CLINICAL FOCUS REVIEW

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Management of Patient–Ventilator Asynchrony

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Patient–ventilator asynchrony is most commonly recognized as a patient who seems to be "fighting" the ventilator, whose efforts, either inspiratory or expiratory, are not in synchrony with the ventilator. It is a mismatch between the patient demand for flow, volume, or pressure as functions of time and what the ventilator is supplying to the patient. Although possibly an oversimplification, asynchrony implies that either the patient wants an inspiration that the ventilator does not adequately deliver, or the ventilator wants to give an inspiration that the patient does not want. Conversely, the patient wants to expire when the ventilator is delivering a breath, or the patient does not want to expire gas when the ventilator has stopped inspiratory support.

Asynchrony is a common problem for both invasive and noninvasive positive pressure mechanical ventilation.[1–6] It has been reported that as many as 24% of patients undergoing invasive mechanical ventilation in the intensive care unit (ICU) unit have severe asynchrony with an asynchrony index greater than 10% with a much higher incidence for noninvasive ventilation. (The asynchrony index is the fraction of the number of asynchrony events divided by the total respiratory rate, including wasted efforts, multiplied by 100.) The incidence of asynchrony in anesthetized patients in contrast has not been studied and is unknown.

Many of the reports of the incidence of asynchrony have relied on manual inspection of pressure–time or flow–time waveforms. However, the sensitivity of real-time visual detection of asynchrony is low, so one could reasonably expect that the actual incidence of asynchrony is higher than reported.[7] Fabry *et al.*[8] demonstrated a number of years ago that when esophageal pressure monitoring (a surrogate for pleural pressure and sensitive monitor of patient effort) was added to gas flow/airway pressure monitoring, the incidence of asynchrony was significantly higher. More recently there have been reports of using automated frameworks for the analysis of waveforms including frameworks based on machine learning.[8–12] Phan *et al.*[13] compared the sensitivity of a group of experienced respiratory therapists to an automated system. Both the clinicians and the automated system utilized pressure–time and flow–time data but were blinded to esophageal/transdiaphragmatic pressure waveform (a very sensitive monitor of patient effort), which were used to establish the definitive assessment of asynchrony. Specificity was high for both clinicians and the automated system (greater than 98%), but the automated system was twice as sensitive as clinicians (83.2% *vs.* 41.1%).

An important question is whether synchrony affects outcome. Multiple studies have shown an association between asynchrony and duration of mechanical ventilation,[14–16] and there has been one report noting an association between asynchrony and mortality.[17] More obviously, asynchrony is a factor in patient comfort.[18] Anxiety and dyspnea are common sensations for patients undergoing mechanical ventilation.[18–20] When a patient is "fighting the ventilator," we have the obligation to find some method to reduce the obvious distress.

It must be emphasized that the challenge to interpreting all the studies relating patient–ventilator asynchrony to outcome is they are observational, not prospective. It is quite plausible that asynchronies reflect patient characteristics that are themselves the actual cause of poorer outcomes. At this time, there is no evidence that disentangles these complexities, leading to the conclusion that asynchrony worsens outcome, and the contribution of perioperative/procedural ventilator asynchronies to outcomes from anesthesia and surgery is even more uncertain.

The management of patients undergoing mechanical ventilation is a common task for the anesthesiologist, and understanding asynchrony and how to correct it may be a useful component of intraoperative management.[21] In many, if not most, cases the need for optimal surgical operating conditions entails the use of neuromuscular blocking drugs. This simplifies ventilator management. However, the anesthesiologist also frequently deals with patients who are spontaneously breathing with ventilator assistance. The lighter plane of anesthesia associated with spontaneous ventilation and the avoidance of neuromuscular blocking drugs can shorten recovery and also avoids complications caused by neuromuscular blockers and/or deep anesthesia. If one wants to maintain spontaneous ventilation, understanding how to deal with patient–ventilator asynchrony is vital.

In addition to operating room anesthesia, a substantial number of anesthesiologists are engaged in the practice of critical care. For any critical care provider, it is imperative to recognize, classify, and find methods to decrease patient–ventilator asynchrony.

