Old and New Trends in Invasive Mechanical Ventilation

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The aim of mechanical ventilation is to decrease the work of breathing and to reverse acute hypoxemia and/or respiratory acidosis. Most of critically ill patients require invasive mechanical ventilation [1]. There are three main types of invasive mechanical ventilation: controlled, assist-control, and assisted.

In controlled mechanical ventilation, the ventilator delivers a set tidal volume or pressure independently from the patient respiratory activity. In assist-control ventilation, the ventilator delivers a set tidal volume when triggered by the patient's inspiratory effort or independently, if such an effort does not occur within a preselected time. In assisted ventilation, the ventilator assists the respiratory effort of the patient according to the change of his breathing pattern.

The modality of mechanical ventilation is important to optimize respiratory function according to the patient's characteristics. Studies have shown that optimal setting of mechanical ventilation and its use according to physiopathologic rationale may improve outcome [2].

Different modes of invasive mechanical ventilation have been developed and used in daily clinical practice; in this chapter we discuss the *conventional*, *non-conventional,* and the most recent modes of invasive mechanical ventilation in critically ill patients.

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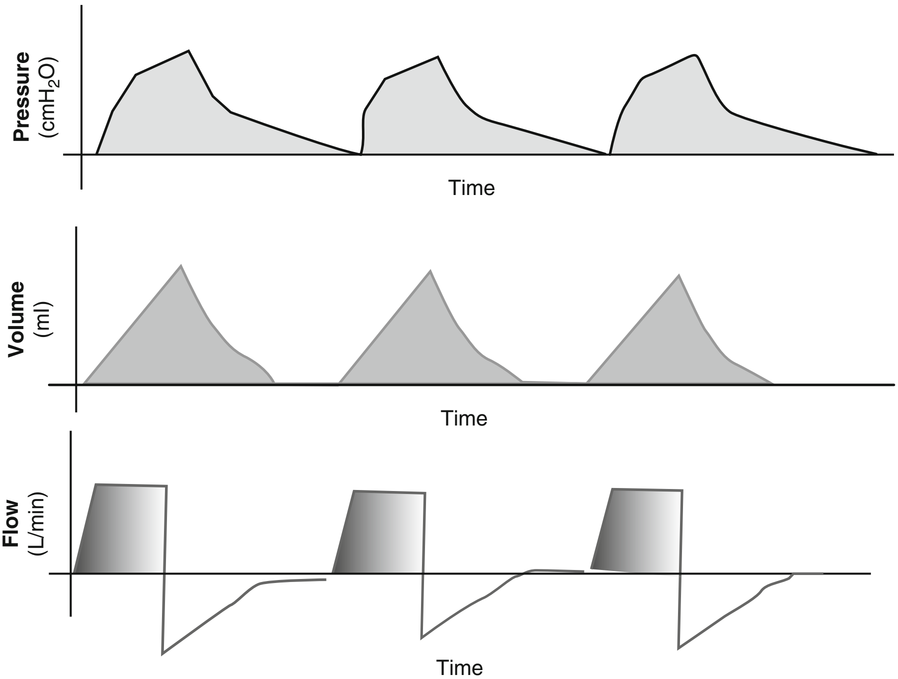

Fig. 23.1 Pressure, volume, and flow curves during volume control ventilation

23.1 Conventional Modes of Invasive Mechanical Ventilation

23.1.1 Volume-Cycled Ventilation Modes

Volume-cycled ventilation is the oldest mode of ventilation used in the operating room or intensive care unit. Volume control, assist-control, intermittent mandatory ventilation, and synchronized intermittent mandatory ventilation are different modes of volume-cycled ventilation.

In *volume control ventilation*, the operator is required to set a fixed tidal volume, respiratory rate, inspired oxygen fraction, inspiratory flow, and the alarm limits for airway pressure. The alarm limits of airway pressure are very important because in this type of ventilation, the variation of airway pressure is determined by the compliance of the patient's respiratory system. In volume control ventilation, the respiratory effort depends completely on the ventilator because the patient is not able to breathe adequately.

Figure 23.1 shows the pressure, volume, and flow curves during volume control ventilation.

