Basic Invasive Mechanical Ventilation

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Abstract: Invasive mechanical ventilation is a lifesaving intervention for patients with respiratory failure. The most commonly used modes of mechanical ventilation are assist-control, synchronized intermittent mandatory ventilation, and pressure support ventilation. When employed as a diagnostic tool, the ventilator provides data on the static compliance of the respiratory system and airway resistance. The clinical scenario and the data obtained from the ventilator allow the clinician to provide effective and safe invasive mechanical ventilation through manipulation of the ventilator settings. While life-sustaining in many circumstances, mechanical ventilation may also be toxic and should be withdrawn when clinically appropriate.

Key Words: assist-control ventilation, mechanical ventilation, pressure support ventilation, synchronized intermittent mandatory ventilation, ventilator weaning

The need for mechanical ventilation is a frequent reason for admission to an intensive care unit. Mechanical ventilation following endotracheal intubation is often used to improve pulmonary gas exchange during acute hypoxemic or hypercapnic respiratory failure with respiratory acidosis.[1] Mechanical ventilation also redistributes blood flow from working respiratory muscles to other vital organs and is therefore a useful adjunct in the management of shock from any cause.

This article will review basic invasive mechanical ventilator modes and settings, the use of the ventilator as a diagnostic tool, and complications of mechanical ventilation. Weaning and extubation will also be discussed.

Ventilator Basics

Once the trachea has been successfully intubated and proper endotracheal tube placement has been verified by clinical and radiographic means, ventilator settings must be selected.[2] The first parameter to be chosen is the ventilator mode.[3] The mode determines how the ventilator initiates a breath, how the breath is delivered, and when the breath is terminated. Despite the availability of several new modes of ventilator support, time-tested modes such as assist-control (AC), synchronized intermittent mandatory ventilation (SIMV), and pressure support ventilation (PSV) are the most commonly used and the focus of this review.

Assist-Control

Assist-control is a commonly used mode of mechanical ventilation in medical intensive care units. A key concept in the AC mode is that the tidal volume (V_T) of each delivered breath is the same, regardless of whether it was triggered by the patient or the ventilator. At the start of a cycle, the ventilator senses a patient's attempt at inhalation by detecting negative airway pressure or inspiratory flow. The pressure or flow threshold needed to trigger a breath is generally set by the respiratory therapist and is termed the *trigger sensitivity*.[4]

Key Points

- Assist-control is a patient- or time-triggered, flow-limited, and volume-cycled mode of mechanical ventilation.
- Synchronized intermittent mandatory ventilation is similar to assist-control mode except that breaths taken by the patient beyond those delivered by the ventilator are not supported; pressure support may be added to these breaths to augment their volumes.
- Simple math using data obtained from the ventilator may be used to calculate the inspiratory-to-expiratory time ratio, the static compliance of the respiratory system, and the airway resistance.
- An increase in peak inspiratory pressure without a concomitant increase in plateau pressure suggests an increase in airway resistance, while an increase in both peak inspiratory and plateau pressure suggests a decrease in the static compliance of the respiratory system.
- The mechanical ventilator, while lifesaving in many circumstances may also be toxic and should be withdrawn as soon as clinically appropriate; a spontaneous breathing trial helps to identify those patients who may be successfully extubated.

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Accepted March 22, 2009.

0038-4348/0−2000/10200-1238

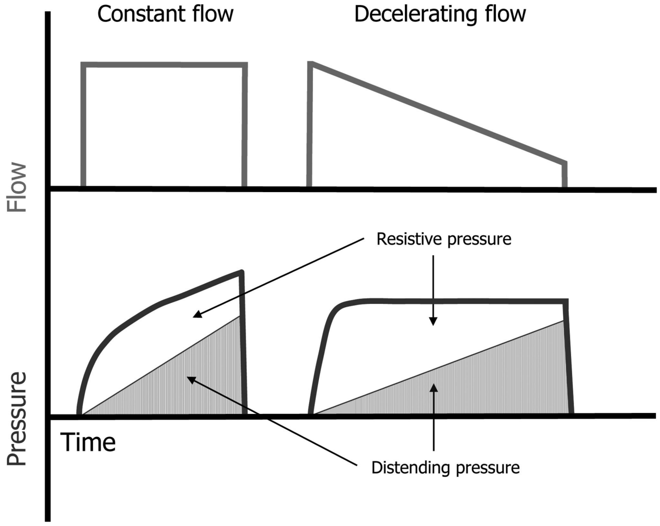

Fig. 1 **Flow-pressure waveforms. The left tracing represents a constant or square waveform. When flow is delivered at a constant rate, resistive pressure remains fairly constant (reflecting constant flow) while distending pressure increases with delivery of the tidal breath. In the tracing on the right, a decelerating or ramp waveform is shown. Since flow is decreasing, resistive pressure decreases as distending pressure increases. The net effect is an essentially constant pressure during the tidal breath.**

