease sedation *Interventions to decrease DH* -Decrease airway resistance -Decrease T_Im (low assist level, - Increase V'th *Application of external PEEP to balance PEEPi*
	Ineffective efforts	Inspiratory efforts not followed by ventilator triggering	-Low inspiratory muscle output -Delayed opening of exhalation valve in the previous breath		
	Auto-triggering	Ventilator triggering in the absence of patient effort	-Low threshold for triggering -Circuit leaks -Presence of water in the circuit -Cardiogenic oscillators -Hiccup	-Absence of the initial pressure drop below PEEP -Triggering occurring synchronously with cardiogenic oscillations,	-Increase triggering threshold -Elimination in circuit leaks
Inflation phase	**Excessive Assist**			-Abrupt decrease in inspiratory flow to V'th - Square shaped Paw	Decrease PS level
	Insufficient Assist			-Rounded or constant inspiratory flow waveform	-Increase assist level -Decrease ventilation demands
Cycling off phase	**Delayed opening expiratory valve**	$T_I M > T_I N$	- Long time constant of the respiratory system (Obstructive lung disease) -High Assist level -DH Low V'th	-A small spike (increase) in Paw near the end of breath. - Abrupt decrease in inspiratory flow followed by an exponential decline toward the end of mechanical inspiration	Increase V'th, - Decrease the PS level -Decrease the rise time - Measures to decrease DH
	Premature opening of expiratory valve	$T_I M < T_I N$	-Short time constant (restrictive lung disease, ARDS) -High V'th Low PS level	-Zero or low inspiratory flow for short time instantaneously after Paw decreases to PEEP level -Convex pattern of expiratory flow	-Decrease V'th, -Increase the PS level -Decrease rising time
	Double triggering	One inspiratory effort triggers the ventilator twice	-Strong inspiratory efforts		-Decrease V'th, -Increase the PS level -Decrease rise time -Decrease ventilation demands

DH: Dynamic Hyperinflation; PEEP: Positive —end-expiratory Pressure; PEEPi: intrinsic Positive —end-expiratory Pressure; PS: Pressure support;V'th Flow threshold for cycling off; $T_I M$: mechanical inspiratory time; $T_I N$:neural inspiratory time; Paw: Airway pressure.

Table 1

other hand, in certain conditions, PAV+ may result in inappropriate ventilation assist.

With PAV+ inspiratory effort drives the ventilator, implying that this mode should be applied with caution in patients with depressed respiratory centre (i.e. central nervous system diseases, sedatives, metabolic or respiratory alkalosis) and decreased respiratory muscle output (i.e. neuromuscular disorders) as these may lead to hypoventilation. PAV+ may be associated with inadequate ventilation assist in patients with dynamic hyperinflation. With the presence of dynamic hyperinflation in flow and pressure triggering systems, a portion of the patient's inspiratory effort is dissipated to trigger the ventilator.

Since with PAV/PAV+ the signals for pressure delivery are inspiratory flow and volume, the assisted inspiratory effort is reduced by an amount equal to that needed to trigger the ventilator.

Neurally adjusted ventilatory assist (NAVA) – uses the electrical activity of the diaphragm (EAdi) to trigger and cycle off inflation and delivers pressure in proportion to the patient's inspiratory effort. The EAdi signal is proportional to the intensity of the diaphragmatic contraction. The more the diaphragm contracts, the greater the level of support delivered by the ventilator. Detection and quantification of the (EAdi) are obtained using an oesophageal array of bipolar electrodes mounted on a feeding tube and processed to provide the highest possible quality of the signal. The triggering occurs when the EAdi increase above a minimum default value (usually set at 0.5 μVolts). A 70% decrease in EAdi from its maximum value cycles-off the ventilator. During the inflation phase, the pressure provided by the ventilator for a given level of EAdi depends on an operator-adjustable proportionality factor that determines how much pressure will be delivered for a given EAdi amplitude. Adequate ventilator support implies that all the receptors of the respiratory system's feedback mechanism are sufficiently functional and that their signals are interpreted correctly by the respiratory centre. Since the mechanical breath is tightly linked to inspiratory muscle, ventilation on this mode has been proven to be associated with a lower rate of patient–ventilator asynchronies.

Weaning the patient from mechanical ventilation

Although often life saving, mechanical ventilation is associated with several life-threatening complications. Accordingly, it is important to discontinue mechanical ventilation and extubate the patient at the earliest possible time.

Weaning – defined as the entire process of liberating the patient from mechanical support and the endotracheal tube – consumes over 40% of total ventilator time. Depending on the spontaneous breathing trials (SBT) required for a successful extubation, patients are categorized as having simple (extubated after one SBT), difficult (extubated after the second or third SBT within 7 days from the first attempt) or prolonged weaning (extubated more than three SBT or longer than 7 days from the first attempt). Weaning failure – defined as the failure to pass an SBT or the need for re-intubation or NIV support within 48 hours following extubation – has been associated with unfavorable outcome.

To minimize mechanical ventilation-induced complications, weaning should be started as soon as possible. The patient's readiness for weaning should be evaluated daily using established objective criteria including adequate oxygenation, haemodynamic stability, an adequate conscious level, adequate cough, secretion management and rapid shallow breathing index (RSBI, the ratio of respiratory rate to tidal volume; RSBI <100 after 2 minutes of an SBT). An SBT simulates patient's ability to undertake the entire respiratory workload without assistance. Although the appropriated SBT technique remains controversial, recent evidence supports that an SBT should be performed either with a T-piece or the unassisted ventilation method (without PSV and PEEP), as both methods most accurately simulate the post-extubation respiratory workload.

