# Chapter 6
# Ventilators and Modes

**Shekhar T. Venkataraman, Bradley A. Kuch, and Ashok P. Sarnaik**

## 6.1 Basic Concepts and Design

### *6.1.1 Spontaneous Breathing*

Normal breathing is mostly automatic except during activities such as speaking, breath holding, voluntary hyperventilation and voluntary cough. Spontaneous breathing is rhythmic and regulated by neural and chemical mechanisms. The rhythmicity is controlled by neurons in the brainstem which can be modified by higher brain centers, mechanoreceptors in the lungs and upper airways, and chemoreceptors in the brainstem and the carotid body. Arterial oxygen and carbon dioxide tensions and acidity of the blood influence both the rate and depth of the breathing.

A breath is defined as one cycle of flow of gas into the lung (inspiration) and flow of gas out of the lung (exhalation). A breath has 4 phases: (1) breath initiation,

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S. T. Venkataraman (✉)
Professor, Departments of Critical Care Medicine and Pediatrics, University of Pittsburgh School of Medicine, Pittsburgh, PA, USA
e-mail: venkataramanst@upmc.edu

Medical Director, Respiratory Care Services, Children's Hospital of Pittsburgh, 4401 Penn Avenue, Faculty Pavilion 2117, Pittsburgh, PA 15224, USA

B. A. Kuch
Director, Respiratory Care Services and Transport Team & Clinical Research Associate, Department of Pediatric Critical Care Medicine, UPMC Children's Hospital of Pittsburgh, 4401 Penn Ave, Pittsburgh, PA 15224, USA

A. P. Sarnaik
Professor of Pediatrics, Former Pediatrician in Chief and Interim Chairman Children's Hospital of Michigan, Wayne State University School of Medicine, 3901 Beaubien, Detroit, MI 48201, USA

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(2) inspiratory phase when lungs are inflated, (3) start of exhalation, and (4) expiratory phase when lungs deflate. Trigger is the variable that initiates a breath. Cycling refers to the switch from the end of inspiration to the start of exhalation. For a spontaneous breath, both trigger and cycling are controlled by neural output from the respiratory centers in the brainstem, modified by inputs from mechanoreceptors and chemoreceptors. Neural output stimulates the inspiratory muscles, principally the diaphragm, to contract which causes gas to flow into the lungs. Exhalation is normally passive and starts when the inspiratory neural output is inhibited. The size of the breath is the tidal volume. Inspiratory time is defined as the period from the start of the positive airflow to the start of the negative airflow. Expiratory time is defined as the period from the start of the negative flow to the start of the positive flow. Total cycle time is the sum of inspiratory and expiratory times and is equal to the inverse of breathing frequency. The inspiratory-expiratory (I:E) ratio is defined as the ratio of inspiratory time to expiratory time.

### 6.1.2 Equation of Motion

In order for gas to flow into and out of the lungs, a pressure gradient has to be generated between the proximal airway and the alveolus, known as the transrespiratory pressure ($P_{tr}$). During spontaneous breathing, the respiratory muscles create $P_{tr}$ by decreasing the alveolar pressure relative to the proximal airway pressure as a result of negative pressure in the thorax. The pressure generated by the respiratory muscles during spontaneous breathing is expressed as $P_{mus}$ which is a conceptual pressure that cannot be directly measured. Thoracic structures impede lung inflation and therefore, a certain amount of force is required to overcome this impedance. The factors that contribute to this impedance are: (1) Elasticity of the lungs, chest wall, and abdomen, (2) Respiratory system resistance (airflow and tissue resistance) of the lung, chest wall and abdomen), and (3) Inertance of the gas. The equation of motion provides a simple and useful model of the mechanical behavior of the respiratory system which states that $P_{tr}$ required to inflate the lung to a certain volume is equal to the sum of the pressures required to overcome each of the impedance factors. The pressure required to overcome inertance is usually negligible and is ignored. Therefore, $P_{tr}$ required to inflate the lung can then be expressed as a simplified linear equation:

$$P_{tr} = P_{Elasticity} + P_{TotalResistance}$$

or

$$P_{tr} = (Elastance \times Volume) + (Resistance \times Flow)$$

Artificial respiration requires a device to move gas into and out of the lungs. This can be achieved manually or automatically. An example of a manual ventilator is the self-inflating resuscitator bag. Manual compression of the bag causes gas to flow into the lungs by creating a pressure gradient between the bag and patient's lungs. A ventilator, on the other hand, is a device that works automatically to move gas into and out of the lungs. Positive pressure ventilators create $P_{tr}$ by increasing the proximal airway pressure relative to the alveolar pressure. Negative pressure ventilators, conversely, create $P_{tr}$ by decreasing the alveolar pressure relative to the proximal airway pressure. There are three possible ways a $P_{tr}$ may be generated: (1) by the ventilator alone, (2) by a spontaneous breath alone, or (3) a combination of the two. Therefore, the equation of motion can be re-expressed as:

$$P_{tr} = P_{mus} + P_{vent}$$

where $P_{vent}$ is the pressure generated by the ventilator during inspiration and $P_{mus}$ is the theoretical chest wall transmural pressure generated by the inspiratory respiratory muscles that would produce movements identical to those produced by the ventilator. When a ventilator performs all the work of breathing, then $P_{tr} = P_{vent}$. During complete spontaneous breathing $P_{tr} = P_{mus}$. When a spontaneous breath is augmented or supported by a ventilator breath then $P_{tr} = P_{mus} + P_{vent}$. In a sense, a ventilator is a machine that does external work in the form of mechanical breaths and can either replace the patient's work of breathing completely or partially, or augment a patient's breathing efforts.

## 6.2 Basic Design of a Ventilator

In the pediatric intensive care unit, mechanical ventilation of a patient requires the following components: (1) High pressure gas source, (2) Oxygen blender, (3) Ventilator, and (4) Humidification system. High pressure compressed gas source to power the ventilator can be from tanks, compressors, or wall outlets. Ventilators used in the critical care setting use either compressed gases from the wall outlets or a compressor. Ventilators that use wall outlets have pressure reducing valves internally to modulate the operating pressure of the ventilator. When compressed gas is the input source, the ventilator functions mainly as a controller. The sources for air and oxygen are usually separate so that the inspired concentration of oxygen may be controlled using a blender. The output from the ventilator is a mechanical breath whose size and timing are controlled and determined by pressure and flow waveforms. To achieve this, all ventilators have a control system (pneumatic, electrical or electronic) to regulate the pressure, volume, or flow waveform, a cycling mechanism, and a system to provide end-expiratory pressure.

## 6.3 Modes of Ventilation

Mode of ventilation is a predetermined pattern of interaction between the patient and the ventilator. It includes the sequence of breaths, breath patterns, control variables within and between breaths, and the schemes used to provide feedback as well as effecting the variables during mechanical ventilation.