Assist-control (AC) is a common mode of mechanical ventilation used in medical intensive care units. A key concept in the AC mode is that the tidal volume of each delivered breath is the same, regardless of whether it was triggered by the

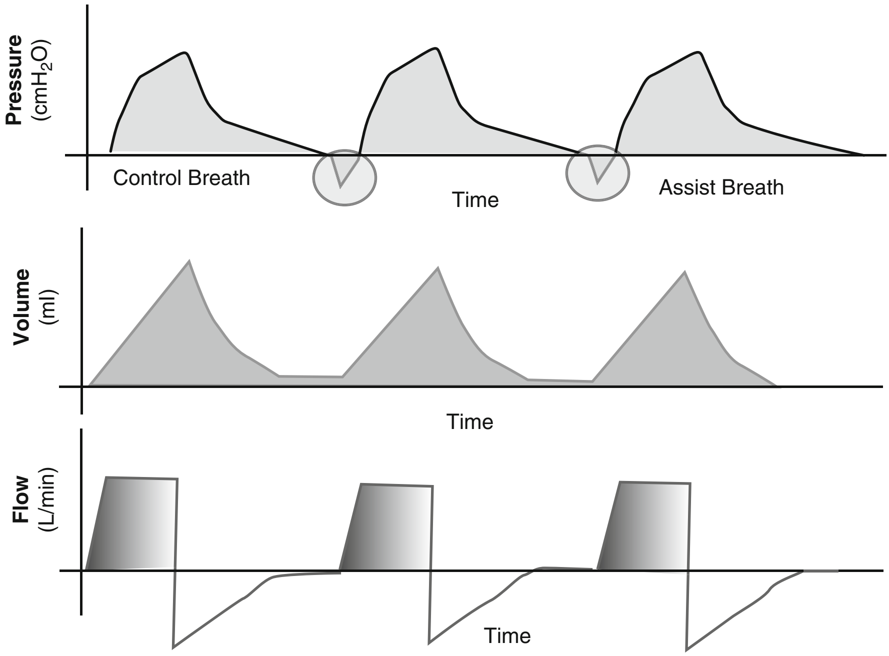

Fig. 23.2 Pressure, volume, and flow curves during assist control ventilation. The ventilator delivers the first breath, while the patient initiates the second and third breaths with a drop in airway pressure

patient or the ventilator. At the start of an inspiratory 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 operator and is termed the trigger sensitivity [3]. 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 tidal volume. However, if the patient starts a breath, the ventilator in AC mode will deliver the set tidal volume; these breaths are patient-triggered rather than time-triggered.

Figure 23.2 shows the pressure, volume, and flow curves for assist-control ventilation.

Synchronized intermittent mandatory ventilation (SIMV) is another commonly used mode of mechanical ventilation [4]. As 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. A key concept is that ventilator-assisted breaths are different than spontaneous breaths.

Figure 23.3 shows the pressure, volume, and flow curves for synchronized intermittent mandatory ventilation.