If the patient does not initiate a breath before a requisite period of time determined by the set respiratory rate (RR), the ventilator will deliver the set V_T. For example, if RR is set at 12 breaths per minute and the patient is not initiating breaths, the ventilator will deliver a breath every 5 seconds; this is called *time-triggering*. Similarly, if RR is 15 breaths per minute, the ventilator will deliver a breath every 4 seconds. However, if the patient initiates a breath, the ventilator in AC mode will deliver the set V_T; these breaths are *patient-triggered* rather than time-triggered.

Regardless of whether the breath is patient-triggered or time-triggered, the exhalation valve closes and the ventilator generates inspiratory flow at a set rate and pattern. The patient is *limited* to that flow rate and pattern during inhalation. Flow may be either constant (square waveform) or decelerating (ramp waveform) (Fig. 1).[5] A square waveform is generally selected when inspiratory time is to be minimized thus allowing more time for exhalation (ie obstructive lung diseases). Ramp waveforms are useful for ventilating a heterogeneous lung, such as in the acute respiratory distress syndrome (ARDS). Often the flow rate and pattern are selected to maximize patient comfort and patient-ventilator synchrony. Inspiratory flow lasts until the set V_T is delivered at which time the breath is "cycled-off" (and so the term *volume-cycled* mechanical ventilation).

Thus, the AC mode is patient- or time-triggered, flow-limited, and volume-cycled. An important correlate to this mode is that the airway pressures generated by chosen ventilator settings are determined by the compliance of the respiratory system and the resistance of the airways.

When the exhalation valve opens, the patient is allowed to exhale passively or actively until the airway pressure reaches end-expiratory pressure. This pressure is typically set

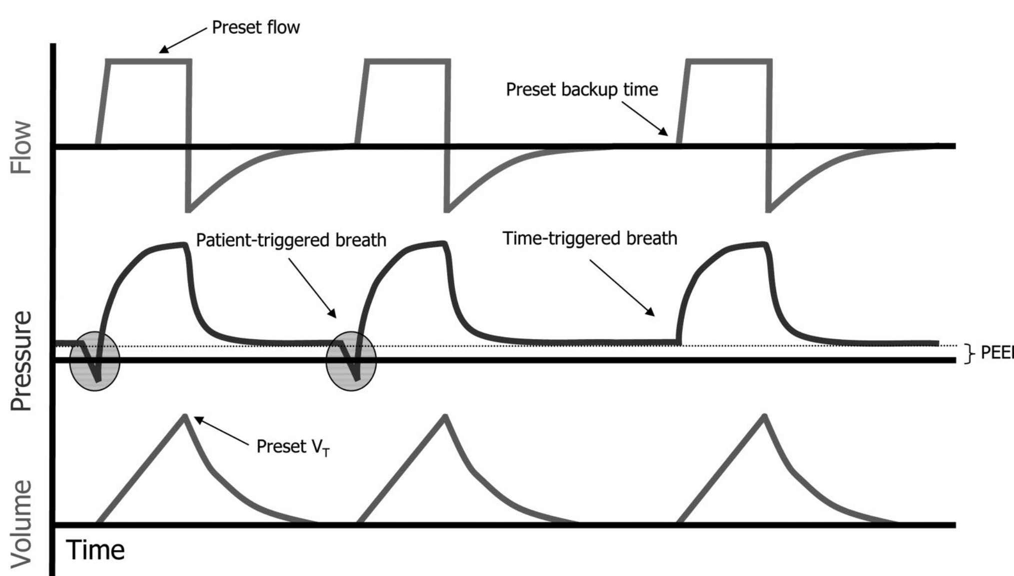

Fig. 2 **Assist-control (AC) mode. Flow, pressure, and volume tracings of three separate breaths are presented. The first two breaths are initiated by the patient (patient-*triggered*) via a drop in airway pressure (circled). The breath is delivered by constant flow (flow-*limited*), shown as a rapid increase in flow to a preset level. Flow lasts until a preset tidal volume (V_T) is reached (volume-*cycled*). The exhalation port of the ventilator then opens and the patient passively or actively exhales. In the third breath, the preset backup time limit is met (the patient did not initiate a breath) and the ventilator delivers the breath (time-*triggered*). Note that patient-triggered and time-triggered breaths deliver the same inspiratory flow and tidal volume in the assist-control mode.**

slightly higher than atmospheric pressure to prevent atelectasis, decrease inspiratory work of breathing, or improve gas exchange depending on the clinical scenario. This positive end-expiratory pressure (PEEP) is generated by a resistor in the exhalation port of the ventilator (Fig. 2).[6]