### *6.3.1 Ventilator Breath*

Figure 6.1 shows the components of a breath in a pressure-controlled mode. Point 1 is the trigger and initiation of inspiration, 2 is the peak inspiratory flow, 3 is the end of inspiration (cycling), 4 is the peak expiratory flow, 5 is the time taken to fully deflate the lung during expiration, 6 is the end of deflation, and 7 is the expiratory phase before the next inspiration. Inspiratory time = Period between 1 and 3. Expiratory time = Period between 3 and the end of 7. PIP is the peak inspiratory pressure. PEEP is the positive end-expiratory pressure.

A ventilator breath, just like a spontaneous breath, has a trigger to initiate the breath, an inspiratory phase where a tidal volume is delivered, cycling mechanism by which inspiration is terminated, and an expiratory phase initiated. Inspiratory time is defined as the period from the trigger to start inspiration to the point of

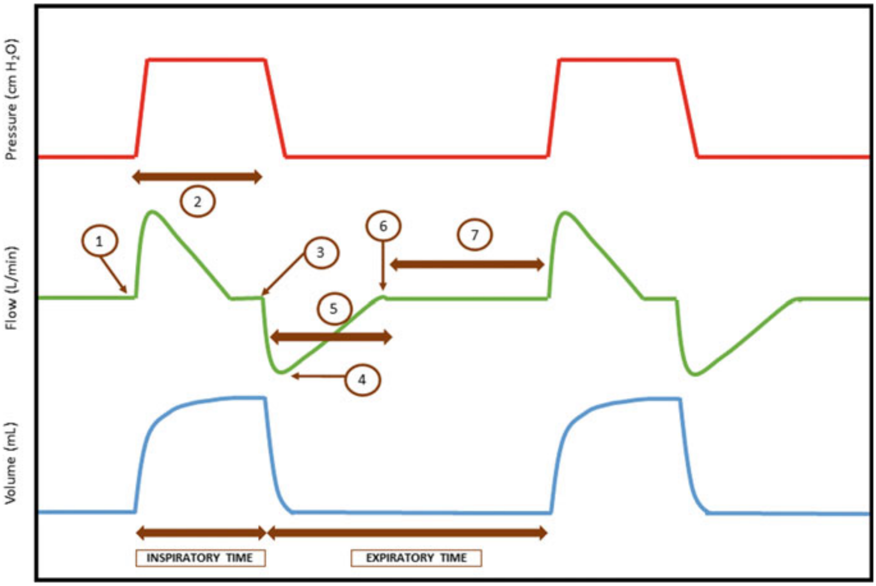


**Fig. 6.1** Scalar waveform with pressure, flow and volume over time curves showing different components of a breath for a pressure-controlled time-cycled breath

cycling. Expiratory time is defined as the period from the point of cycling to the trigger for the next mechanical breath. Total cycle time ($T_{tot}$) is the sum of inspiratory ($T_i$) and expiratory times ($T_e$) and is equal to the inverse of breathing frequency. The inspiratory-expiratory (I:E) ratio is defined as the ratio of $T_i$ to $T_e$. Percent inspiratory time (also called the duty cycle) is defined as the percent of $T_{tot}$ that is spent in inspiration. The tidal volume ($V_T$) is the integral of flow with respect to time. For constant flow inspiration, this simply reduces to the product of flow and inspiratory time.

### 6.3.2 Control Variables

During the inspiratory phase of a ventilator breath, pressure, volume, or flow as a function of time may be predetermined. It is important to understand what is meant by the term "control" when it is applied to ventilators and the different modes. Only one variable can be controlled during the inspiratory phase which becomes the independent variable and the other variables vary according to the respiratory system compliance and resistance. Control also refers to the waveform of the variable which is fixed breath to breath. For example, pressure-control refers to the pressure waveform being controlled during inspiration, usually a "square-wave" or rectangular waveform as well as the predetermined pressure limit. With volume control, the shape of the volume waveform as well as the predetermined volume limit is controlled while flow and pressure vary. With flow control, the flow waveform is controlled while volume and pressure vary. The most common flow waveform used in ventilators for pediatric use is rectangular and is referred to as constant-flow inspiration. When constant-flow inspiration is combined with time-cycling, it is identical to volume-control and these terms may be used interchangeably. Time-control is a category of ventilator modes in which the flow, volume and pressure during the set $T_i$ depend on the mechanics of the respiratory system. High frequency oscillatory ventilation (HFOV) and high frequency percussive ventilation are examples of time-controlled ventilation.

### 6.3.3 Phases of a Breath

All ventilators are equipped with mechanisms to provide four basic functions: (1) initiate lung inflation, (2) inflate the lungs with a tidal volume, (3) terminate lung inflation, and (4) allow the lungs to empty. Trigger is the signal which starts inspiration. Time, pressure, flow, minimum minute ventilation, apnea interval, or electrical signals are used as inspiratory triggers. Cycling refers to the termination of inspiration and the start of exhalation. Time, pressure, volume, flow, and electrical signals are used as cycling signals.

### 6.3.4 Classification of Breaths

The criteria used to start (trigger) and stop (cycle) inspiration are used to classify breaths. Both triggering and cycling events can be initiated by either the ventilator or the patient. When inspiratory flow starts with a ventilator-generated signal, it is referred to as ventilator-triggering and is independent of a patient-initiated signal. Similarly, when inspiration starts on a patient-generated signal, it is referred to as patient-triggering and is independent of a ventilator-generated signal. The trigger to initiate a breath may be pressure, volume, flow, or time.

Ventilator-cycling refers to ending inspiration based on signals from the ventilator independent of signals based on patient factors. Time-cycling is a common criterion and refers to the time that has elapsed from the start of inspiration and is the same breath-to-breath. Patient cycling occurs when a signal based on the patient's respiratory mechanics, which affects the equation of motion, reaches a threshold value. Similar to the trigger, the variable to cycle a breath from inspiration to exhalation may be pressure, volume, flow, or time.

When the start and end of a breath is determined by the patient, it is referred to as a *spontaneous breath* (Table 6.1). A spontaneous breath is both patient-triggered and patient-cycled. An *unassisted spontaneous breath* refers to a breath where the patient determines both the timing and size of the breath. Normal breathing is an example of unassisted spontaneous breathing. T-piece breathing or breaths during continuous positive airway pressure (CPAP) are also examples of unassisted spontaneous breathing. The size of the breath is determined solely by the effort of the patient with no additional help from the ventilator. An *assisted spontaneous breath* refers to a breath where the ventilator does some of the inspiratory work indicated by an increase in airway pressure above the baseline. For an assisted breath, the patient must initiate a breath, and then the ventilator is triggered to provide a positive pressure breath. With an assisted spontaneous breath, the ventilator contributes to the size of the breath but the patient determines the timing of the breath. Pressure-supported breath is an example of an assisted spontaneous breath. The size of the breath or tidal volume is determined by the effort made by the patient as well as the work done by the ventilator during that breath. A *mandatory breath* is one in which the end of inspiration is determined by the ventilator, independent of the patient. A mandatory breath may be patient-triggered or machine-triggered. The inspiratory time is not under the control of the patient.

