Basic Modes of Mechanical Ventilation

Jared Ward, DO, MPH[a,*], Christopher Noel, MD[b]

KEYWORDS

• Mechanical ventilation • Ventilator modes • Ventilator management

KEY POINTS

- Respiratory failure requiring mechanical ventilation is common; emergency medicine providers must have expertise in ventilator management.
- Ventilators overcome resistance and compliance of the respiratory system to deliver gas flow. The relative contribution of each is easily measured and can help guide management.
- There is no perfect mode of mechanical ventilation. Each has its strengths and weaknesses and can be adapted to most clinical scenarios. The best mode is often the one that providers and staff are most familiar with.

INTRODUCTION

Emergency medicine (EM) providers are responsible for caring for a broad range of critically ill patients in acute, uncertain states of disease. Many of these patients require invasive mechanical ventilation for respiratory support and can spend prolonged periods of time under the care of EM providers.

With this responsibility, EM providers must have expertise in ventilator management. Yet, surveys indicate limited education and comfort with ventilator management.[1,2] Certainly, there is an opportunity for improvement.

This article aims to bridge the gap by providing an overview of ventilator management with an emphasis on modes, patient–ventilator interactions, and troubleshooting.

GOALS AND GENERAL PRINCIPLES OF MECHANICAL VENTILATION

Goals

The primary goals of mechanical ventilation are to provide physiologic support while minimizing harm. To this end, mechanical ventilation is used to maintain adequate

[a] Critical Care, Inspira Health Network, Inspira Medical Center Vineland, 1505 West Sherman Avenue, Vineland, NJ 08360, USA; [b] Division of Critical Care, Cooper University Health Care, Cooper Medical School of Rowan University, Cooper University Hospital, One Cooper Plaza, D429, Camden, NJ 08103, USA

* Corresponding author.

E-mail address: WardJ@ihn.org

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gas exchange while minimizing harm due to excessive pressure, volume, and cyclic deformation of the lung. Like many critical interventions, it is supportive; it does not fix the underlying process that warrants its use.

Respiratory Mechanics

Mechanical ventilation provides respiratory support by generating positive pressure gas flow into a patient's lungs during inspiration and allowing for passive expiration. In passive or paralyzed patients, inspiration will be entirely controlled by the ventilator. In patients with respiratory drive, the inspiratory gas flow will occur as the result of patient effort and ventilator work.[3]

To deliver breaths, ventilators pressurize gas to overcome resistance to gas flow (from the ventilator tubing, endotracheal tube, and airways) and the elastic recoil of the lungs and surrounding structures. More simply, the pressure needed to inflate the lung is determined by the *resistance* and *compliance* of the respiratory system. Higher pressures are required when resistance increases, compliance worsens (the respiratory system becomes stiffer as indicated by a smaller change in volume per unit change in pressure), or both occur.

Understanding where the problem lies—high resistance or poor compliance—can help identify the initial cause of respiratory failure or sudden decompensation on the ventilator and guide management accordingly. Common causes for high resistance and poor compliance are shown in **Fig. 1**.

Expiration is a passive process that results from the pressure gradient between higher pressure in the alveoli and lower pressure at the ventilator. Importantly, ventilators can apply a positive end-expiratory pressure (PEEP) to lessen this pressure gradient and prevent excessive lung collapse.

Defining a Breath

The amount and timing of gas flow are determined by the inputs to the ventilator. Providers specify when a ventilator breath will occur, how it will be delivered (eg, an

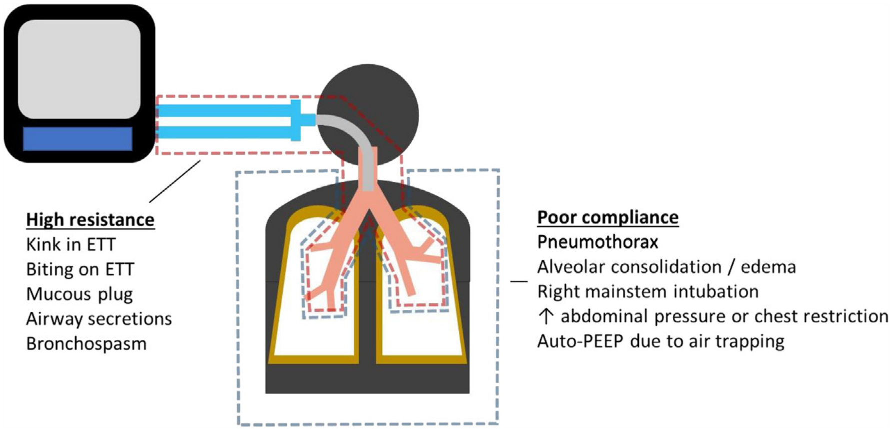

Fig. 1. Common causes for high airway resistance and poor compliance. Areas of the respiratory circuit affecting resistance include the ventilator tubing, endotracheal tube, and airways to the level of the bronchioles. Areas of the respiratory circuit affecting compliance include the lung parenchyma (alveoli), pleural space, chest wall, abdomen, and anything external to the chest wall that exerts collapsing force on the alveoli.