AC mode has several advantages including low work of breathing, as every breath is supported and tidal volume is guaranteed.[7,8] However, there is concern that tachypnea could lead to hyperventilation and respiratory alkalosis. "Breath stacking" can occur when the patient initiates a second breath before exhaling the first. The results are high volumes and pressures in the system. Hyperventilation and breath stacking can usually be overcome by choosing optimal ventilator settings and appropriate sedation.

Synchronized Intermittent Mandatory Ventilation

Synchronized intermittent mandatory ventilation (SIMV) is another commonly used mode of mechanical ventilation (Fig. 3).[9,10] Like AC, SIMV delivers a minimum number of fully assisted breaths per minute that are synchronized with the patient's respiratory effort. These breaths are patient- or time-triggered, flow-limited, and volume-cycled. However, any breaths taken between volume-cycled breaths are not assisted; the volumes of these breaths are determined by the patient's strength, effort, and lung mechanics.[11] A key concept is that ventilator-assisted breaths are different than spontaneous breaths. Another important concept is that AC and SIMV are identical modes in patients who are not spontaneously breathing due to heavy sedation or paralysis. High respiratory rates on SIMV allow little time for spontaneous breathing (a strategy very similar to AC), whereas low respiratory rates allow for just the opposite.

SIMV has been purported to allow the patient to "exercise" their respiratory musculature while on the ventilator by allowing spontaneous breaths and less ventilator support.[12,13] However, SIMV may increase work of breathing and cause respiratory muscle fatigue that may thwart weaning and extubation.

Pressure Support Ventilation

A common strategy is to combine SIMV with an additional ventilator mode known as pressure support ventilation (PSV) (Fig. 4).[14] In this situation, inspiratory pressure is added to spontaneous breaths to overcome the resistance of the endotracheal tube or to increase the volume of spontaneous breaths. PSV may also be used as a stand-alone mode to facilitate spontaneous breathing.

PSV mode is patient-triggered, pressure-limited, and flow-cycled. With this strategy, breaths are assisted by a set inspiratory pressure that is delivered until inspiratory flow drops below a set threshold. When added to SIMV, PSV is applied only to the spontaneous breaths taken between vol-