**Table 6.1** Classification of breaths

| Trigger | Inspiratory phase | Cycling | Classification |
|---|---|---|---|
| Patient | Unassisted | Patient | Spontaneous without assist |
| Patient | Mechanical support | Patient | Spontaneous with assist |
| Patient | Mechanical support | Ventilator | Mandatory |
| Ventilator | Mechanical support | Ventilator | Mandatory |

The size of the breath is determined either entirely by the ventilator or a combination of the spontaneous effort and the ventilator work.

### Trigger

Time-triggered breaths: When a ventilator initiates a breath after a preset time has elapsed from the end of the last exhalation, it is termed as a time-triggered breath. All time-triggered breaths are mandatory breaths. Time to trigger is dependent on the set ventilator rate.

Pressure-triggered breaths: When the ventilator detects a threshold change in pressure from baseline and initiates inspiration, it is termed as pressure triggering. A decrease in circuit pressure is detected by the ventilator pressure sensors and interpreted as a patient effort. While this form of triggering is available in modern ventilators, it has been superseded by flow-triggering.

Flow-triggered breaths: Ventilators that provide flow triggering has a constant bias flow of gas through the circuit during the expiratory phase. When there is no patient effort and with no leaks in the system, there is no difference in the flow across the inspiratory and expiratory flow sensors. Since the difference in flow is zero, no ventilator breath is triggered. Inspiratory effort by the patient or a leak in the system creates a difference in the flow across the inspiratory and expiratory flow sensors. When this difference in flow reaches a preset threshold value, it triggers a breath. This is referred to as flow-triggering.

### Trigger Sensitivity

Inspiratory trigger sensitivity refers to the threshold value that needs to be set for patient-initiated breaths and is only applicable to pressure- and flow-triggering since time-triggered breaths are always machine-triggered mandatory breaths. The minimal pressure or flow that needs to be detected in the circuit can be set for any patient-initiated breaths. The actual level of the trigger threshold will depend on the patient's efforts as well as the need to avoid different forms of asynchrony. When the patient is capable of making a strong effort, a higher threshold may be chosen. However, when a patient's inspiratory effort is weak or poor, the threshold should be the lowest that the patient can trigger. A disadvantage of a very low threshold is auto-triggering which is triggering of a breath due to changes in the threshold not created by the patient, such as a leak in the system. A high threshold will increase the trigger work of breathing and may be uncomfortable for the patient. An ideal threshold is one which allows all of the patient's efforts to be triggered without any discomfort or patient-ventilator asynchrony. In most ventilators, the threshold value is the actual value of the trigger such as cm of $H_2O$ for pressure- and L/min for flow-triggering. In some ventilators, the range of threshold values does not represent the actual values, but only degrees of change.

During inspiration, based on the control variable, a preset value is reached before the end of inspiration. Inspiration is pressure-targeted, volume-targeted, or flow-targeted depending on whether a preset value for pressure, volume, or flow is reached before inspiration ends. Cycling may occur due to attainment of preset pressure, volume, flow or time. The criteria for determining the phase variables during a mechanical breath are shown in Fig. 6.2. The above-mentioned description allows one to describe a breath based on the control variable, trigger, targeted variable during inspiration and the cycling mechanism.

### *6.3.5 Breath Sequences*

A breath sequence can be defined as a set of breaths producing minute ventilation. All the breaths delivered by the ventilator may be mandatory or spontaneous or a combination of both. As described above, the spontaneous breaths may or may not be assisted/supported. Therefore, the 3 basic breath sequences that a ventilator delivers are as follows: (1) Continuous Mandatory Ventilation, (CMV), (2) Intermittent Mandatory Ventilation (IMV), and (3) Continuous Spontaneous Ventilation (CSV). CMV refers to a breath sequence when all the breaths are mandatory (Fig. 6.3). During CMV, spontaneous breaths do not occur between mandatory breaths.

Assist-Control refers to a mode of ventilation when a patient can receive either a ventilator-initiated or patient-initiated mandatory breath (Fig. 6.4). Machine-triggered breaths are not preceded by a spontaneous breath. Patient-triggered breaths are preceded by a spontaneous breath which creates a negative deflection in the pressure–time curve (denoted by the arrows in the Fig. 6.4). While the breaths have different triggers, all the breaths shown are machine-cycled. This breath sequence is also called Assist-Control. In assist-control (AC) mode, every patient breath is triggered by pressure or flow generated by the patient inspiratory effort and “assisted” with either preselected inspiratory pressure or volume. When the patient does not make any effort of breathing such as with neuromuscular blockade, the total number of breaths is equal to the set rate.

Figure 6.4 shows three examples of the total number of breaths in the Assist-Control mode. In this example, the control rate (back-up rate) is set at 24 breaths per minute. When the patient makes no effort, the total number of breaths is 24 breaths/min. When the patient breathes at a frequency of 16 breaths/min, which is less than the set back-up rate, the ventilator will assist all the patient's breaths, and the patient will receive 8 additional machine-triggered breaths/min (Fig. 6.4). When the patient breathes at a frequency of 32 breaths/min, which is higher than the set back-up rate, all the breaths are patient-triggered mandatory breaths. Although useful in some patients, the AC mode cannot be used in the weaning process, which involves gradual decrease in ventilator support.

CSV refers to a breath sequence when all the breaths are spontaneous. During CSV, spontaneous breaths may or may not be supported with positive pressure. Three examples of CSV are shown in Fig. 6.5. Figure 6.5a shows normal continuous spontaneous breathing without any positive pressure support. During inspiration and exhalation, the airway pressures are around atmospheric (0 cm). Figure 6.5b shows CSV with CPAP. During inspiration and exhalation, the airway pressures fluctuate around the CPAP level. No ventilatory assistance is provided.