applied pressure or flow rate), and when it will end via the trigger, control, and cycling variables.[3,4]

- *Trigger*: The trigger variable determines when inspiration occurs. This is specified as time (since the last breath) or either pressure or flow to detect when a patient makes an inspiratory effort. Whether pressure or flow serves as the trigger for patient-initiated breaths is rarely of clinical importance.
- *Control (or limit)*: The control variable determines how a ventilator delivers a breath. It is either flow or pressure. With flow, a breath is delivered at a specific flow rate (eg, 60 L per min). With pressure, the ventilator maintains a specific pressure during inspiration, and flow occurs as a result of the pressure differential between the ventilator and the patient's lungs.

The control variable must be either flow *or* pressure. It is impossible to specify both at the same time.

- *Cycling*: The cycling variable determines when inspiration ends and expiration begins. It is either time, volume, or flow—with flow specifying a percentage of peak inspiratory flow when inspiration ends.

The combination of trigger, control, and cycling variables, among others,[5] helps define specific ventilator modes.

COMMON MODES OF MECHANICAL VENTILATION

A ventilator mode is the set of rules, or algorithms, used to deliver breaths throughout the respiratory cycle and is the first selection made when initiating mechanical ventilation.

The names for ventilator modes and the specific algorithms used to define them can vary across different ventilator manufacturers but generally work in the same way. The most common ventilator modes are forms of volume control (VC)—also known as volume assist control, pressure control (PC)—also known as pressure assist control, and pressure support (PS). These are sufficient for most, if not all, clinical scenarios. Other modes rely on more complex algorithms and include pressure-regulated VC (PRVC), synchronized intermittent mandatory ventilation (SIMV), and airway pressure release ventilation (APRV).

The trigger, control, and cycling variables used for each mode are shown in **Table 1**.

Volume Control

In VC ventilation, the same prespecified tidal volume is delivered with each inspiratory cycle, regardless of whether the breath is time or patient triggered (**Fig. 2**).

The key provider settings include:

- Flow rate*
- Tidal volume
- Respiratory rate
- PEEP
- Fraction of inspired oxygen (FiO_2)

* Depending on the ventilator, the user will input either the flow rate and tidal volume or the inspiratory time and tidal volume.

In VC ventilation, pressure is not controlled. It is a dependent variable determined by airway resistance and lung compliance. As resistance increases or compliance worsens, the flow will remain constant, and pressures will rise.

Table 1
Variables defining common ventilator modes

Mode	Trigger	Control	Cycling
Volume control	Time or patient initiated (pressure or flow)	Flow	Volume
Pressure control	Time or patient initiated	Pressure	Time
Pressure support	Patient initiated	Pressure	Flow
Pressure regulated volume control	Time or patient initiated	Pressure	Time

SIMV and APRV are not included as they are beyond the scope of this article.

Advantages of VC ventilation include guaranteed tidal volumes, stable minute ventilation, and the ability to specify a flow rate, which could be advantageous in a setting of high airway resistance.

Disadvantages are that injurious pressures may be generated in the setting of worsening lung compliance or high resistance.

Pressure Control

In PC ventilation, a constant inspiratory pressure is applied throughout inspiration, regardless of whether the ventilator or the patient initiates the breath (Fig. 3).

The key provider settings include:

- Inspiratory pressure*
- Inspiratory time
- Respiratory rate
- PEEP
- FiO_2

* Depending on the ventilator, the user will input either the total inspiratory pressure desired or the inspiratory pressure to be applied above PEEP.

In this mode, flow and resulting tidal volume are dependent variables and vary with changes in airway resistance and lung compliance.

One advantage of PC is that airway and pulmonary pressures never exceed the selected inspiratory pressure. Thus, the risk for barotrauma can be minimized. Another advantage is that patients control their inspiratory flow rate—air flow will increase in proportion to their inspiratory effort, improving patient comfort and minimizing patient–ventilator dyssynchrony.

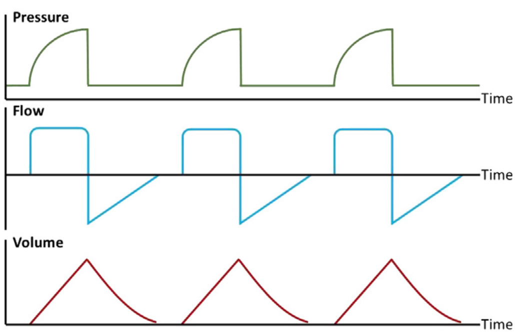

Fig. 2. Volume control waveforms.