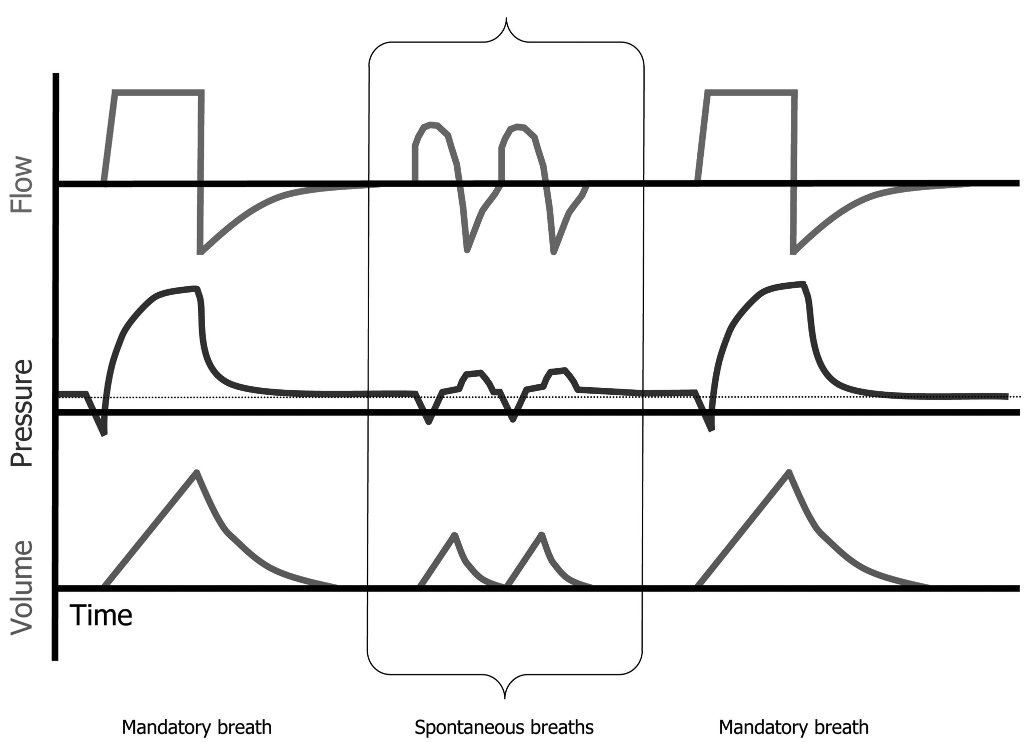

Fig. 3 **Synchronized intermittent mandatory ventilation (SIMV) mode. As in assist-control mode, mandatory breaths are patient-*triggered*, flow-*limited*, and volume-*cycled*. However, breaths taken between mandatory breaths (bracketed) are not supported. Rate, flow, and volume are determined by the patient's strength, effort, and lung mechanics.**

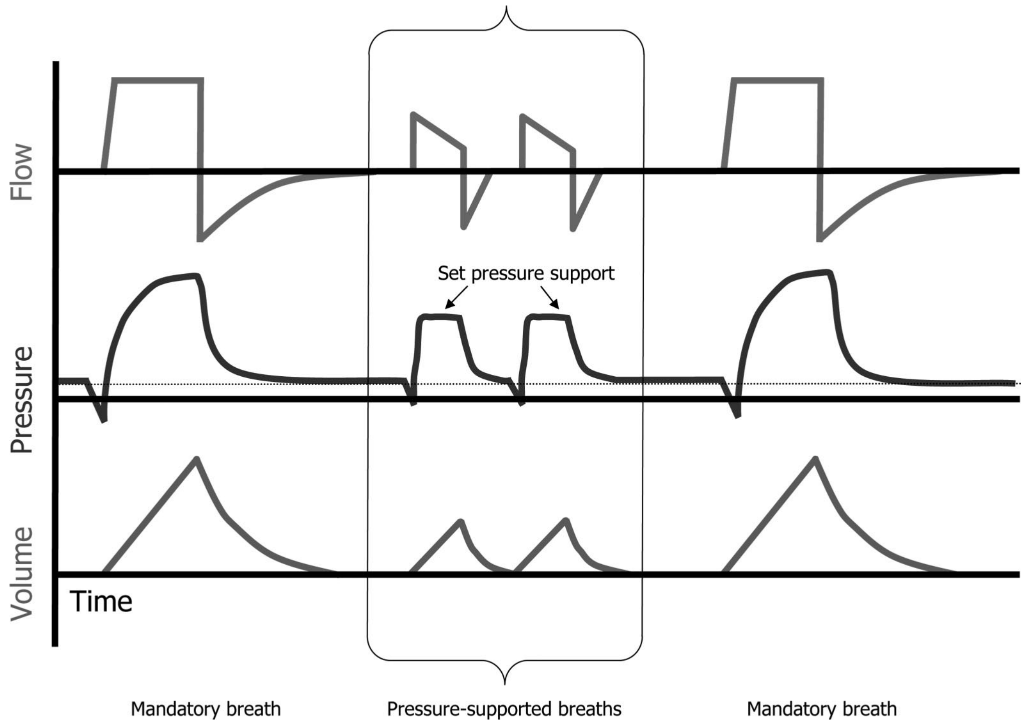

Fig. 4 **Synchronized intermittent mandatory ventilation plus pressure support ventilation (SIMV + PSV) mode. The first and last breath tracings are identical to those seen in SIMV. However, during pressure-supported breaths (bracketed), the ventilator delivers a set inspiratory pressure which is terminated when the flow drops below a set threshold. Spontaneous breaths are patient-*triggered*, pressure-*limited*, and flow-*cycled*.**

ume-guaranteed (volume-cycled) breaths. During PSV alone, all breaths are spontaneous. Airway pressures drop to the set level of PEEP during exhalation and rise by the amount of selected pressure support during inhalation. RR and V_T are determined by the patient; there is no set RR or V_T.