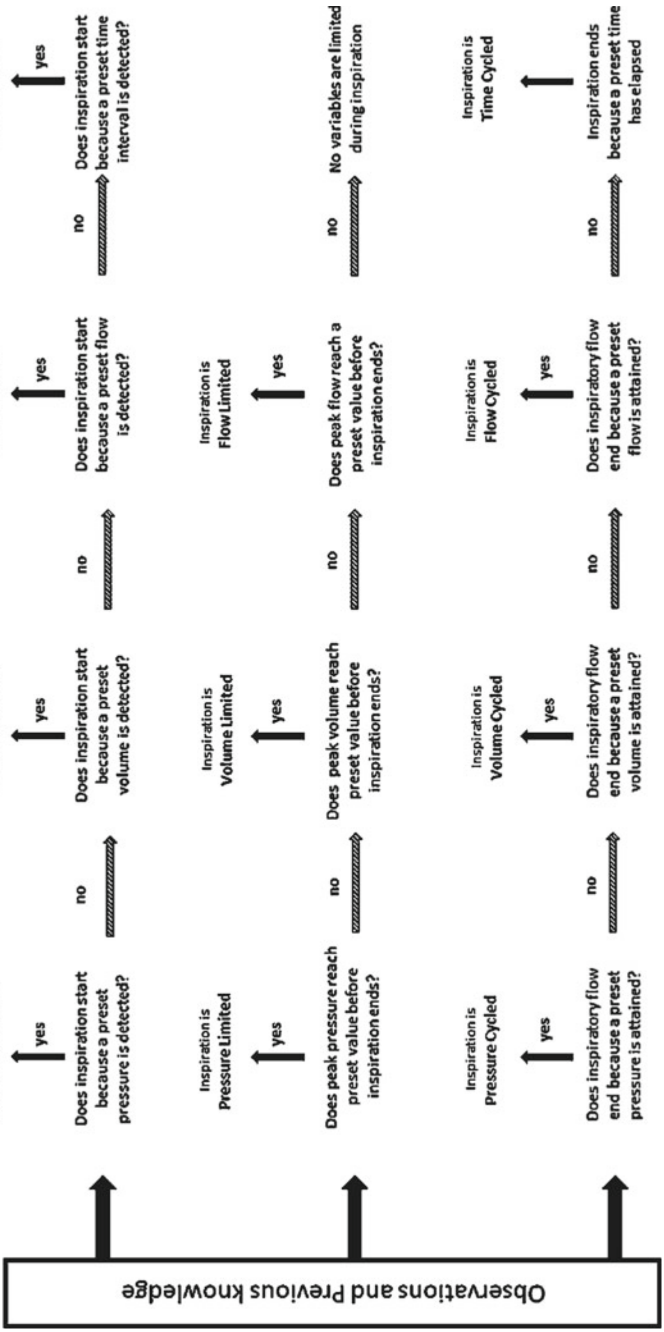


**Fig. 6.2** Criteria for determining the phase variables during a ventilator-assisted breath ( Reproduced from Chatburn RL: Classification of mechanical ventilators, respiratory care equipment, Philadelphia, 1995, JB Lippincott)

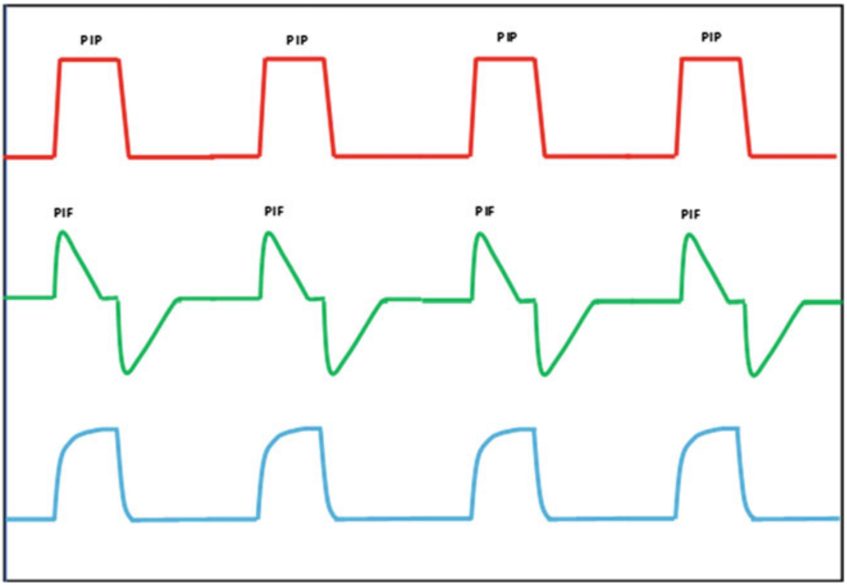


**Fig. 6.3** Continuous mandatory ventilation (CMV) with pressure-control ventilation. All the breaths are machine-triggered and machine-cycled

Figure 6.5c shows pressure-support ventilation which is defined as CSV with a positive pressure mechanical assistance with every breath above a baseline level of PEEP.

IMV refers to a breath sequence when spontaneous breaths occur between mandatory breaths. These breaths may or may not be synchronized. When IMV is synchronized to the patient's inspiratory efforts, it is referred to as synchronized IMV (SIMV) (Fig. 6.6). With SIMV, at set intervals, the ventilator's timing circuit becomes activated and a timing "window" appears (shaded area) just before the next mandatory breath is to be delivered. If the patient initiates a breath in the timing window, then the ventilator will deliver a mandatory breath synchronized to the spontaneous breath. If no spontaneous effort occurs, then the ventilator will deliver a mandatory breath at the end of the timing window.

### 6.3.6 Ventilatory Pattern

A ventilatory pattern is a sequence of breaths (CMV, IMV, or CSV) with a designated control variable (volume control (VC), pressure control (PC) or dual-control (DC). Dual-control modes of ventilation are auto-regulated pressure-controlled modes of mechanical ventilation with a user-selected tidal volume target. Dual control modes use both the pressure and volume signal to control the breath size.

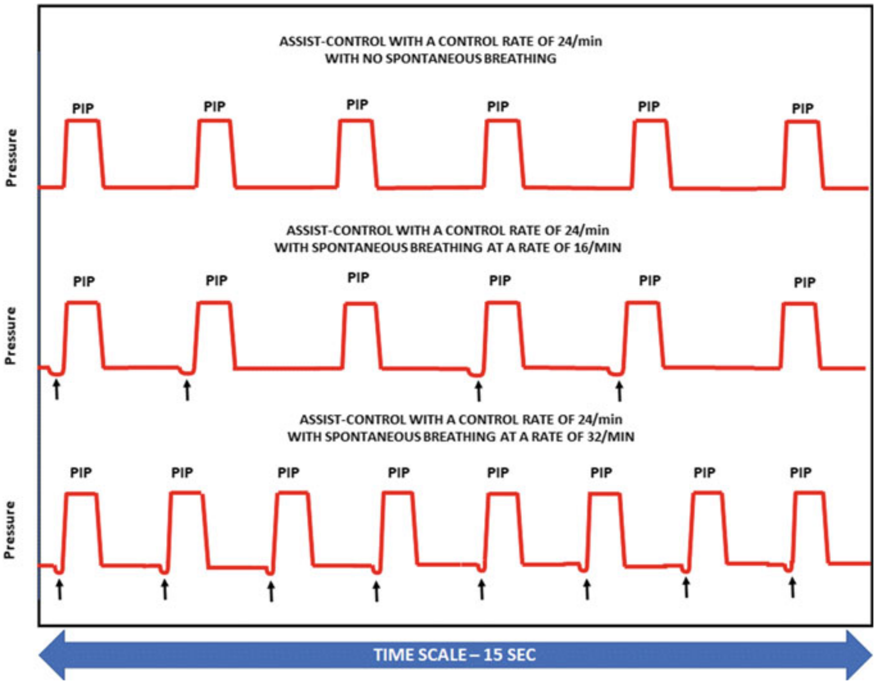


**Fig. 6.4** Assist-Control continuous mandatory entilation with pressure-control ventilation. Spontaneous breaths appear as negative deflections in the pressure–time waveform (black arrows)