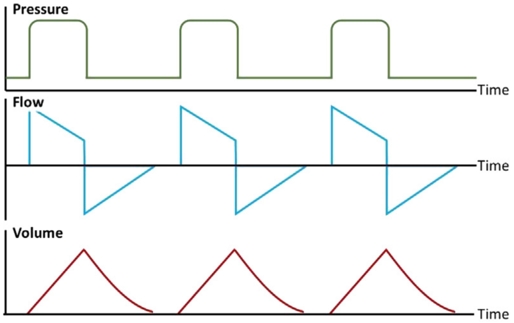

Fig. 3. Pressure control waveforms.

A disadvantage is that the delivered tidal volume can vary. As resistance decreases or compliance improves, the same pressure may lead to excessive tidal volumes. Alternatively, if resistance increases or compliance worsens, the same pressure will generate much smaller volumes and result in poor ventilation, carbon dioxide retention, and ventilatory failure.

Pressure-Regulated Volume Control

PRVC is a mode of mechanical ventilation that uses an adaptive targeting scheme to automatically adjust the inspiratory pressure to achieve a specified tidal volume[5] (**Fig. 4**).

The key provider settings include:

- Target tidal volume
- Inspiratory time
- Respiratory rate
- PEEP
- FiO_2

The commonly used name for this mode, PRVC, is misleading. Flow and volume are not controlled. Pressure is the control variable, and flow varies with changes in airway resistance, lung compliance, and patient effort.

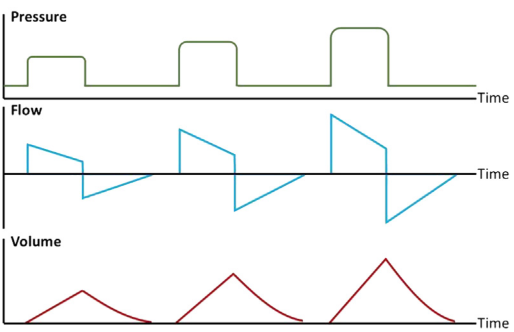

Fig. 4. Pressure-regulated volume control waveforms. In this example, the ventilator automatically increases the inspiratory pressure to achieve the desired tidal volume.

To achieve a target tidal volume, PRVC monitors the tidal volume resulting from the applied inspiratory pressure. If the tidal volume is higher than the target, the applied pressure for the next breath is decreased. If it is less than target, the applied pressure is increased for the next breath. In this way, PRVC allows for breath-by-breath pressure adjustments to achieve the desired volumes in the face of changing resistance, compliance, and patient effort. PRVC theoretically provides the benefits of variable flow from PC with the guaranteed minute ventilation of VC without requiring the user to adjust the inspiratory pressure.

A disadvantage of PRVC is the potential for patient–ventilator dyssynchrony in patients with high respiratory drives. If a patient develops increased work of breathing and is generating large tidal volumes at a given inspiratory pressure, the adaptive targeting scheme will continue to reduce the inspiratory pressure with each subsequent breath. This results in less support from the ventilator and an increase in patient work of breathing.[6] PRVC should, therefore, be used in patients who have stable respiratory drives.

Pressure Support

PS ventilation is a mode of mechanical ventilation whereby the inspiratory pressure is controlled, but all breaths, flow, and inspiratory time are determined by the patient (Fig. 5).

The provider settings include:

- Inspiratory pressure
- Percentage of peak inspiratory flow rate to terminate inspiration
- PEEP
- FiO_2

In PS, there is no set respiratory rate or inspiratory time. All breaths are triggered by the patient, and inspiration continues until the inspiratory flow decays below a selected value (eg, 30% of peak flow).

PS is often used in weaning patients off mechanical ventilation as patients control the inspiratory flow rate, duration of inspiration, and respiratory rate. Patients with a depressed respiratory drive, high oxygen consumption, or elevated airway resistance are not appropriate candidates for PS that generally excludes its use in the emergency department.

EVALUATING RESPIRATORY MECHANICS

Evaluating Respiratory Mechanics in Different Modes

Changes in resistance and compliance manifest differently with different modes of mechanical ventilation.

Volume control

In VC ventilation, increased resistance or worsening compliance or both result in increases in pressure. The two scenarios can be differentiated by comparing the maximum pressure during inspiration or peak pressure, and the pressure required to keep the lung inflated once the inspiratory flow has stopped or plateau pressure.

The peak pressure is simply the highest pressure observed on the pressure versus time displayed on the ventilator. The plateau pressure is measured by performing an inspiratory hold maneuver, where the ventilator ceases airflow at the end of inspiration and measures the pressure in the respiratory circuit. Because the lungs are fully inflated and exhalation has not yet occurred, this represents the total pressure in the lungs, inclusive of PEEP, at a specified volume.