A Very Brief Overview of Mechanical Ventilation

Because asynchrony is a mismatch of ventilator delivery and patient demand, specific characteristics of the ventilator will

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impact the smooth coordination of patient effort and ventilator delivery. The modern ICU ventilator is a complex device whose operations are controlled by sophisticated microprocessors.[22–24] There are multiple ventilators in the marketplace, each with their own proprietary features. It would be impossible to discuss all the various modes of ventilation that are available in the critical care environment, but very relevant to the practice of anesthesia is the fact that modern anesthesia machine ventilators have incorporated many of the advances developed for ICU ventilators. Perhaps the most significant of these is the incorporation of a mechanism to sense and respond to a patient's ventilatory effort and the ability to generate much higher flows than in the past.

The various modes of mechanical ventilation in current practice may be classified based on the following questions.[25] 1. What is the trigger to initiate the inspiratory arm of a mechanical breath (flow, pressure, time)? 2. What is the variable that limits the mechanical breath (volume, pressure, flow, time)? 3. What terminates, or "cycles," the inspiratory arm of the mechanical breath (volume, pressure, flow, time)? Table 1 outlines this classification scheme for some modes of ventilation commonly available on anesthesia machines.

Within this classification scheme, the earliest ventilators were very simple. The only options were controlled ventilation with time-triggered, volume- or pressure-controlled, and time- or volume-cycled ventilation. In these modes of ventilation, all breaths were determined by the clinician. In volume-controlled ventilation, the machine generated a constant flow, and the tidal volume was determined by the inspiratory time. In pressure-controlled ventilation, the inspiratory pressure was selected by the clinician along with the inspiratory time (fig. 1). If patients made spontaneous ventilatory effort while undergoing this mode of ventilation, they were working against a closed system (no sensor to detect or respond to patient effort). The first refinement of these basic modes of ventilation was the addition of a sensor for patient effort, which triggered the clinician-designed breath. Synchronized intermittent mandatory ventilation was the first mode to allow for patient-determined, spontaneous, unassisted breaths between the mandatory breaths. Modern refinements include more sensitive pressure and flow sensors and rapid response times that minimize the work of breathing. The introduction of inspiratory pressure support allows the spontaneous efforts by the patient to be supported, similar to how the anesthesiologist assists efforts by squeezing the reservoir bag when the patient makes an inspiratory effort. In this mode, if the patient makes an inspiratory effort that is detected by the machine, the breath is augmented with a preselected level of pressure above positive end-expiratory pressure (PEEP) with a high initial inspiratory flow followed by a decelerating flow pattern to maintain the pressure (fig. 1). This support is terminated when the inspiratory flow decreases to a level predetermined by the manufacturer.[22–24] There are several other innovations in mechanical ventilation that have not yet been widely implemented into clinical care, but space limitations preclude discussion in this concise review.

The Anesthesia Machine Ventilator

Anesthesia machines continue to support the older mandatory volume-controlled and pressure-controlled ventilation (time-triggered, volume- or pressure-delivered, time-cycled; fig. 1). They provide easily adjusted PEEP, as well as patient-initiated modes such as synchronized mandatory ventilation, pressure support (fig. 1), and pressure-controlled volume-guaranteed ventilation (in which the preset tidal volume is generated with the minimum pressure by machine calculation of any changes in resistance or compliance and adjustment for the changes.[22–24]

Although anesthesia machine ventilators have evolved in parallel with critical care ventilators, significant differences remain. In general, anesthesia machine ventilators cannot provide the peak flow that is needed by some critically ill patients. In addition, the "rise time," *i.e.*, the time needed to reach peak flow, may not be adequate. Many modern critical care ventilators offer an "autoflow" mode in which the microprocessor adjusts inspiratory flow to meet patient demand and pressure-controlled, volume-guaranteed modes, a feature not available on many anesthesia machine ventilators. The pressure/flow sensor is also often not in the Y connector to the airway, as in a critical care ventilator, which limits precision.