Out of the 9 theoretical combinations based on 3 breath sequences and 3 control variables, only 8 are operational. These are VC-CMV, PC-CMV, VC-IMV, PC-IMV, PC-CSV, DC-CMV, DC-IMV and DC-CSV. VC-CSV is theoretically not possible because, by definition, all volume-controlled breaths are machine-cycled and therefore, mandatory breaths. These 8 ventilatory patterns are available in most modern ventilators (Table 6.2). Only one ventilatory pattern can be present in a mode of ventilation. Ventilatory patterns can be used as a mode classification system.

### 6.3.7 Targeting Schemes

The targeting scheme is best defined as the method of feedback control used to deliver a particular pattern of ventilation. There are several types of such feedback control mechanisms. A target can be defined as a predetermined goal of the ventilator output.

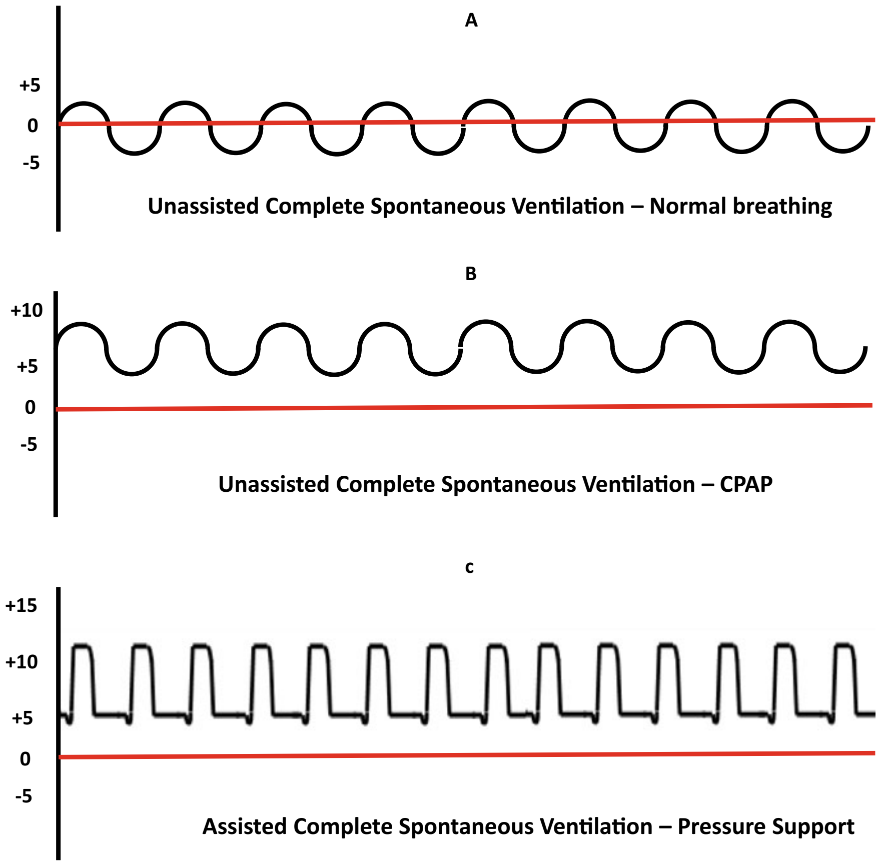


**Fig. 6.5** Continuous spontaneous ventilation (CSV). **a** Normal breathing. **b** Spontaneous ventilation with CPAP. **c** Pressure support ventilation with PEEP

*Set point*: An example of this is Pressure-Control ventilation where a predetermined Pressure Limit is set during inspiration. The ventilator's pressure sensors will provide feedback to a flow regulator which adjusts the flow rate to maintain the set pressure limit. When there is a leak in the system and the pressure limit does not reach its set value, flow will increase to help achieve the set pressure limit.

*Dual targeting*: An example of this is Volume-Assured Pressure Support. The breath starts with pressure support at a preset pressure limit and when the ventilator senses that the targeted volume will not be delivered within that breath, the ventilator switches to volume control and increases the flow for the remaining portion of the inspiratory time to achieve the volume target.

*Servo control*: Examples of this are NAVA, Automatic Tube Compensation (ATC) and Proportional Assist Ventilation. In NAVA, for example, the level of

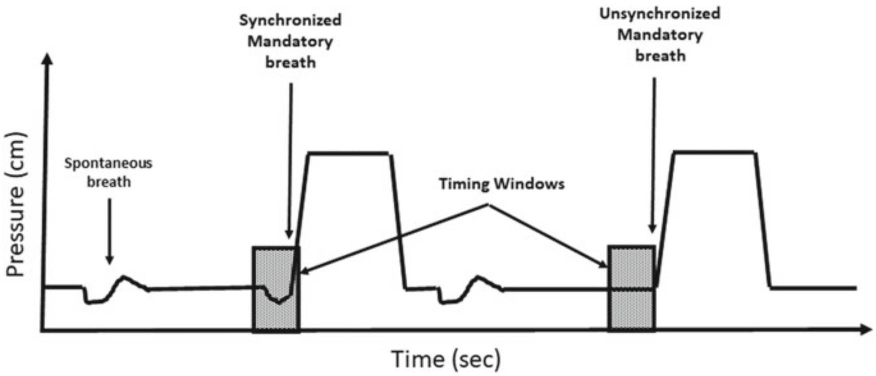


**Fig. 6.6** Synchronized intermittent mandatory ventilation (SIMV). Shaded rectangles indicate timing windows with examples of synchronized and unsynchronized mandatory breaths

**Table 6.2** Ventilatory patterns by breath control variable and accepted acronym

| Breath control variable | Breath sequence | Acronym | Example |
|---|---|---|---|
| Volume | Continuous mandatory ventilation | VC-CMV | Volume-controlled time-cycled ventilation |
| | Intermittent mandatory ventilation | VC-IMV | SIMV-Volume-control |
| Pressure | Continuous mandatory ventilation | PC-CMV | Pressure-controlled time-cycled ventilation |
| | Intermittent mandatory ventilation | PC-IMV | SIMV-pressure-control |
| | Continuous spontaneous ventilation | PC-CSV | Pressure-support |
| Dual-Control | Continuous mandatory ventilation | DC-CMV | Pressure-regulated volume control (PRVC) |
| | Intermittent mandatory ventilation | DC-IMV | SIMV-PRVC |
| | Continuous spontaneous ventilation | DC-CSV | Volume-support |

ventilator support is proportional to the magnitude of the electrical activity of the diaphragm (Edi). A patient’s signal is used as servo control to determine the level of support from the ventilator.