Setting and Using the Ventilator

Routine initial ventilator settings are shown in the Table.[15–18] These settings are aimed at achieving a safe or supranormal level of oxygenation and a relatively normal partial pressure of arterial carbon dioxide (P_aCO_2) in the peri-intubation period. This may not always be desirable. For example, a higher initial respiratory rate should be chosen for a patient with severe metabolic acidosis and preintubation respiratory compensation. Subsequent ventilator changes are based on the clinical scenario, arterial blood gas measurements, and calculations of the static compliance of the respiratory system and airway resistance (see below). For example, a low V_T on the order of 6 mL/kg predicted body weight is beneficial in ARDS,[19] and prolongation of expiratory time is recommended in status asthmaticus.[20] To improve oxygenation, the fraction of inspired oxygen (F_iO_2) and/or PEEP may be increased. PEEP improves oxygenation by preventing alveolar collapse and decreasing intrapulmonary shunt.[6] To increase ventilation, V_T and/or RR may be increased.

Table. Initial ventilator settings[a]

Parameter	Setting
Mode	AC or SIMV
F_iO_2	1.0
V_T	8–10 mL/kg
RR	10–12 breaths/min
$\dot{V}_i$	60 L/min
PEEP	5 cm H_2O

[a] *AC, assist-control; SIMV, synchronized intermittent mandatory ventilation; F_iO_2, fraction of inspired oxygen; V_T, tidal volume; mL/kg, milliliters per kilogram; RR, respiratory rate; $\dot{V}_i$, inspiratory flow rate; L, liters; PEEP, positive end-expiratory pressure; cm H_2O, centimeters of water.*

Inspiratory and Expiratory Times

Simple math may be used to calculate total cycle time, inspiratory time, and expiratory time during delivery of an assisted breath. The total cycle time (also referred to as the respiratory cycle time) equals inspiratory time plus expiratory time (Fig. 5). It is determined by—and inversely related to—RR. For example, if RR is 12 breaths per minute and the patient is not breathing above the set rate, the total cycle time is 5 seconds; if RR is 20 breaths per minute, the total cycle time is 3 seconds. Inspiratory time is determined by V_T and

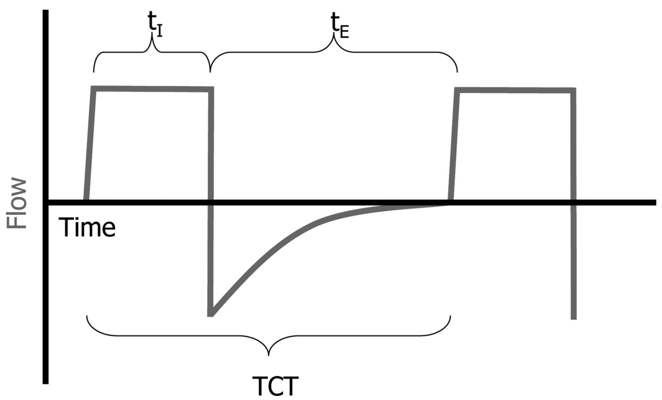

Fig. 5 **Flow tracing showing components of a breath. Total cycle time (TCT), which is set by the respiratory rate, is the sum of inspiratory time (t_I) and expiratory time (t_E).**

the inspiratory flow rate ($\dot{V}_i$). For example, if V_T is 1000 milliliters and inspiratory flow is 60 liters per minute (1 liter per second), then inspiratory time is 1 second. These concepts can be used to calculate the inspiratory-to-expiratory time (I:E) ratio (Fig. 6).