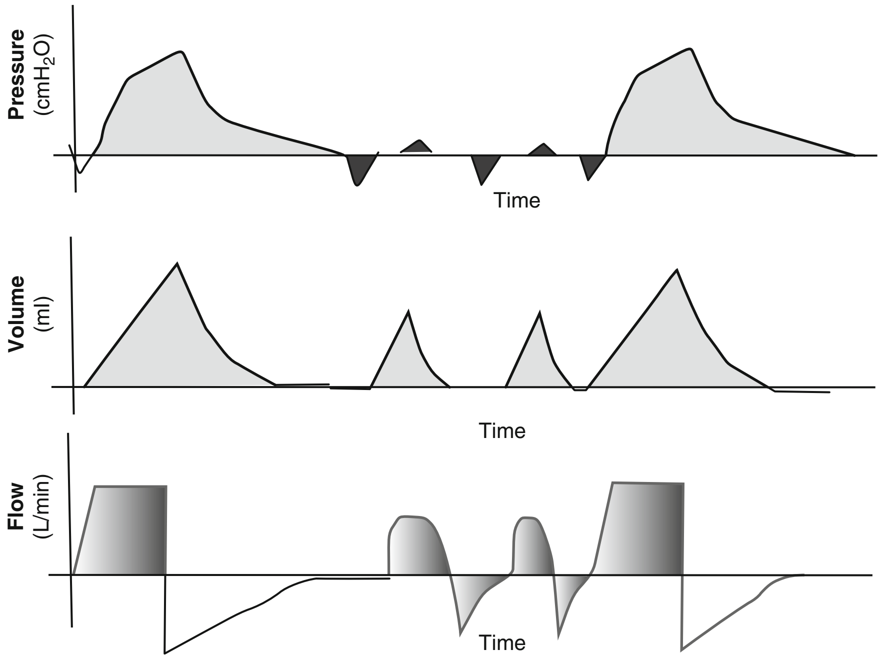

Fig. 23.3 Pressure, volume, and flow curves during synchronized intermittent mandatory ventilation. The first and fourth breaths are mandatory and patient-triggered, while the second and the third unsupported breaths are determined by the patient's inspiratory effort and respiratory compliance

23.1.2 Pressure-Cycled Ventilation Modes

Pressure-cycled ventilation is characterized by the setting of an inspiratory pressure that results in a delivered tidal volume determined by the dynamic compliance of the patient. Pressure control, pressure support, and airway pressure release are different modes of pressure-cycled ventilation.

Pressure control ventilation (PCV) is pressure- and time-cycled ventilation, which produces a tidal volume that varies according to the compliance or impedance of respiratory system [5]. In PCV during the inspiration, gas flows in the ventilator circuit to pressurize the system until the pressure level set by the operator was reached. The gas flow lasts until the alveolar pressure rises at the level of ventilator circuit pressure; after that the flow is stopped. In this way a gradient between the preset pressure, ventilator circuit pressure, and alveolar pressure is established, but if the gap between this three-step gradient is very large, flow is brisk.

Figure 23.4 shows pressure, volume, and flow curves for pressure control ventilation.

Pressure support ventilation (PSV) is patient-triggered, pressure-limited, and flow-cycled [6]. With this strategy, breaths are assisted by a set inspiratory pressure that is delivered until inspiratory flow drops below a set threshold. In this mode of ventilation, the inspiratory pressure facilitates the spontaneous breath triggered by