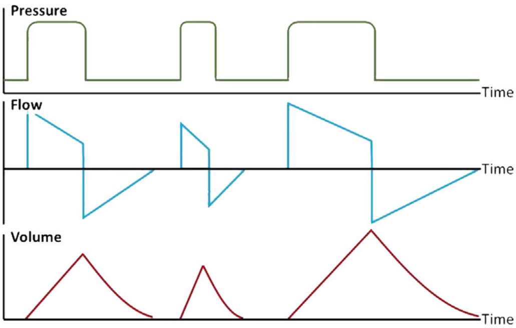

Fig. 5. Pressure support waveforms, showing fixed inspiratory pressure but varying inspiratory time, respiratory rate, and tidal volume based on patient effort.

A large differential between the peak and plateau pressure will be observed when the limiting factor to gas delivery is resistance to airflow (eg, obstructed airway and normal lungs). A small differential will occur when the limiting factor is the compliance of the respiratory systems (eg, widely patent airways, diffuse alveolar disease). This is shown in the pressure versus time curve in **Fig. 6**.

Pressure control or pressure support

In PC and PS ventilation, the inspiratory pressure is fixed at the value set by the operator. Therefore, higher resistance or worsening compliance will both cause a decrease in observed tidal volumes without a way to reliably differentiate between these two scenarios.

Pressure-regulated volume control

As an adaptive mode, PRVC varies the inspiratory pressure based on the mechanics of the respiratory system. Higher resistance or worsening compliance causes the ventilator to increase the inspiratory pressure to achieve the target tidal volume. The difference between the peak and plateau pressures can be measured with an inspiratory hold, just as in VC.

Auto-Positive End-Expiratory Pressure

A special cause of worsening respiratory compliance occurs when patients do not fully exhale before the initiation of the next breath. Air becomes trapped in the lungs such that there is retained pressure in excess of the applied-PEEP or auto-PEEP.

As auto-PEEP builds, higher and higher inspiratory pressures are required to deliver a desired tidal volume. Left unchecked, this can lead to pneumothorax or compromised venous return and cardiovascular collapse.

Auto-PEEP is measured using an end-expiratory hold maneuver. An end-expiratory hold maneuver stops airflow at the end of expiration and evaluates the pressure at this time. This pressure represents the sum of the retained pressure (auto-PEEP) and applied pressure (PEEP) and is referred to as the total-PEEP. Normally, the total-PEEP will equal the applied-PEEP. When air trapping occurs, the total-PEEP measurement will be higher than the applied-PEEP due to auto-PEEP.

The flow versus time display can often give a clue to air trapping and the presence of auto-PEEP when it does not return to the zero baselines by the end of expiration (representing incomplete exhalation). However, relying on this can miss significant auto-PEEP, so an end-expiratory hold maneuver should be performed.

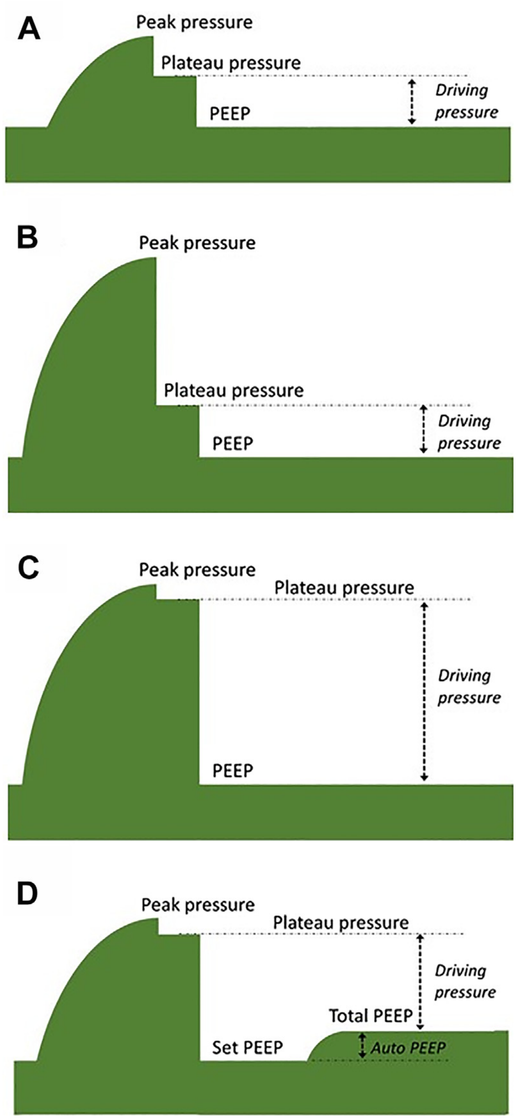

Fig. 6. (*A*) Normal pressure versus time curve in volume control ventilation. (*B*) Elevated peak airway pressures without elevation of plateau pressure secondary to increased resistance. (*C*) Elevated peak and plateau pressures due to poor compliance. (*D*) Elevated peak and plateau pressures due to auto-PEEP from air trapping.