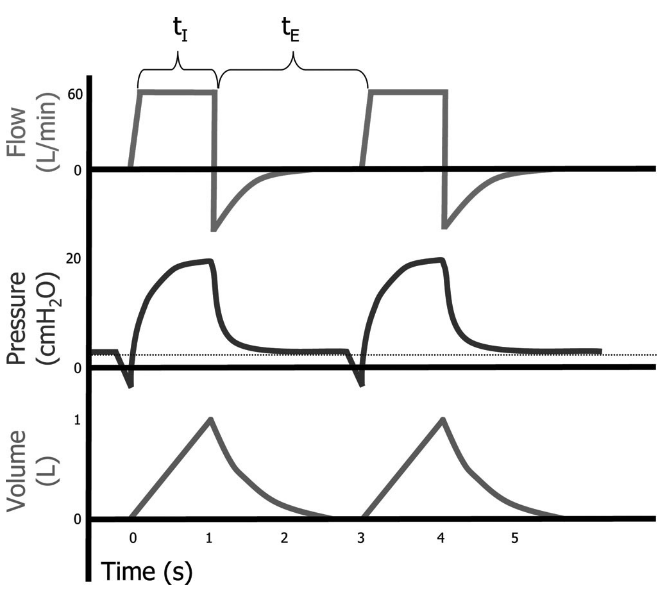

Fig. 6 **How to determine the inspiratory-to-expiratory time ratio. In the above example, the patient is breathing 20 times per minute. Thus, the total cycle time is 3 seconds (60 seconds per minute divided by 20 breaths per minute). A 1-liter tidal volume delivered at 60 liters per minute (1 liter per second) takes 1 second to deliver, leaving 2 seconds available for exhalation. The ventilator inspiratory-to-expiratory time ratio (I:E) is thus 1:2. Importantly, patient expiratory time may be shorter or longer than the amount of time allotted. In the above example the patient completes exhalation (as signaled by a return of expiratory flow to baseline) well before the next breath is delivered. Abbreviations: t_I, inspiratory time; t_E, expiratory time; L/min, liters per minute; cm H_2O, centimeters of water; L, liters; s, seconds.**

Auto-PEEP. Incomplete emptying of alveolar gas at the end of exhalation elevates alveolar pressure relative to airway opening (mouth) pressure, a state referred to as auto-positive end-expiratory pressure or auto-PEEP. This occurs when patient expiratory times are longer than the allotted expiratory time (as occurs in obstructive lung disease)[21] and is signaled by persistent expiratory flow at the time the next breath is delivered (Fig. 7, *A*). Auto-PEEP is measured by performing an expiratory hold maneuver (Fig. 7, *B*). Consequences of auto-PEEP include decreased cardiac preload and increased work of breathing since auto-PEEP must be overcome by the patient to trigger a breath. A common strategy to decrease auto-PEEP is to prolong expiratory time. This may be accomplished by decreasing RR, which runs the risk of increasing P_aCO_2. Hypercapnia may be tolerated in a strategy of "permissive hypercapnia" provided sudden and severe changes in pH and P_aCO_2 are avoided.[22] Increasing the inspiratory flow rate may further prolong expiratory time, although at the cost of higher peak inspiratory pressure (PIP). In severe cases of auto-PEEP signaled by hypotension, tachycardia, and high airway pressures, disconnecting the patient from the ventilator and manually decompressing the thorax may be necessary to restore hemodynamic stability.

Measuring Compliance and Resistance

As mentioned above, pressures generated during tidal volume delivery are influenced by the compliance of the respiratory system and airway resistance. These values may be estimated by performing an inspiratory hold maneuver (Fig. 8).

Since compliance is the differential change in volume for a given change in pressure ($C = dV/dP$), the static compliance of the respiratory system (C_{strs}) can be calculated by

$$C_{strs} = \frac{V_T}{P_{plat} - PEEP_{total}}$$

Normal compliance in a mechanically ventilated patient is 60–80 mL/cm H_2O. Low compliance is common in pulmonary edema, interstitial lung disease, lung hyperinflation, pleural disease, obesity, and ascites. In patients with low C_{strs}, the plateau pressure (P_{plat}) is higher for any set V_T. To decrease the risk of over-inflation lung injury (termed volutrauma), a common recommendation is to keep P_{plat} less than 30 cm H_2O by lowering V_T and avoiding excess PEEP. Note that interventions that increase C_{strs} invariably favor weaning and return to spontaneous breathing.

Resistance is pressure divided by flow. Thus airway resistance (R_{aw}) is calculated by

$$R_{aw} = \frac{PIP - P_{plat}}{\dot{V}_i}$$

Normal airway resistance is less than 15 cm H_2O/L/s. Increased airway resistance suggests kinking or plugging of