Asynchrony: Classification and Etiology

There are multiple types of patient–ventilator asynchrony. The details of the mismatch between patient and machine are specific for each type of asynchrony. Furthermore, the

Table 1. Classification Scheme of Modes of Ventilation

Mode	Initiation	Limit	Cycle
Volume-controlled	Time	Volume	Time/volume
Pressure-controlled	Time	Pressure	Time
Volume-controlled, assist-controlled	Time/flow/pressure	Volume	Time/volume
Pressure-controlled, assist-controlled	Time/Flow/pressure	Pressure	Time
Synchronized intermittent mandatory	Time/Flow/pressure	Volume	Time/volume
Pressure-controlled, volume-guaranteed	Time	Volume/pressure	Time/volume
Pressure support	Pressure/flow	Pressure	Flow

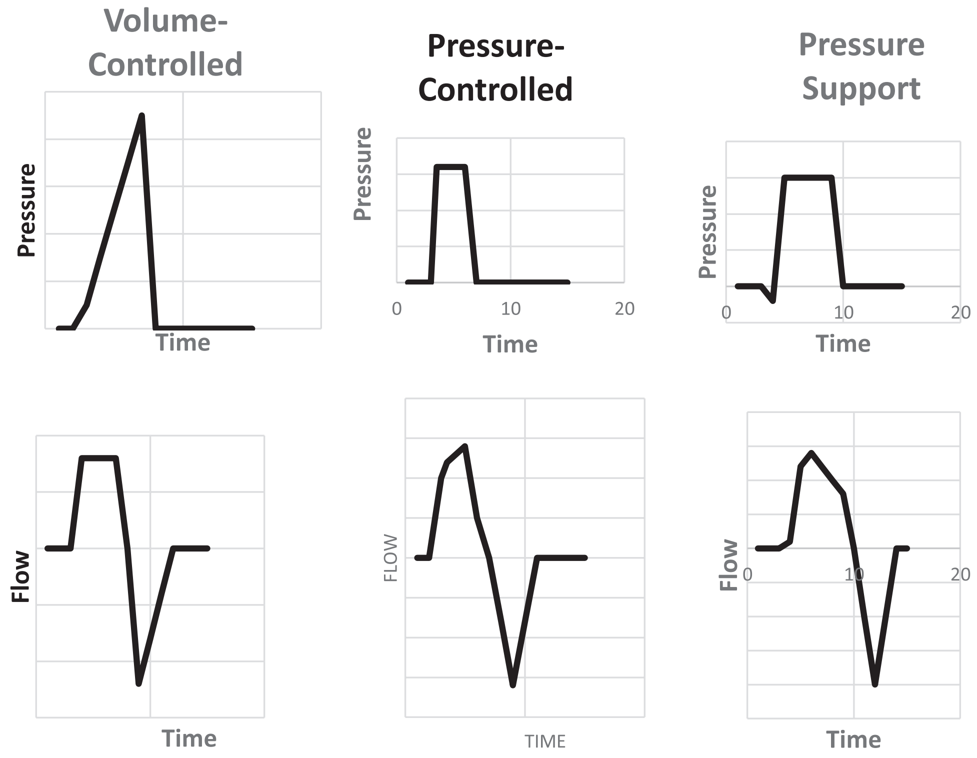

Fig. 1. Schematic illustration of pressure waveforms for common modes of mechanical ventilation. In volume control there is a "ramp up" pressure waveform with a square wave flow waveform. Note the inspiratory and expiratory phases of the flow waveform. Volume-controlled ventilation is a time-cycled, volume-limited, and volume-cycled mode of ventilation. In pressure control, the pressure waveform is a square wave, whereas the inspiratory flow is exponentially increasing. Pressure-controlled ventilation is time-cycled, pressure-limited, and time-cycled. In pressure support, note the small downward deflection in the pressure wave followed by a square wave of pressure support. When the flow decreases to a threshold value, pressure support is terminated.

pathophysiology that leads to a particular asynchrony is specific not only to the patient but also to the mode of ventilation and the settings of that mode of ventilation.