Auto-PEEP can occur because of severe bronchospasm or inappropriate ventilator settings or both. Strategies to reduce auto-PEEP include decreasing respiratory rate and shortening the inspiratory time to lengthen expiration (Fig. 7).

Driving Pressure

Driving pressure is defined as the difference between the plateau pressure and the total-PEEP. Conceptually, it represents the pressure above the PEEP required to

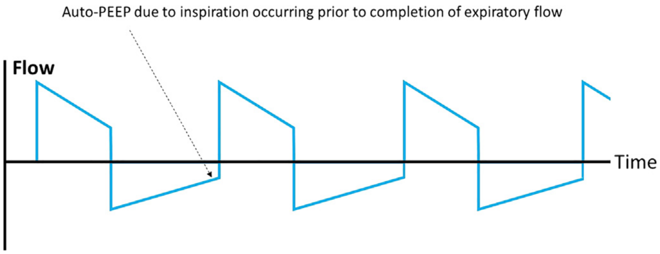

Fig. 7. Flow-time graph indicating auto-PEEP.

keep the lung inflated to a chosen tidal volume. The static compliance of the lung is equal to the tidal volume divided by the driving pressure.

$$\textit{static compliance} = \frac{\textit{tidal volume}}{\textit{plateau pressure} - \textit{total PEEP}} = \frac{\textit{tidal volume}}{\textit{driving pressure}}$$

Therefore, driving pressure is inversely proportional with pulmonary compliance. Less compliant, or "stiffer," lungs will require higher driving pressures to achieve the same tidal volume.

Driving pressures strongly correlates with mortality in patients with ARDS, with values < 15 cm H_2O thought to be protective.[7]

When to Measure Respiratory Mechanics

The inspiratory and expiratory hold maneuvers are key to understanding a patient's respiratory mechanics. However, they should only be measured when a patient is passive and compliant with the ventilator. Otherwise, a patient's negative inspiratory efforts can lead to an underestimate of the plateau pressure and an overestimation of lung compliance. Importantly, paralytics should not be given for the sole purpose of getting accurate measurements.

INITIAL SETTINGS

Tidal Volume

The initial tidal volume should be 6 to 8 cc/kg predicted body weight for most patients and adjusted as needed to ensure that the plateau pressure is $\leq$ 30 cm H_2O.[8,9]

Patients without ARDS may tolerate higher tidal volumes of 10 mL/kg predicted body weight without ill effect.[10] However, ARDS is often underrecognized, so targeting 6 to 8 cc/kg predicted body weight for most patients, and certainly less than 6 cc/kg predicted body weight in patients with ARDS is advised.[11–13]

If using PC, the inspiratory pressure should be set to achieve these targets with an ongoing patient reassessment to avoid excessive tidal volumes.

Positive End-Expiratory Pressure

A PEEP should be set for all patients to minimize traumatic opening and closing of alveoli, known as atelectotrauma.[13]

Higher PEEP values ($\geq$5 mmHg) should be selected in the setting of ARDS to minimize atelectotrauma and intrapulmonary shunt and pulmonary edema to decrease venous return and reduce afterload.[14]

PEEP optimization is a complex topic without a consensus approach. A straightforward approach is to set PEEP according to the PEEP/FiO_2 tables used by ARDS

Network investigators, which showed a decreased mortality with low tidal volume ventilation in ARDS.[9] Another strategy is to set PEEP to maximize compliance by setting the PEEP at the level that results in the lowest driving pressure.

Respiratory Rate

The initial respiratory rate should provide adequate ventilation and be comfortable for the patient. The 14 to 18 breaths per minute is reasonable for most patients. However, for patients with metabolic acidosis (eg, salicylate overdose), the respiratory rate should be increased to match or exceed their pre-intubation minute ventilation. Failing to do so may worsen acidosis and can precipitate complications, such as cardiac arrest.[14]

Fraction of Inspired Oxygen

FiO_2 should be initially set at 100% in the setting of hypoxia and rapidly weaned to target a PaO_2 of 60 to 100 mmHg or SpO_2 92% to 96%[15,16] (**Fig. 8**).

COMMON TROUBLESHOOTING SCENARIOS

Elevated Peak Airway Pressures

The plateau pressure should be measured with an inspiratory hold maneuver to differentiate between high resistance (large peak-plateau pressure differential) and poor compliance (small differential) scenarios, as previously discussed (**Fig. 9**).