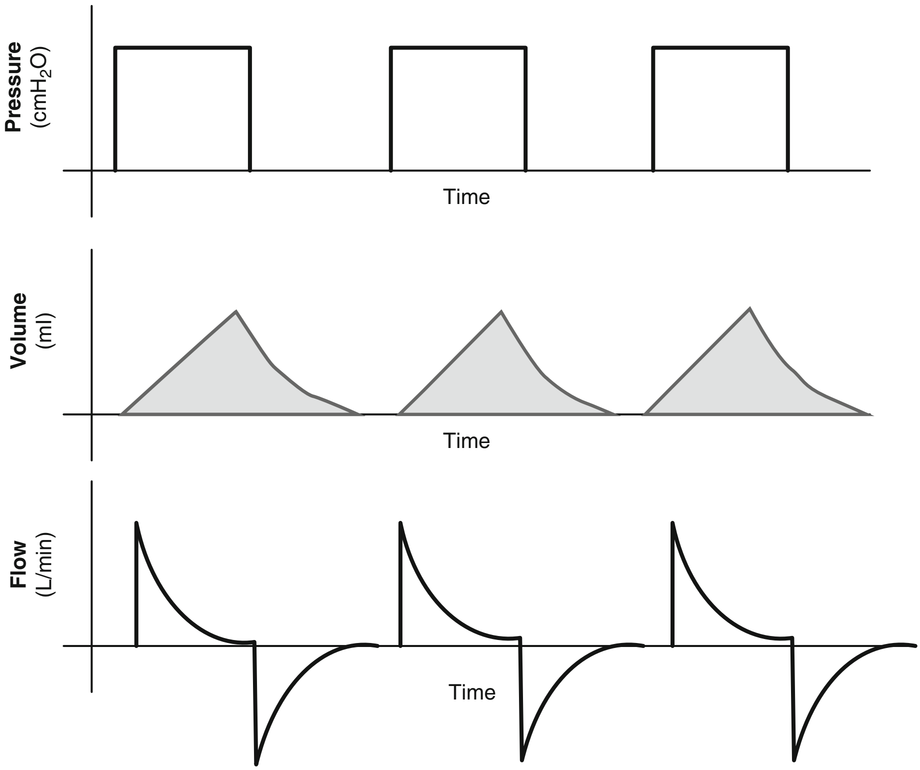

Fig. 23.4 Pressure, volume, and flow curves during pressure control ventilation. A decelerating inspiratory flow pattern is delivered resulting in a fixed pressure throughout the breath

the patient who controls his own respiratory rate and tidal volume. PSV may be used to overcome the resistance of endotracheal tube, to facilitate the respiratory effort of the patient, and to wean critically ill patients.

Figure 23.5 shows pressure, volume, and flow curves for pressure support ventilation.

Airway pressure release ventilation (APRV) may be considered as a partial ventilatory support mode with the possibility to allow spontaneous breathing in each point of ventilation cycle [7]. APRV is a time-cycled ventilation in which the operator sets two levels of pressure (pressure high and pressure low) and the time that the patient spends to maintain each level of pressure (time high and time low) [7]. Theoretically, maximizing the time spent at pressure high allows optimal alveolar recruitment and improved oxygenation; the brief intermittent release of breath to pressure low allows adequate ventilation. Furthermore, the time spent at pressure high may be customized to allow spontaneous breathing and progressive alveolar recruitment at the set level of pressure. Attention should be given in the setting of time low, because if it is too short intrinsic PEEP will result [8]. Spontaneous breaths may be supported or not, according to the patient's clinical needs.

Figure 23.6 shows pressure-time curves during APRV.

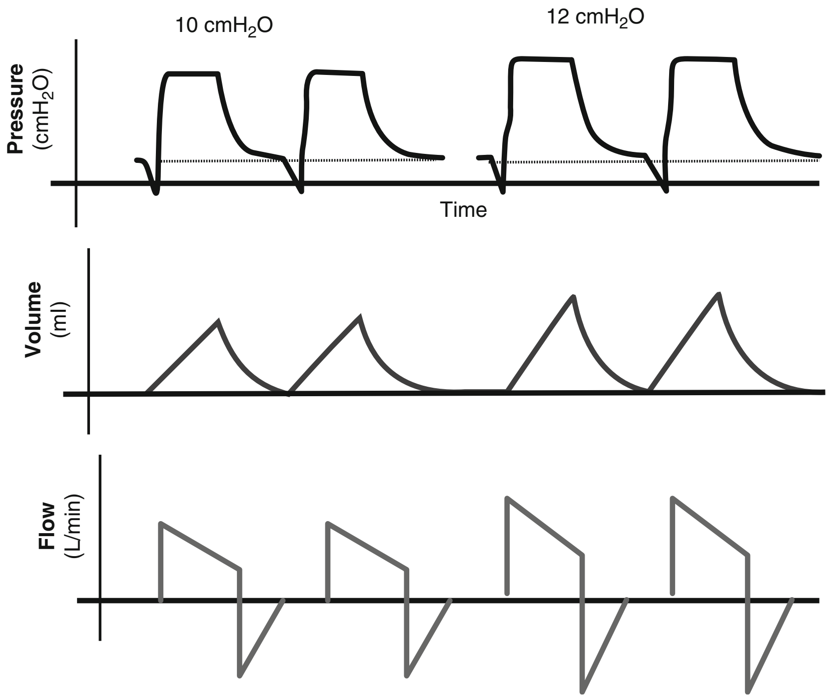

Fig. 23.5 Pressure, volume, and flow curves during pressure support ventilation. Spontaneous breaths are patient-triggered at different levels of pressure support (10 and 12 cmH_2O)