The question of why patients "fight the ventilator" can only be considered within the context of patient characteristics, the mode of ventilation, and the type of asynchrony. However, it will facilitate our initial attempt to understand what causes asynchrony by focusing on the various types. We will touch more on the limited options for altering patient characteristics and the more extensive options for modifying the ventilator later when we consider how we can correct asynchrony.

In more severe cases, asynchrony might lead to sufficient patient discomfort to be manifested as agitation, retractions, coughing, very forceful exhalations, paradoxical thoracic–abdominal respiratory effort, or use of accessory muscles. When asynchrony is not as severe, recognition is generally only possible by analysis of pressure–time and flow–time waveforms.[26] This also is necessary for classifying the asynchrony, which is an important exercise because it may provide clues regarding how to correct the asynchrony. Patient–ventilator asynchrony can be due to trigger, flow, or cycling problems. Within the category of inspiratory trigger asynchronies there are three types.

Inspiratory Trigger Asynchronies

Ineffective Trigger. In this asynchrony, the patient makes inspiratory effort, but the ventilator does not respond with a mechanical breath (illustrated schematically in fig. 2A). Either the patient makes too weak an effort for the flow or pressure sensor/trigger or the sensor is not set at an adequate threshold. There are multiple patient factors that can result in ineffective triggers, such as excessive sedation and weakness/debility. There are factors that reflect both patient and machine characteristics such as auto-PEEP, when the expiratory time is shorter than the time needed to fully deflate the lungs, leading to hyperinflation (auto-PEEP is recognized by observing the presence of expiratory flow at the end of expiration on the flow *vs.* time graph on the ventilator screen.). There are also factors that reflect ventilator settings, such as excessive pressure support or overventilation.

When ineffective triggers are detected, the provider should optimize the level of sedation. If possible, one