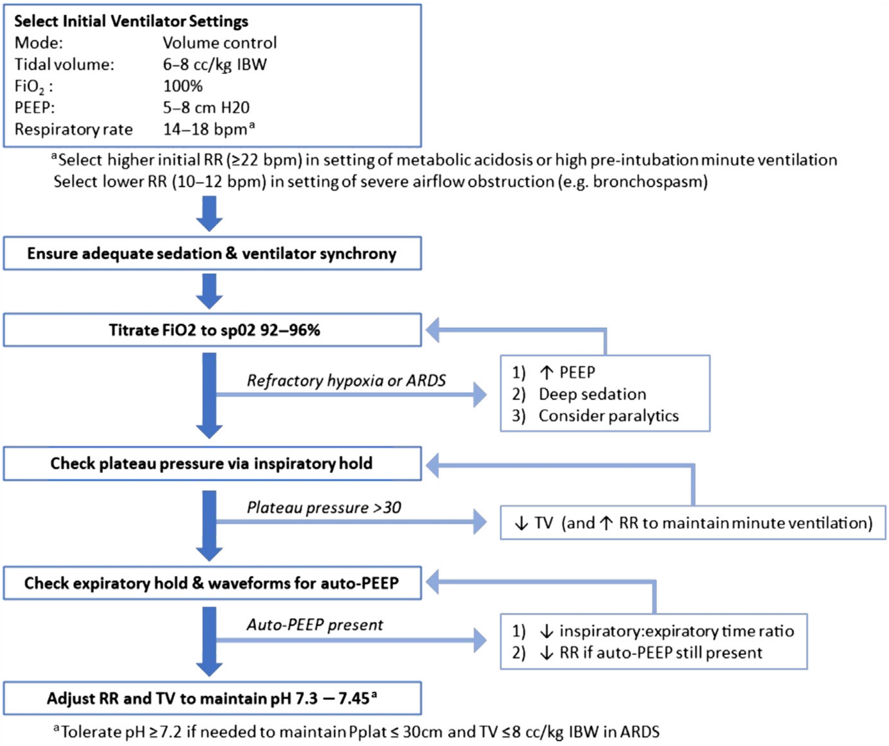

Fig. 8. Algorithm for initiating mechanical ventilation. BPM, breaths per minute; H_2O, water; IBW, ideal body weight; RR, respiratory rate.

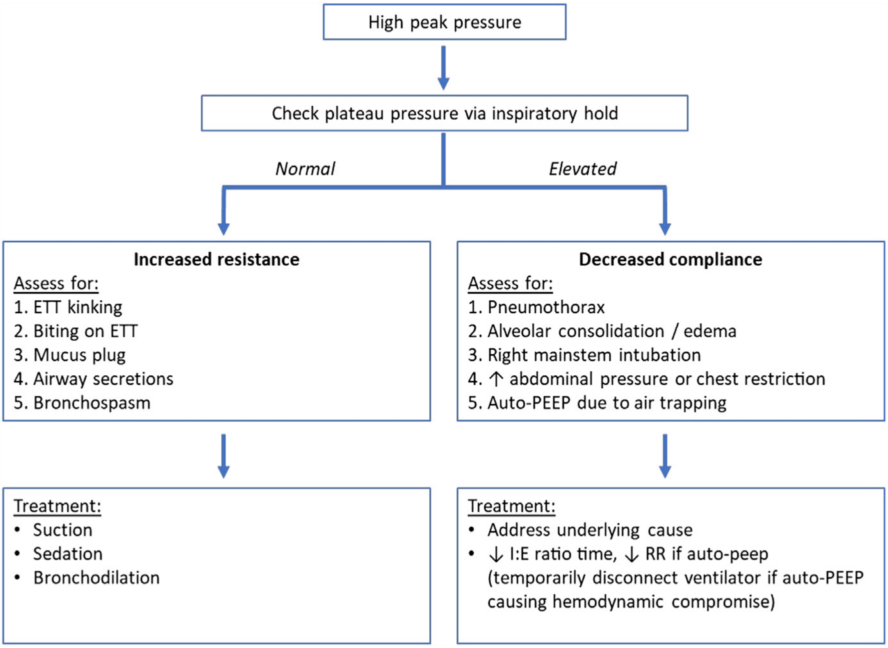

Fig. 9. Management algorithm for addressing elevated peak airway pressure.

Dyssynchrony

Patient–ventilator dyssynchrony arises from mechanical ventilation mimicking, but not matching, a patient's spontaneous respiratory mechanics. It is common and increases work of breathing, patient discomfort and reduces the effectiveness of ventilatory support[17] (Fig. 10).

Dyssynchrony is important to recognize and can easily be identified on ventilator waveforms. There are three major types of patient–ventilator dyssynchrony: flow, trigger, and cycle.