*Adaptive targeting*: This specifically refers to a control system that will adapt the output to changing respiratory conditions using a feedback mechanism. A good example is the pressure regulated volume control (PRVC) mode. The inspiratory pressure is automatically adjusted to achieve an average tidal volume target, and this varies from breath to breath—adapting to the changing compliance.

## 6.4 Commonly Used Modes

The following is a description of some of the most common modes used in infants and children in more detail. The two most common forms of mandatory modes used in infants and children are pressure-controlled, time-cycled and volume-controlled time-cycled modes of ventilation. Pressure-controlled time-cycled ventilation would be classified as PC-CMV or PC-IMV according to the modern taxonomy. Similarly, volume-controlled time-cycled ventilation would be classified as VC-CMV or VC-IMV.

### *6.4.1 Volume-Controlled Mandatory Breaths*

Volume-controlled ventilation (VCV) can be delivered either by volume-cycled breath, where inspiration is terminated after a preset volume is delivered or by volume-controlled time-cycled breaths, where the cycling mechanism is preset time, and the tidal volume delivered is regulated by adjusting the inspiratory flow rate. The flow waveforms in VCV can be rectangular, decelerating, accelerating and sinusoidal but the tidal volume is delivered throughout inspiration. The peak inspiratory pressure (PIP) is variable and depends on the flow rate, the total resistance, and the total compliance of the ventilator circuit and the patient's lungs. Changes in resistance or compliance will be reflected by a change in PIP, and the ventilator can be set to alarm at a pressure limit that is generally set 5 to 10 cm above the PIP.

The tidal volume delivered by the ventilator is distributed between the ventilator circuit, the airways, and the patient's lungs. The compliances and resistances of the ventilator circuit, the endotracheal or tracheostomy tube, and the patient independently and together affect the distribution of tidal volume delivered by the ventilator. A decrease in the compliance or an increase in the resistance of the ventilator circuit will affect the actual tidal volume delivered to the patient. While most modern ventilators deliver the preset tidal volumes reliably, the tidal volumes delivered to the patient on a breath-to-breath basis may not always be constant. The ventilator circuit includes an internal volume and the external tubing. The actual tidal volume or the effective tidal volume ($V_{Teff}$) delivered to the patient can be approximated by the following formula:

$$V_{Teff} = V_{Tdel} - V_{Tcircuit}$$

where, $V_{Tdel}$ is tidal volume delivered by the ventilator and $V_{Tcircuit}$ is the volume of gas that is distributed to the ventilator circuit. $V_{Tdel}$ is equal to the inspired tidal volume, when there is no leak in the total respiratory system. When there is a leak in the system, however, such as with the use of uncuffed endotracheal tubes, then

$V_{Tdel}$ is less than the inspired tidal volume. $V_{Tcircuit}$ can be estimated by the following formula:

$$V_{Tcircuit} = C_{vent} \times (PIP - PEEP),$$

where, $C_{vent}$ is the compliance of the ventilator circuit, PIP is the peak inspiratory pressure reached in the circuit during inspiration and PEEP is the level of positive end-expiratory pressure.

During exhalation, expiratory flow curves depend on the type of expiratory resistance or PEEP valve in the system. Changes in pressure, flow, and volume curves in response to changes in compliance and resistance are discussed in the chapter on ventilator graphics (Chap. 9).

### *6.4.2 Pressure-Controlled Mandatory Breaths*

Pressure-controlled, time-cycled ventilation is widely used in infants and children with lung disease. In this mode, inspiratory flow is high at the start of inspiration and the inspiratory pressure rises quickly (Fig. 6.1). In older ventilators, there was a provision to control the inspiratory flow which was usually set at 4–10 L/kg/min. In modern ventilators, the rate of increase in pressure in the early phase of inspiration is controlled by the inspiratory “rise time”, which can be adjusted to make the inspiratory pressure rise quickly or slowly. Once the inspiratory pressure reaches the preset limit, the inspiratory valve closes. If the pressure limit were to drift, such as with an endotracheal tube leak, the ventilator will open the inspiratory valve and sufficient flow is allowed to enter the circuit to maintain the pressure limit. During the inspiratory phase with pressure-controlled time-cycled ventilation, the expiratory valve remains closed until the inspiratory time is completed. When the inspiratory time is completed, the expiratory phase begins and the pressure decreases to the baseline positive end-expiratory pressure (PEEP). The tidal volume delivered depends on the compliance and resistance of the respiratory system and the pressure difference between the pressure-limit and PEEP. The inspiratory flow into the lung is a decelerating waveform (high at first and then declining) (Fig. 6.1). When inspiratory time is set to at least 5 times the time-constant of the respiratory system, inflation will be complete and the inspiratory flow will reach zero flow before the end of inspiration. If the inspiratory time is shorter, there will not be full inflation and the inspiratory flow will not reach zero flow when exhalation begins.

### *6.4.3 Pressure-Regulated Volume Control*

Dual-control breath-to-breath mode with mandatory pressure-controlled, time-cycled breath is referred to as pressure-regulated volume control (PRVC) (with Maquet Servo series), adaptive pressure ventilation (APV) (with Hamilton Galileo), autoflow (Evita 4), or variable pressure control (Venturi), depending on the manufacturer. In this form of pressure-regulated, time-cycled ventilation, delivered tidal volume is used as a feedback control for continuously adjusting the pressure limit. All breaths in these modes are time or patient triggered, pressure controlled, and time cycled mandatory breaths.