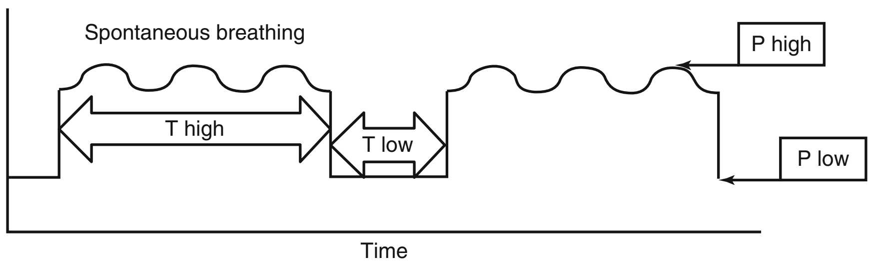

Fig. 23.6 Pressure-time curves during APRV. *P high* pressure high, *P low* pressure low, *T high* time high, *T low* time low

23.2 New Modes of Invasive Mechanical Ventilation

The patient's tailored modes are the new methods developed for invasive mechanical ventilation. These new modes of ventilation may offer several advantages to optimize the patient's respiratory effort and ventilator synchrony. It has been shown that increased patient's ventilator asynchrony might be associated with prolonged weaning and higher morbidity and mortality [2].

23.2.1 Proportional Assist Ventilation

Proportional assist ventilation (PAV) has the ability to provide the best synchronism between the patient's effort and ventilator partial assistance. In this ventilation, the ventilator generates a level of pressure in proportion to the patient's effort, and the ventilator output is under the full control of the patient's respiratory center.

In spontaneous breathing, the pressure generated by the inspiratory muscles (Pmus) is used to overcome the compliance and resistance of the respiratory system. In mechanically ventilated patients, the total pressure applied to the respiratory system (Ptot) equals the Pmus from the patient plus supplied airway pressure (Pappl). In PAV, the support is supplied by a combination of volume assist (VA) and flow assist (FA) based on the percentage of total work of breathing (WOB) that is dialed in for the ventilator to give [9]. The balance of the total WOB is then assumed by the patient. Since his inspiratory muscles have only to cope with the afterload, which has been reduced by the dialed WOB to be done by the ventilator (VA and FA), the ventilator essentially amplifies the patient effort [9]. The new generation of PAV (i.e., PAV +), allowing a better continuous estimation of the respiratory system resistance and compliance, seems to provide more flexible setting of the support according to the patients' need [10].

Figure 23.7 shows pressure, volume, and flow curves for proportional assist ventilation.

23.2.2 Neurally Adjusted Ventilatory Assist

Neurally adjusted ventilatory assist (NAVA) has been developed with the aim to overcome the limitation of PAV. In this ventilation the electrical activity of the inspiratory muscles can be used as an index of the inspiratory neural drive [11]. For this reason NAVA requires the placement of a gastric feeding tube with bipolar electrodes that measure the electrical signal leading to diaphragmatic stimulation by the vagus nerve (Edi). The diaphragmatic bipolar electrodes are not affected by the activity of postural and expiratory muscles. The signal obtained by the active region of the diaphragm is transferred to the ventilator, which regulates the respiratory support needed by the patient [12].

NAVA can be used if the respiratory center, phrenic nerves, and diaphragmatic activity of the neuromuscular junction are intact and the respiratory drive is not affected by sedation [13]. This situation implies that the complex system of feedback needed by NAVA is functional and the signal is not compromised. NAVA may be a promising tool for the future of mechanical ventilation.