Flow dyssynchrony, or flow starvation, occurs in VC ventilation when flow does not meet patient demands. On a pressure versus time curve, the normal convex shape becomes concave, and the observed airway pressure decreases. Flow starvation can be fixed by increasing the flow rate or changing to PC ventilation (Fig.11).

Trigger dyssynchrony refers to when too many or too few patient-triggered breaths are delivered. The most common types of trigger dyssynchrony are ineffective triggering, auto-triggering, or double triggering and can occur in any of the modes previously discussed.

Ineffective triggering occurs when the ventilator does not deliver a breath after a patient inspiratory effort. It is most commonly because of inappropriate flow or pressure trigger settings. The clinician observes a negative deflection in the flow or pressure versus time curve (indicating a patient inspiratory effort) not immediately followed by a ventilator breath. Conversely, auto-triggering occurs when ventilator breaths are delivered without patient inspiratory effort. This is commonly caused by condensation in the ventilator tubing, vigorous cardiac activity, or circuit leaks when the flow or pressure trigger sensitivity is too sensitive. Adjusting the trigger sensitivity usually resolves ineffective and auto-triggering. Both scenarios are depicted in Fig. 12.

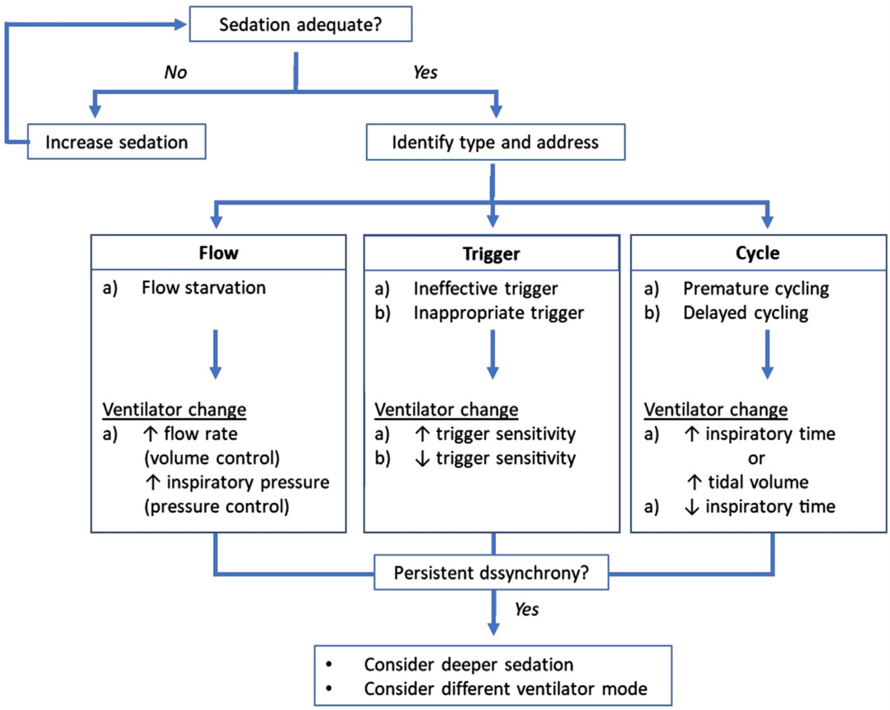

Fig. 10. Algorithm to manage common forms of ventilator dyssynchrony.

Cycle dyssynchrony occurs when inspiratory gas flow stops prematurely or continues into a patient's natural expiratory phase. An example of a patient's expiratory phase beginning before the end of the ventilator delivered breath is shown in Fig. 13. In PC, VC, and PRVC, this can be fixed by shortening or lengthening the inspiratory time, respectively. In PS, this is addressed by reducing or increasing the percentage of peak flow when cycling from inspiration to expiration occurs (Fig. 14).

Double triggering occurs when a second breath is triggered immediately after the first and is commonly referred to as "stacked breaths." This most often occurs in VC, PC, or PRVC due to a form of cycle dyssynchrony known as premature cycling, where the patient's respiratory drive exceeds the ventilator-delivered volume or inspiratory time. Increasing sedation, tidal volumes or flow, inspiratory pressure, or inspiratory time can fix this form of double triggering.

Leak

A leak should be suspected if the measured exhaled volume does not equal the inspiratory volume, or the volume versus time curve does not return to baseline before the next breath.

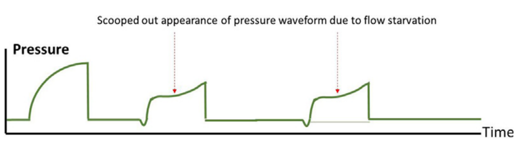

Fig. 11. Pressure–time graph showing flow starvation.