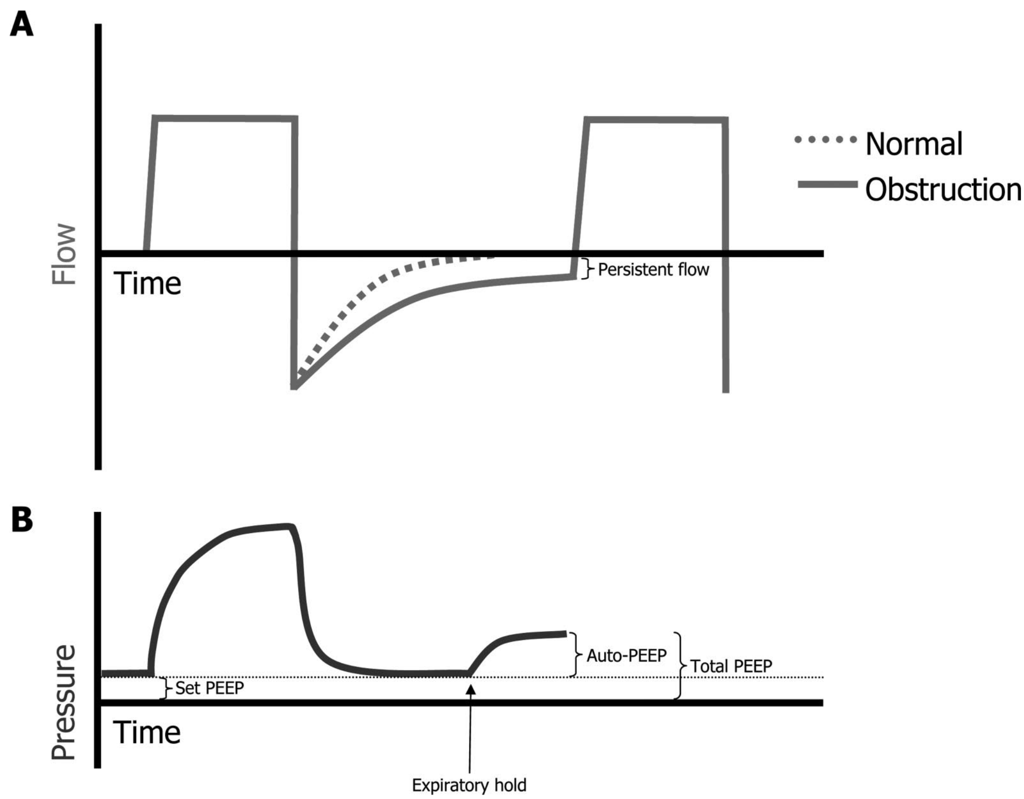

Fig. 7 *A.* **Persistence of end-expiratory flow in the setting of auto-positive end-expiratory pressure (auto-PEEP). Auto-PEEP is end-expiratory pressure above that generated by the ventilator. It is due to inadequate expiratory time before the next breath is delivered. Note that auto-PEEP generates persistent flow at the end of exhalation compared to the desired scenario in which flow returns to zero before the next breath is initiated.** ***B.*** **The expiratory hold maneuver. At the end of exhalation, the expiratory port is occluded allowing for equilibration of alveolar and airway opening pressures. The pressure measured at the airway opening minus set PEEP is auto-PEEP.**

the endotracheal tube, intraluminal mucus, or bronchospasm. Interventions that lower R_{aw} further benefit spontaneous breathing.

A change in PIP is a common diagnostic problem in a mechanically ventilated patient. Decreased PIP is usually due to an air leak in the ventilator circuit. Increased PIP (causing the ventilator to alarm) should be investigated initially by physical exam and by performing an inspiratory hold maneuver. An increase in PIP without a concomitant increase in P_{plat} suggests increased airway resistance and the need to evaluate the patency of the endotracheal tube and the need for bronchodilators. An increase in both PIP and P_{plat} suggests decreased compliance of the respiratory system. Figure 9 shows a differential diagnosis of an increased PIP.

Complications of Intubation and Mechanical Ventilation

Numerous complications of intubation and mechanical ventilation may arise. Toxic effects of lung over-inflation (volutrauma) include pneumothorax and acute lung injury. Volutrauma is minimized by adjusting the ventilator settings—particularly V_T and PEEP—to keep P_{plat} less than 30 cm H_2O. Oxygen toxicity is proportional to the duration of time that the patient is exposed to F_iO_2 greater than 0.6. Cardiac output may be increased or decreased based on the preload- and afterload-reducing effects of positive pressure ventilation.

Ventilator-associated pneumonia (VAP) develops at a rate of approximately 1% per day and has an attributable mortality rate as high as 20–50%.[23] Hand washing, elevation of the head of the bed, non-nasal intubation, and proper nutrition all reduce the rate of VAP. Avoidance of unnecessary antibiotics decreases the risk of VAP with a resistant pathogen.

Complications from the endotracheal tube itself include hard and soft palate injuries, laryngeal dysfunction, tracheal stenosis, tracheomalacia, and near-fatal or fatal obstruction.