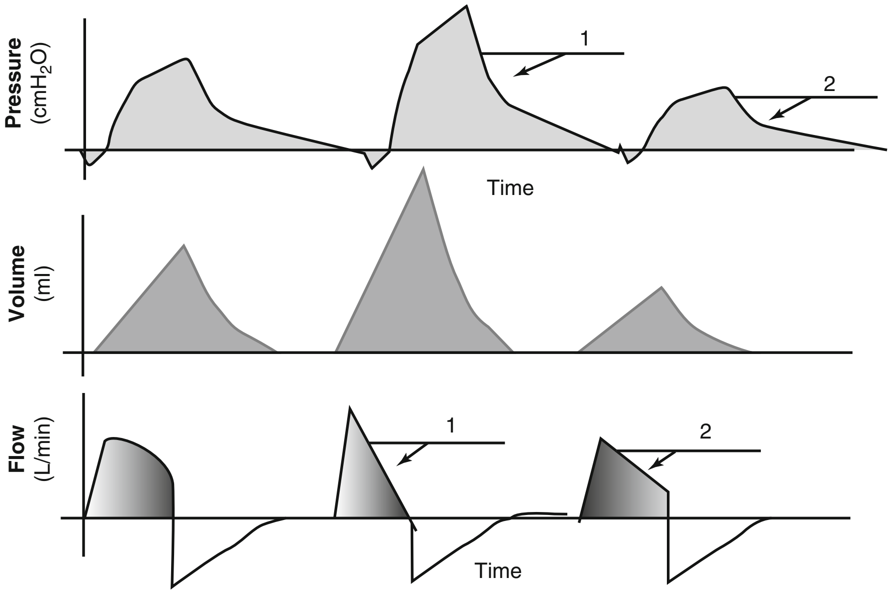

Fig. 23.7 Volume and flow curves for proportional assist ventilation. *1* increased effort of patient associated to an increase in the delivered pressure, *2* decreased effort of patient associated to a decrease in the delivered pressure

23.2.3 Noisy Pressure Support Ventilation

Pressure support ventilation (PSV) is frequently used and mechanical ventilation strategy that permits spontaneous breathing (SB) is investigated. PSV supports every triggered breath with positive pressure, leading to enhanced ventilation or perfusion of dependent zones, with potential improvement of gas exchange, though the work of breathing may increase. Random variation of tidal volume (VT) and respiratory frequency (noisy) may improve lung function during mechanical ventilation [14]. The beneficial effects of noisy ventilation have been demonstrated both in experimental and clinical studies in controlled mechanical ventilation. Basically, noisy PSV differs from other assisted mechanical ventilation modes that may also increase the variability of the respiratory pattern (e.g., proportional assist ventilation) by the fact that the variability does not depend on changes in the patient's inspiratory efforts; rather, it is generated externally by the mechanical ventilator [15]. Thus, *noisy PSV* is able to guarantee a given level of variability by generating different pressure support values, even if the patient is not able to vary the respiratory pattern due to the underlying disease or sedation [16]. In a previous study of a depletion model of acute lung injury, it was reported that the variability level of 30 % seems to represent a reasonable compromise to improve lung functional variables during noisy pressure support ventilation.

Figure 23.8 shows pressure and volume curves for noisy pressure support ventilation.

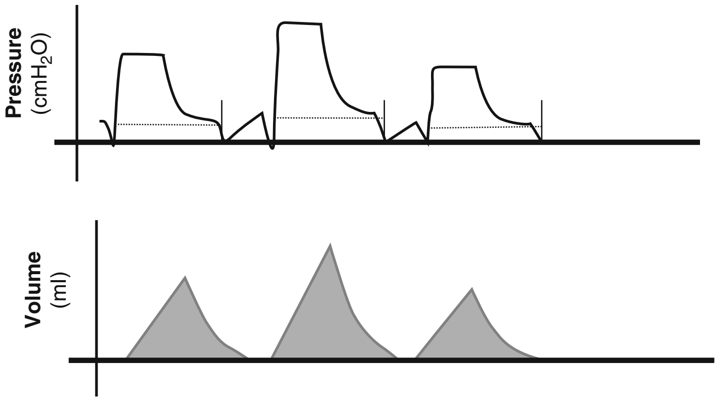

Fig. 23.8 Pressure and volume curves during noisy pressure support ventilation. The variability in the delivered pressure generates a different tidal volume for each breath