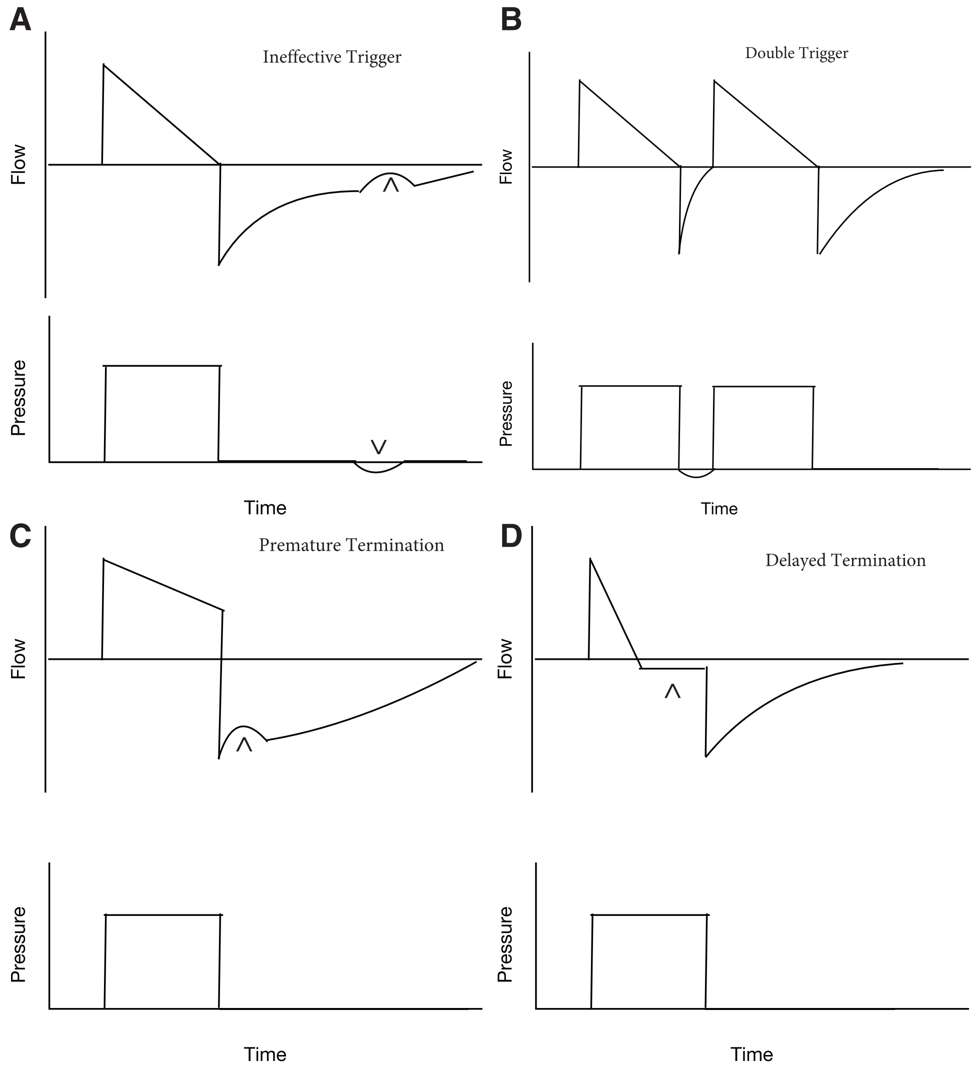

Fig. 2. (*A*) Schematic illustration of ineffective effort. Note the small upper deflection in the flow waveform (indicated by the *caret*) and the small downward deflection in the pressure waveform (indicated by the *inverted caret*). These are signs of patient effort, which is not followed by a full breath. (*B*) Schematic illustration of double triggering. Note second breath immediately after the return to expiratory flow from the first breath to zero. (*C*) Schematic illustration of premature termination. Note the small upward deflection in the expiratory phase of the flow waveform (indicated by the *caret*) reflecting inspiratory effort by the patient attempt. (*D*) Schematic illustration of delayed termination. Note the negative flow in the flow waveform while the inspiratory pressure is still maintained (indicated by the *caret*), reflecting the patient attempt to expire. This precedes full expiratory flow when inspiratory pressure is released.

can adjust the sensitivity of the trigger for initiation of a mechanical breath. Excessive ventilation (with hypocarbia) should be avoided, and auto-PEEP should be minimized by administering bronchodilators and avoiding hyperinflation, because if auto-PEEP is high, the negative pressure that the patient will need to generate to trigger a machine breath will also be high.

Autotrigger. Autotrigger refers to the delivery of a mechanical breath in the absence of patient effort. This asynchrony can result from cardiac oscillations (if the flow or pressure sensor is at too sensitive a level), oscillations in flow caused by secretions, or endotracheal tube cuff leaks interpreted by the ventilator as a negative pressure signaling an inspiratory effort.

When autotriggering is detected, one should ensure that the airway is cleared of secretions and also that there are no leaks. If possible, the sensitivity of the flow or the pressure sensor should be adjusted.

Double Triggering. Double triggering is recognized by two mechanical breaths "stacked," one after the other, without expiration between them or an expiratory time less than half of the mean inspiratory time (illustrated schematically in fig. 2B). This is a particularly concerning asynchrony because the delivery of two mechanical breaths without full expiration between can lead to increased intrathoracic pressure with resultant impaired venous return and hypotension and patient discomfort. In some cases, double triggering is an extension of other asynchronies, specifically premature termination (the ventilator ends the breath before the patient's efforts transition to expiration) or reverse triggering (the phenomena in which a mechanical breath triggers a patient effort). Double triggering in general reflects inadequate machine support, such as flow starvation or a low level of pressure support.

If double triggering is due to premature termination of the mechanical breath, the best strategy is to increase the inspiratory time or convert to pressure support. However, double triggering can also be the result of reverse triggering. This is difficult to treat and may require an increase in tidal volume, although that entails considering the risk of worsened lung injury. Reverse triggering,[27] in which instead of a patient effort triggering a mechanical breath, a mechanical breath triggers a patient breath, can also lead to double triggering. Reverse triggering reflects ventilator support not commensurate to the patient's neural drive. It can be addressed by increasing tidal volume with the associated risk of lung injury.

Flow Asynchrony

Flow asynchrony is a general term for mechanical flow that is inadequate for patient demand. In pressure control ventilation modes, it may reflect an inadequate pressure rise time. Generally, it can be recognized by a concave pressure–time curve. Clinically, it is recognized as "air hunger."

