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 (VT) 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] 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 VT. 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 VT; 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 VT is delivered at which time the breath is cycled-off (and so the term volume-cycled mechanical ventilation).

Figure 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.

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 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]

Figure 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 (VT) 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.

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.

**Figure 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.

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.

**Figure 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.
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 volume-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 inspiration. RR and Vt are determined by the patient; there is no set RR or Vt.

**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 Vt and the inspiratory flow rate (Vi). For example, if Vt 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).

![Figure 5.](image)

Flow tracing showing components of a breath. Total cycle time (TCT), which is set by the respiratory rate, is the sum of inspiratory time (ti) and expiratory time (te).

![Figure 6.](image)

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: ti, inspiratory time; te, expiratory time; L/min, liters per minute; cm H2O, 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)\[^{20}\] 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\textsubscript{a}CO\textsubscript{2}. Hypercapnia may be tolerated in a strategy of permissive hypercapnia provided sudden and severe changes in pH and P\textsubscript{a}CO\textsubscript{2} are avoided.\[^{21}\] 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.
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.

**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).

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 (Pplat). Then the patient is allowed to exhale to set PEEP. The gradient between PIP and Pplat allows for calculation of airway resistance; Pplat helps gauge the degree of lung inflation and allows for calculation of the static compliance of the respiratory system (see text).

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

\[
C_{strs} = \frac{V_T}{P_{plat} - \text{PEEP}_{total}}
\]

Normal compliance in a mechanically ventilated patient is 60–80 mL/cm H₂O. Low compliance is common in pulmonary edema, interstitial lung disease, lung hyperinflation, pleural disease, obesity, and ascites. In patients with low Cstrs, 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 Pplat less than 30 cm H₂O by lowering V_T and avoiding excess PEEP. Note that interventions that increase Cstrs invariably favor weaning and return to spontaneous breathing.

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

\[
R_{aw} = \frac{\text{PIP} - P_{plat}}{\dot{V}_i}
\]

Normal airway resistance is less than 15 cm H₂O/L/s. Increased airway resistance suggests kinking or plugging of 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 $P_{\text{plat}}$ 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 $P_{\text{plat}}$ suggests decreased compliance of the respiratory system. Figure 9 shows a differential diagnosis of an increased PIP.

Figure 9.

Approach to a high peak pressure alarm. Abbreviations: PIP, peak inspiratory pressure; $R_{\text{aw}}$, airway resistance; $C_{\text{st}}$, static compliance of the respiratory system; ETT, endotracheal tube.