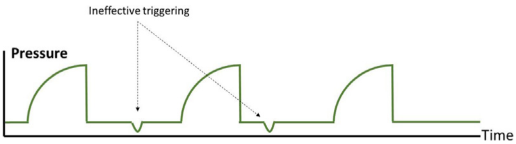

Fig. 12. Pressure–time graph showing ineffective triggering whereby the ventilator does not deliver a breath despite a negative pressure inspiratory effort by the patient due to inappropriate trigger sensitivity settings.

PITFALLS

Inadequate Analgosedation

Attempting to troubleshoot respiratory mechanics or dyssynchrony without adequate analgosedation will result in inaccurate measurements and misleading waveforms. Therefore, ensure adequate analgosedation before measuring the plateau pressure, checking for auto-PEEP, dramatically changing settings, or switching modes.

Assuming a Ventilator Mode Will Fix Poor Respiratory Mechanics

As discussed, ventilator settings should be chosen to target a plateau pressure less than 30 cm H_2O and driving pressure less than 15 cm H_2O. When pulmonary compliance is extremely poor, however, these goals may not be possible. Switching modes will not change the situation and may be harmful. For example, switching from VC to PC to achieve a lower inspiratory pressure will result in smaller and possibly inadequate volumes and hypoventilation.

Failing to Reassess

As with any intervention, reassessment is the key. Airway pressures, tidal volumes, oxygenation, and synchrony should be frequently monitored, particularly if the patient's conditions change.

DISCUSSION

Mechanically ventilated patients are common in the ED. Unfortunately, these patients sometimes remain in the ED for prolonged periods of time, with resulting in increased duration of mechanical ventilation, longer ICU length of stay, and higher mortality.[18–20]

Early ventilator management represents an opportunity for improvement. Indeed, less than half of ED patients with identified ARDS received low tidal volume ventilation in one observational study.[21] This is particularly concerning as ventilator-induced lung injury can occur in as little as 20 minutes.[22] Patients without ARDS may also be at risk as large tidal volumes within the first 48 hours of care have been associated with subsequent development of ARDS.[23] Fortunately, best practice strategies can be successfully implemented in the ED to decrease mortality, duration of ventilation, and hospital length of stay.[24]

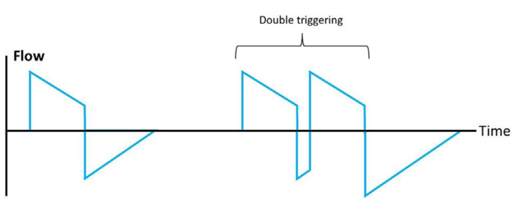

Fig. 13. Flow-time graph showing double-triggering.

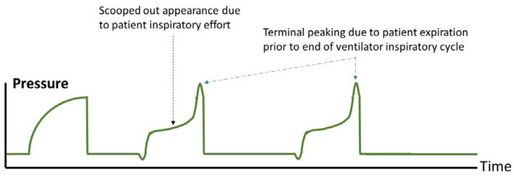

Fig. 14. Pressure versus time curve in volume control showing early scooping and a late spike in pressure as a patient makes a vigorous inspiratory effort and then attempts to exhale when the ventilator breath is still being delivered.

Education is another opportunity for improvement. Commonly, ventilated patients are managed by physicians without subspecialty training, and there is evidence of insufficient mechanical ventilation education and management for this group.[25] Furthermore, a survey of EM attending physicians showed many received 3 hours or less ventilator training over the last year and many identified a respiratory therapist as being primarily responsible for ventilator management. Higher ventilator management scores correlated with prior emphasis on mechanical ventilation in the physician's residency training; however, a previous study of EM residents reported an infrequent exposure to and a little education on mechanical ventilation.[1,2]

All of these data highlight several important findings. There is increasing importance for EM providers to understand various modes of mechanical ventilation, initiate best practice ventilator settings early, and identify and treat complications of the ventilator when they arise. Understanding why changes in resistance and compliance occur, how they are represented graphically, and where they correlate anatomically is paramount to troubleshooting.

SUMMARY

Acute respiratory failure requiring invasive mechanical ventilation is a common presentation in the emergency department. EM providers can further improve care for these patients by understanding common modes of mechanical ventilation, recognizing changes in respiratory mechanics, and tailoring ventilator settings and therapies accordingly.

CLINICS CARE POINTS

- Respiratory failure requiring mechanical ventilation is common; emergency medicine providers must have expertise in ventilator management.
- Ventilators overcome resistance and compliance of the respiratory system to deliver gas flow. The relative contribution of each is easily measured and can help guide management.
- There is no perfect mode of mechanical ventilation. Each has its strengths and weaknesses and can be adapted to most clinical scenarios. The best mode is often the one that providers and staff are most familiar with.

DISCLOSURE

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