This type of asynchrony was more common in earlier ventilators. Many modern ventilators are equipped with an "autoflow" capability that can reduce the incidence of this type of asynchrony. If this is not available, inspiratory flow asynchrony is best dealt with simply by increasing gas flow.

Expiratory Trigger Asynchronies

Premature Cycling (Also Called Premature Termination). In premature cycling, as the term implies, the mechanical breath is terminated while the patient is still making inspiratory effort. It can be recognized by an upward "bump" during the expiratory flow portion of a flow–time curve (illustrated schematically in fig. 2C). A possible consequence of premature termination is double triggering. As would be expected, premature cycling is best dealt with by increasing the inspiratory time.

Delayed Cycling (Also Called Delayed Termination). Delayed cycling is the reverse of a premature termination and is recognized by a dip in the inspiratory flow before the release of inward flow at the onset of expiration (illustrated schematically in fig. 2D). A consequence of delayed termination is hyperinflation, which can then lead to ineffective triggers. If delayed termination is detected, one should shorten the inspiratory time.

Correcting Patient–Ventilator Asynchrony

If we view asynchrony as a mismatch between what the patient wants and what the ventilator is delivering, then correction of asynchrony could theoretically be achieved by either altering patient characteristics or the mode/settings of the ventilator. The most common approach in anesthesia practice is the former, specifically increasing the depth of sedation or anesthesia. In many cases, practitioners resort to neuromuscular blocking drugs and then controlled ventilation. This simplifies ventilator management, although there are still controversies and subtleties in the selection of ventilator mode and settings. There is general consensus in the critical care literature that low tidal volume, "lung protective" ventilation leads to improved outcomes. However, there is still some debate on the optimal strategy for operative anesthesia.[28–30] It is also notable that in both the ICU and the operating room, setting a tidal volume that is lower than what the patient is seeking may provoke patient–ventilator asynchrony.

Although deepening sedation and paralysis is without doubt an effective method to control asynchrony, there are consequences. In the critical care environment, deeper sedation is associated with increasing length of stay and mortality (although sedation in the ICU is usually prolonged over days rather than the hours typical of operative anesthesia). In addition, neuromuscular blocking drugs have been specifically associated with severe weakness and critical illness myopathy, which makes weaning the patient from mechanical ventilation very difficult.

When pharmacologic measures are taken to relieve asynchrony, it might be appropriate to take selective measures. For example, an endotracheal tube is extremely noxious, stimulating the cough reflex and making synchronization of patient respiratory effort and mechanical breaths challenging. It would be rational to treat asynchronies that can be correlated with endotracheal tube–induced cough with drugs more specific to the gag reflex such as opioids or lidocaine.

In the critical care arena, there are more therapeutic options. Usually the critically ill patient will have specific pathophysiology that is contributing to asynchrony. For example, excessive lung water can stimulate J receptors in the lung, leading to increased air hunger. This can be treated with diuretics. We often encounter patients in critical care who have a metabolic acidosis increasing respiratory drive as a compensatory mechanism. Correction of this could lead to less air hunger.

As noted above, the goal in critical care is to avoid excessive sedation, and there are excellent arguments, such as shortened length of stay in the postanesthesia care unit and decreased risk of postoperative respiratory depression, for the same to apply in the operating room. Given that asynchrony is a mismatch between the patient and the machine, if we have limited options for changing the patient, then we need to focus on the ventilator. However, before any effort is made to optimize the ventilator mode and settings, one should first correct any external disturbances because these can corrupt waveforms. Specifically, leaks should be corrected to the extent possible, and the airway should be cleared of secretions or any obstruction to the extent possible. Once external perturbations are corrected, one can consider the ventilator mode and settings.

In a seminal report, Chanques *et al.*[31] found that adapting the ventilator to patient breathing effort reduces asynchrony (specifically breath stacking) significantly, with a reduction in breath stacking asynchrony index from 38 to 2%. They reported that the ventilator changes that were most often found to be effective were changing to pressure support ventilation or increasing the inspiratory time in the assist-control mode (in assist-control each patient effort is supported with a full mechanical breath on top of the mandatory mechanical breaths).