How it works:

1. First, set the target tidal volume, ventilator rate, inspiratory time, PEEP, $FiO_2$, trigger sensitivity, and the inspiratory rise time for PRVC
2. Ventilator delivers a volume-controlled time-cycled breath with a 10% inspiratory pause to measure the plateau pressure ($P_{plat}$).
3. The next breath is a pressure-controlled breath with preset pressure limit or peak inspiratory pressure (PIP) equal to the $P_{plat}$ measured previously.
4. The delivered tidal volume is then measured.
5. If the delivered tidal volume is equal to the set tidal volume, then PRVC is continued with no change in PIP
6. If the delivered tidal volume is less than the set tidal volume, then PIP is increased. The ventilator compares the delivered tidal volume to the set tidal volume and adjusts the PIP until both volumes are equal.
7. If the delivered tidal volume is more than the set tidal volume, then PIP is reduced until the set tidal volume and delivered tidal volume are equal.
8. If there are changes in lung mechanics that affect the delivered tidal volume, adjustments as described above continued automatically to ensure that the set tidal volume is consistently delivered.
9. PIP can only be increased up to 5 cm $H_2O$ below the pressure alarm limit set, at which point it will alarm because the delivered tidal volume will be less than the set tidal volume.
10. There is no lower limit for the reduction in the pressure-limit level. This mode of ventilation appears to be most beneficial when there are rapid changes in lung compliance such as after surfactant administration.

### *6.4.4 Selection of Parameters for Mandatory Breaths*

The following are the parameters of mandatory breaths that are commonly set and titrated: (1) tidal volume or inspiratory pressure limit, (2) ventilator rate, (3) fraction of inspired oxygen ($FiO_2$), (4) PEEP, (5) inspiratory time and (6) inspiratory rise time. A desirable $V_{Teff}$ for most patients is 6–8 ml/kg. Higher $V_T$ may be required in obstructive lung disease when slower respiratory rates are beneficial. The end-inspiratory alveolar pressure ($P_{plat}$), measured using an inspiratory hold maneuver should be preferably less than 30 cm $H_2O$.

Inspiratory rise time refers to the rate at which the ventilator raises the inspiratory pressure (in pressure targeted modes) and flow (in volume targeted flow). It is set as a percent of breath cycle time usually from 0 to 20% or absolute time of 0–0.4 s. The default setting is 5% or 0.15 s. A rapid raise time will achieve the set target (pressure or flow) almost instantaneously while a slower rise time will reach that target more gradually. Very fast rise time may be somewhat uncomfortable for a spontaneously breathing patient and result in turbulence whereas excessively slow rise time may cause "flow starvation" and increased work of breathing.

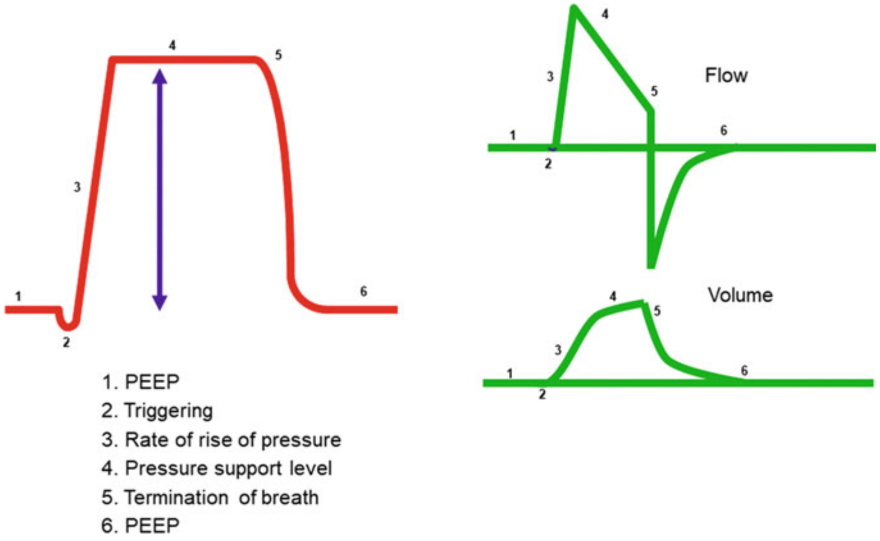
The initial ventilator rate selected depends on the age of the patient and the ventilatory requirements of the patient. The inspiratory time is selected to provide an inspiratory-to-expiratory time (I:E) ratio of at least 1:2 in most patients. Inspiratory time must be selected to allow sufficient time for all lung segments to be inflated. Adjustments to the inspiratory time may be necessary in certain disease conditions. Similarly, sufficient expiratory time must be provided for all lung segments to empty. If inspiration starts before the lung has completely emptied, this will result in air-trapping and inadvertent positive end-expiratory pressure (Auto-PEEP).

$FiO_2$ and PEEP are adjusted to maintain an adequate $PaO_2$. High concentrations of oxygen can produce lung injury and should be avoided. $FiO_2$ less than 0.5 is generally considered safe. In patients with parenchymal lung disease with significant intrapulmonary shunting, the major determinant of oxygenation is lung volume, which is improved with PEEP.

The optimum level PEEP is the level at which lung compliance is the best with improvement in oxygenation and ventilation without significant hemodynamic side effects.

### 6.4.5 *Pressure-Support Ventilation*

A Pressure-Supported breath is one which is patient-triggered, pressure-controlled, and flow-cycled (Fig. 6.7). It is an assisted, spontaneous breath in which the ventilator assists the patient's own spontaneous effort with a mechanical breath with a preset pressure limit. A pressure support breath is triggered either by a negative pressure below PEEP (pressure-triggering) or by a change in flow through the circuit (flow-triggering). The machine delivers high inspiratory flow with a short inspiratory rise time to achieve a peak airway pressure level (pressure support limit) that is selected by the operator and maintains the pressure limit until the inspiratory flow rate decreases to a threshold value (commonly 25 or 30% of the peak inspiratory flow) that can be set in many ventilators. In summary, PSV is patient triggered, pressure controlled, and flow cycled. PSV is entirely dependent on the



1. PEEP
2. Triggering
3. Rate of rise of pressure
4. Pressure support level
5. Termination of breath
6. PEEP

**Fig. 6.7** Components of a pressure-supported breath

patient's effort; if the patient becomes apneic, the ventilator will not provide any mechanical breath. Therefore, PSV is combined with either VC or PC during IMV.

Point 2 is the patient's effort indicated by a negative deflection. Upon sensing this this trigger (change in pressure or flow), the ventilator delivers flow to reach the desired pressure-support level (Point 4) as rapidly as possible. The rate of rise of this pressure can be controlled by adjusting the rise time (Point 3). Ventilator-delivered flow is then servo-adjusted to patient demand to maintain this pressure plateau. During inspiration, the inspiratory flow is maximum at the beginning of the breath and decreases as the lung is inflated and the distal pressures increase. Inspiration is terminated when the flow reaches a pre-set percentage of the peak inspiratory flow (usually 25–30%) (Point 5). Exhalation is passive and returns to the baseline PEEP (Point 6).