In the majority of patients, 30 minutes of spontaneous breathing is adequate in identifying success or failure of the SBT. However, in patients at high risk for reintubation, such as elderly patients with COPD, heart failure or neuromuscular disorders, SBT may have to last for longer (up to 120 minutes). The outcome (successful/failure) of an SBT is defined based on specific criteria. Following successful SBT, patients could proceed to extubation.

Following failure of an SBT and before attempting a new SBT, the pathophysiologic mechanisms that led to weaning failure and the appropriate therapeutic approach must be evaluated. The most common pathophysiologic mechanisms associated with weaning failure are listed in Box 3.

Complications of mechanical ventilation

Although mechanical ventilation is life-saving, it is associated with significant complications that may affect patients outcome.

Ventilator-induced lung injury

Both clinical and experimental studies have shown that mechanical ventilation per se may aggravate or even initiate lung injury even in previously healthy lungs. This entity is histopathologically indistinguishable from ARDS and is called Ventilator-Induced Lung Injury (VILI). The pathophysiological basis of VILI is complex and characterized by different overlapping interactions.

Mechanical ventilation resulting in high distending pressures and volumes can lead to barotrauma or volutrauma. Stress (the transpulmonary pressure) instead of barotrauma and strain (static equals to VT and dynamic equals to VT/FRC ratio) describe the mechanisms of lung injury more accurately. Cyclic opening and collapse of such atelectatic but recruitable lung units

Pathophysiologic mechanisms associated with weaning failure

- Hypoxaemia
- Increased work of breathing:
  - Increased ventilatory demand
  - Increased resistive load
  - Increased elastic load
- Decreased neuromuscular capacity
  - Respiratory muscle weakness-fatigue
  - Decreased ventilatory drive
- Cardiac dysfunction
  - Myocardial ischemia
  - Pulmonary edema
  - Fluid overload
- Psychological dysfunction
  - Delirium
  - Anxiety
- Metabolic, electrolyte and endocrine abnormalities

Box 3

during tidal ventilation contribute to lung injury termed atelectrauma. Different mechanisms related to lungs parenchyma heterogeneity – a key feature in ARDS lung – has been increasingly recognized as a significant determinant in the pathogenesis of VILI. We now know that the same applied stress and strain may have considerably variable effects on different lung units, depending on the heterogeneity of the lung parenchyma. Mechanical injury triggers a pro-inflammatory and pro-injurious cytokine process termed biotrauma that has been associated with injury in previously unaffected lung units and more importantly, with multiple organ failure.

Increased understanding of VILI pathogenesis has led to various preventive ventilator strategies targeting different underlying mechanisms that are summarized in Box 2.

Ventilator-induced diaphragmatic dysfunction (VIDD)

Ventilator-induced diaphragmatic dysfunction (VIDD) refers to a loss of diaphragmatic force-generating capacity specifically related to the use of mechanical ventilation. Data from both clinical and animal studies strongly suggest that the onset of force loss after initiating mechanical ventilation is rapid. Twelve hours of controlled MV results in a 15% reduction in the number of diaphragmatic fibres and this reduction approaches 30% after 18–24 hours. Although assisted mechanical ventilation has been previously associated with attenuation of VIDD, recent evidence supports that excessive level of assistance may also result in diaphragmatic atrophy and contractile dysfunction, albeit at a slower rate. The pathophysiological processes leading to VIDD involves different cellular mechanisms including oxidative stress, activation of several proteolytic pathways, and mitochondrial dysfunction within the diaphragm. VIDD is associated with difficult weaning, weaning failure and increased ICU and hospital mortality.

Ventilator-associated pneumonia (VAP)

Ventilator-associated pneumonia (VAP) refers to pneumonia develops more than 48 hours following endotracheal intubation and mechanical ventilation. Microaspiration from the oropharyngeal cavity and diminished host defense due to decreased cough efficiency and impaired mucociliary clearance are the possible pathogenetic mechanisms. VAP is the second most common infection in the ICU and is associated with an increase in both morbidity and mortality (mortality directly associated with VAP is estimated at 9–13%). Diagnosis of VAP is based on both clinical and microbiological criteria. Various measures to prevent VAP have been suggested including alcohol-based hand hygiene, nursing the patient in a semi-recumbent position, continuous subglottic secretion drainage, use of heat and moisture exchange filters, minimizing ventilator circuit manipulation, thromboprophylaxis and more importantly the early discontinuation of MV. ◆

FURTHER READING

Georgopoulos D, Prinianakis G, Kondili E. Bedside waveforms interpretation as a tool to identify patient-ventilator asynchronies. *Intensive Care Med* 2006; **32:** 34–47.

Branson RD, Hess DR, Chatburn RL, eds. Respiratory care equipment. 2nded. Philadelphia: Lippincott Williams and Wilkins, 2000.

Tobin MJ, ed. Principles and practice of mechanical ventilatio. Mc Graw Hill, 2013.

Rochwerg B, Brochard L, Elliott MW, et al. Official ERS/ATS clinical practice guidelines: noninvasive ventilation for acute respiratory failure. *Eur Respir J* 2017; **50:** 1602426. https://doi.org/10.1183/13993003.02426-2016.

Akoumianaki E, Kondili E, Georgopoulos D. Proportional assist ventilation. Chapter 7 in european respiratory monograph 2012; vol. 55; 97–115.

Perren A, Brochard L. Managing the apparent and hidden difficulties of weaning from mechanical ventilation. *Intensive Care Med* 2013; **39:** 1885–95.

ESICM Academy –ACE e-course: mechanical ventilation https://academy.esicm.org/enrol/index.php?id=162.

Hughes M, Black RG, eds. Advanced respiratory critical care 2011. Oxford University Press, http://ukcatalogue.oup.com/product/9780199569281.do.