This was an important observation demonstrating that asynchrony could often be dealt with very efficiently by changing the ventilator. This was more effective than deepening the level of sedation (which resulted in a decrease in asynchrony index from 41% to 21%).Subirà *et al.*[32] discuss techniques for treating asynchrony based on the classification of the various types of asynchrony and the underlying mismatch of the specific asynchrony (such as premature termination, delayed termination, inadequate flow, etc.).

Implications for Operative Anesthesia

Ventilator management of the patient under anesthesia begins with the challenge of maintaining appropriate surgical operative conditions. Some cases require either paralysis or very deep planes of anesthesia, precluding spontaneous ventilation, either with or without assistance. However, there are certainly many cases for which a totally immobile patient is not necessary, and spontaneous ventilation, with or without machine assistance, is not contraindicated.

As noted above, the modern anesthesia machine offers a number of options. For a patient under deep anesthesia with some spontaneous effort, pressure-controlled volume-controlled ventilation, which minimizes the pressure needed to achieve a set tidal volume, may be useful. Alternatively, synchronized intermittent mandatory ventilation will support spontaneous ventilation while permitting spontaneous ventilation. For either of these modes, asynchrony can be addressed using the same general process noted above for the critically ill patient. This requires a machine that provides pressure and flow *versus* time waveforms and inspection of these wave forms by the anesthesiologist.

Another situation, possibly more common, is the spontaneously ventilating patient with a laryngeal mask airway. Pressure support ventilation may be ideal for this situation, but we note that there are subtleties to the management of patient–ventilator asynchrony when ventilation is noninvasive. One major difference between invasive and noninvasive ventilation is the occurrence of leaks, and there is a significant correlation between the magnitude of leaks and the incidence of ineffective triggering and delayed termination.[33,34] Also, the magnitude of leaks was correlated with the level of pressure support, and it has been observed that the incidence of ineffective triggers can be reduced by decreasing pressure.[35] It has also been demonstrated that the incidence of asynchronies during noninvasive ventilation is sensitive to the trigger used to terminate pressure support.[36–38]

In general, there is a U-shaped curve for optimal pressure support during noninvasive ventilation. A relatively low level would result in inadequate tidal volume with possible air hunger, whereas excessive pressure support could result in hyperinflation.

The studies of noninvasive ventilation in critical care patients suggest that the anesthesiologist will need to carefully select the level of pressure support. The anesthesiologist can minimize asynchrony by selecting a level of pressure support that ensures adequate ventilation while preventing hyperinflation. Furthermore, minimizing leaks, typically by optimizing the laryngeal mask airway fit and seal, will greatly increase the probability of successful management of the spontaneously ventilating operative patient.

Although there are parallels between noninvasive ventilation in the ICU and the spontaneously ventilating patient in the operating room, there are also challenges in the operating room not encountered in the ICU. These include the challenge of varying levels of surgical stimulation, the necessity of maintaining adequate surgical operating conditions, and the need to ensure anesthesia and lack of awareness.

Conclusions

Patient–ventilator asynchrony reflects a mismatch between patient demand and what the ventilator is delivering. It can impede adequate oxygenation and ventilation and may reflect patient distress and discomfort. Although it is a common practice to address patient–ventilator asynchrony by increasing the depth of sedation or using a neuromuscular blocking drug, this strategy has consequences. Although less well known and less practiced, it is also possible to correct asynchrony by understanding the nature of the patient demand–ventilator delivery mismatch and adjusting the ventilator accordingly. This may facilitate management of the spontaneously ventilating patient not only in critical care but also in the operating room. Anesthesia ventilators now look much more like ICU ventilators, and there are many future monitoring trends,[9–13] as well as new ventilator modes (such as assist ventilation or neurally adjusted ventilatory assist), that are being investigated[39] that may improve our ability to detect asynchronies as well as prevent them.

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Competing Interests

Dr. Bailey is chief medical officer of and has stock options in Autonomous HealthCare Inc., Hoboken, New Jersey, which has developed software for recognition and classification of ventilator-patient asynchrony.[22,24]

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