Weaning from the Ventilator

In light of these serious complications, it is important to frequently assess the need for continued intubation and mechanical ventilation.[24] "Weaning" or "liberating" patients

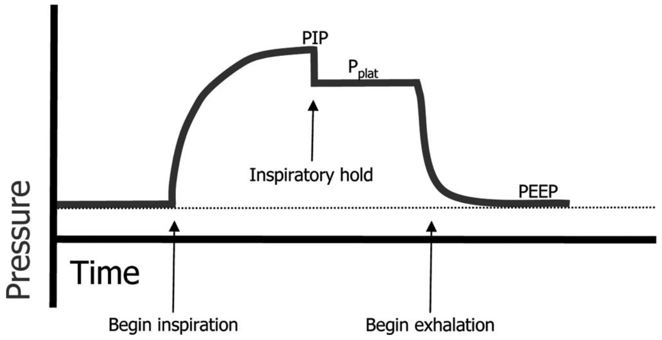

Fig. 8 **The inspiratory hold maneuver. Under conditions of constant flow (commonly 60 liters per minute) airway opening pressure increases from PEEP to peak inspiratory pressure (PIP). Flow is then stopped temporarily (without allowing the patient to exhale) thus eliminating airway resistive pressure. Airway opening pressure drops from PIP to plateau pressure (P_{plat}). Then the patient is allowed to exhale to set PEEP. The gradient between PIP and P_{plat} allows for calculation of airway resistance; P_{plat} helps gauge the degree of lung inflation and allows for calculation of the static compliance of the respiratory system (see text).**

from the ventilator begins by identifying patients who can breathe spontaneously. Patients with reversed sedation, stable vital signs, minimal secretions, and adequate gas exchange are candidates for a spontaneous breathing trial (SBT).[25] An SBT may be conducted by having the patient breathe via a "T-piece," in which the ventilator is disconnected and the patient breathes through the endotracheal tube connected to a humidified oxygen supply. An alternative SBT is to use low level PSV (ie 5 cm H_2O with 5 cm H_2O of PEEP) to overcome the resistance of the endotracheal tube. An SBT is considered a failure if the patient has deteriorating arterial blood gas levels, excessive tachypnea or work of breathing, arrhythmias, hypertension or hypotension, diaphoresis, or anxiety. A patient who is comfortable after 30–120 minutes of an SBT may be evaluated for extubation.

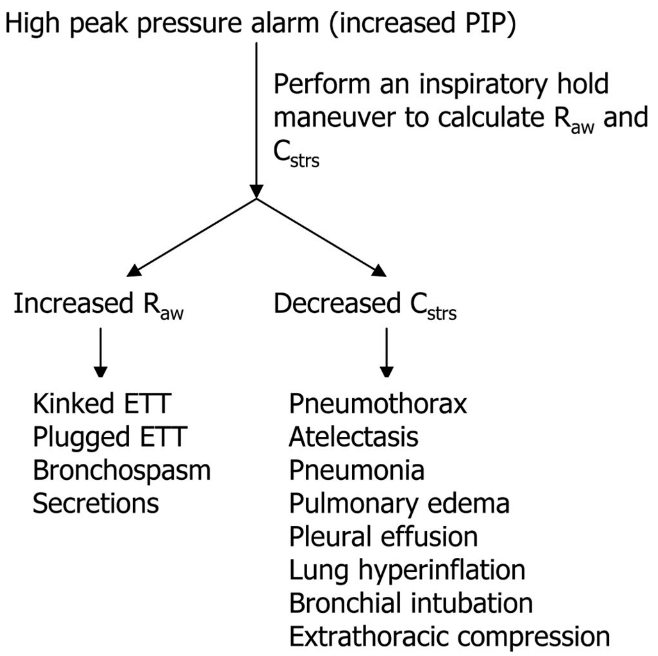

Fig. 9 **Approach to a high peak pressure alarm. Abbreviations: PIP, peak inspiratory pressure; R_{aw}, airway resistance; C_{strs}, static compliance of the respiratory system; ETT, endotracheal tube.**

Conclusion

Invasive mechanical ventilation is a lifesaving intervention for many patients with respiratory failure. Careful attention to ventilator settings and thoughtful adjustments of controllable parameters help to provide competent critical care. The ventilator can also be used as a diagnostic tool. As with all medical interventions mechanical ventilation can be potentially harmful, and it is essential to discontinue mechanical ventilation as soon as safely possible.

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Please see Dr. Muthiah Muthiah and Dr. Muhammad Zaman's editorial on page 1196 of this issue.

"Our own physical body possesses a wisdom which we who inhabit the body lack. We give it orders which make no sense."

—Henry Miller