23.3 Nonconventional Modes of Invasive Mechanical Ventilation

23.3.1 High-Frequency Ventilation

High-frequency ventilation (HFV) was introduced in the clinical practice in the early 1970s, following the experiences by Oberg and Sjostrand (1969). Many HFV techniques are currently in use, all characterized by breathing frequencies higher than 1Hz (60 breaths/min) where tidal exchanges are less than the combined mechanical and anatomical dead space volume, displaying low peak pressures when compared to conventional mechanical ventilation (CMV). High-frequency ventilation (HFV) operates under two fundamentally different concepts of gas transport: convective gas transport and non-convective flow principles. Thus, gas exchange is at least in part by convection that includes direct alveolar ventilation, pendelluft, and asymmetric flow profiles [17]. HFV techniques, with an associated endobronchial convective displacement, have three essential common elements: a high-pressure flow generator, a valve for flow interruption, and a breathing circuit for connection to the patient [18]. The term high-frequency jet ventilation (HFJV) initially described any cyclic frequency of over a rate of 60 exchanges/min. Variants of this high-frequency definition were further described as flow interruption (HFFI), high-frequency (push-pull) oscillation (HFO), and high-frequency positive-pressure ventilation (HFPPV) based on the specific techniques that discriminate them [19–21].

23.3.2 High-Frequency Percussive Ventilation

High-frequency percussive ventilation (HFPV) was introduced with the intent of overcoming the inconveniences of other variants of HFV (e.g., high-frequency

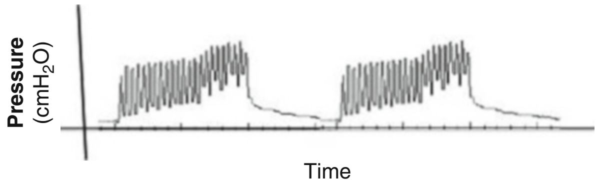

Fig. 23.9 The pressure-time curve for high-frequency percussive ventilation. In the time spent for a single inspiratory phase, HPFV delivers a high percussive pressure with high-frequency set as cycles/min

oscillation, high-frequency jet ventilation) [21]. HFPV associates the positive aspects of conventional mechanical ventilation (CMV) with those of HFV and was initially used for the treatment of acute respiratory diseases caused by burns and smoke inhalation and in the treatment of the newborn affected by hyaline membrane disease or infant respiratory distress syndrome (IRDS). Later on, it was employed in severe gas exchange impairment, where conventional mechanic ventilation (CMV) was useless [21]. Recently HPFV was investigated in a two-compartment heterogeneous mechanical model of the lung whether different mechanical resistive and elastic loads applied to one compartment, while the other is kept constant, would modify gas distribution between the two pathways and air trapping under HFPV [22]. Additionally, these results were compared with those generated in the same model by pressure-controlled ventilation (PCV). In this study the main advantage of HFPV seems to be ventilation at a lower mean airway pressure and lower inspiratory volumes, thus providing a protective effect against volutrauma and barotrauma.

Figure 23.9 shows the pressure-time curve for high-frequency percussive ventilation.

23.3.3 High-Frequency Oscillatory Ventilation

High-frequency oscillatory ventilation keeps the lung open by the application of a constant mean airway pressure. An oscillating piston produces phasic pressure swings around mean airway pressure, which are able to recruit alveolar units and to improve gas exchange, minimizing lung overdistension and atelectasis [23]. Small retrospective studies of HFOV in patients with ARDS and severe hypoxemia and/or elevated plateau airway pressures have revealed significant improvements in oxygenation. For this reason there are increasing evidences to use HFOV in the early phase of ARDS and life-threatening hypoxia [24].

Figure 23.10 shows the pressure-time curve for high-frequency oscillatory ventilation.

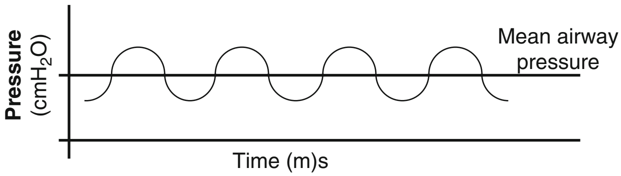

Fig. 23.10 Pressure-time curve for high-frequency oscillatory ventilation. The pressure waveform of HFOV oscillates around mean airway pressure. Time is expressed as ms

Conclusions

Invasive mechanical ventilation plays a relevant role in the overall clinical and therapeutic management of critically ill patients, independently from the presence of a specific lung disease. The optimal setting of mechanical ventilation appears to be associated with better outcome. New modes of mechanical ventilation may further improve the beneficial effects of respiratory assistance in critically ill patients.

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