### *6.4.6 Volume Support Ventilation*

Volume support is a dual-control continuous spontaneous ventilatory mode (DC-CSV). Spontaneous breaths are supported by pressure support with a targeted volume that is set on the ventilator. The pressure support level required to maintain the set tidal volume is adjusted when the delivered tidal volume differs from the set tidal volume. This is a form of closed loop control using tidal volume as the feedback variable for continuously adjusting the pressure support level. This adjustment of the pressure support level is similar to the adjustment of PIP with

PRVC, which is a mandatory mode of ventilation. With Volume Support, it is also important to set minimum minute ventilation that the patient should receive. The minimum ventilation is set on the ventilator to be a backup PRVC mandatory mode with the set tidal volume and a set ventilator rate with its own inspiratory and expiratory times. As long as the minute ventilation, as determined by the preset target tidal volume and the patient's breathing rate, is higher than the preset minute ventilation, the patient will receive volume-support ventilation. When the minute ventilation is less than the pre-set value, initially the targeted tidal volume will be increased above the preset limit up to a limit. Once that limit is reached, the ventilator will switch to PRVC mode with a mandatory rate (preset) and the preset tidal volume.

## 6.5 Other Modes

### *6.5.1 Neurally Adjusted Ventilatory Assist (NAVA)*

Neurally Adjusted Ventilatory Assist (NAVA) is a Pressure-Supported Breath where the trigger for initiation of inspiration is the electromyographic activity of the diaphragm (Edi) monitored by a specifically designed catheter. The Edi signal is used to trigger the breath, to determine the level of pressure support, and to cycle from inspiration to exhalation. The pressure support level provided is proportional to the integral of the Edi. For NAVA to work the phrenic nerve needs to be intact and functioning and the primary inspiratory muscle should be the diaphragm. NAVA is designed to improve patient-ventilator synchrony. By allowing better patient-ventilator synchrony, it may be possible to reduce the amount of sedation that needs to be used in these children. The prerequisites and contraindications are presented in Table 6.3 and must be considered prior to initiating NAVA support.

**Table 6.3** NAVA prerequisites and contraindications

| Prerequisites/Indications | Contraindications |
|---|---|
| Spontaneously respiration | Insufficient/absent respiratory effort |
| Intact phrenic nerve | Bilateral diaphragm paralysis secondary to phrenic nerve damage |
| Anticipation of requiring ventilatory support >48 h | Any contraindications for having an orogastric or a nasogastric tube or need for MRI |
| Difficult to wean patients | Congenital myopathy |
| Patients that have ventilator asynchrony problems unless sedated and/or paralyzed | Esophageal atresia or diaphragmatic hernia |
| Past failed extubations | |
| Requiring BiPAP support | |

The Edi catheter consists of electrical connector, gastric suction port with evacuation holes at the distal end, and an array of 10 electrodes that capture the diaphragmatic signal (Fig. 6.8). The electrodes are arranged in pairs so that they can capture the electrical signals from both hemidiaphragms. The measured Edi signal also provides continuous monitoring of respiratory drive while determining the level of support indicated by the strength of the diaphragm's excitation.

The Edi catheter can be easily placed nasally or orally with the correct size determined by patient size. The ventilator has an Edi catheter position screen to assist with proper placement using QRS waveforms. Proper catheter placement is evaluated and confirmed by the following:

1. As the catheter moves from above the diaphragm to below, QRS waveforms will dampen
2. As the catheter is advanced, the QRS will turn "Blue/Purple", indicating that the electrical sensors are close to the diaphragm.
3. Optimal placement will be shown by the middle 2 waveforms being "Blue/Purple (Fig. 6.9c)".
4. The size of the QRS complexes is largest at the top (proximal) waveform (Fig. 6.9a) since that electrode is closest to the heart. The QRS complexes decrease in size as we go from the top waveform to the bottom (Fig. 6.9b).
5. Correct placement of the Edi catheter is additionally confirmed using a radiograph (Fig. 6.10).

Once in good position, the pressure support level that will result in a desired tidal volume or chest expansion needs to be set. It is set using the equation:

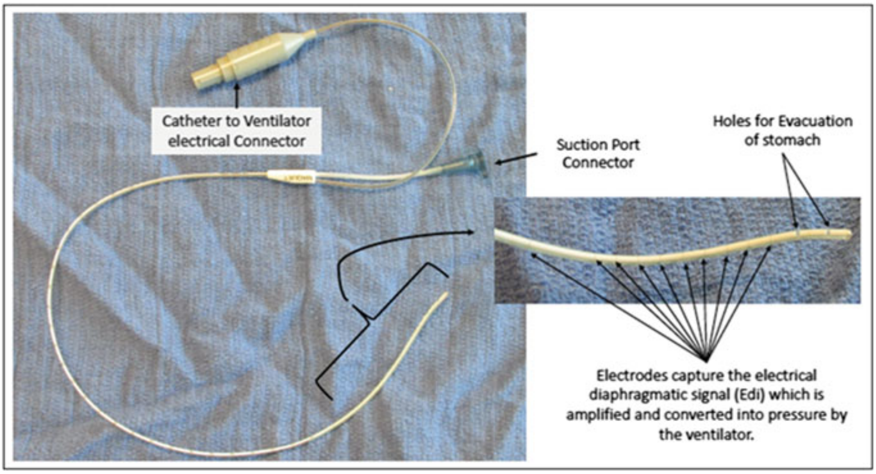


**Fig. 6.8** Anatomy of the Edi catheter consisting of a catheter connector, suction port, and electrode array

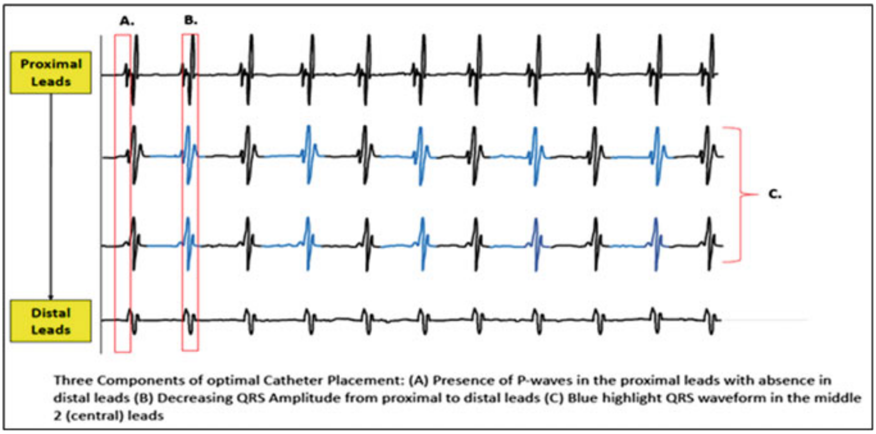


**Fig. 6.9** QRS waveforms demonstrating correct Edi Catheter placement. Size decrease from the Proximal leads to the distal leads with the smallest QRS in the last lead. Most distal lead has absent P-waves. Middle 2 leads have either Blue or purple waves indicating ideal catheter placement

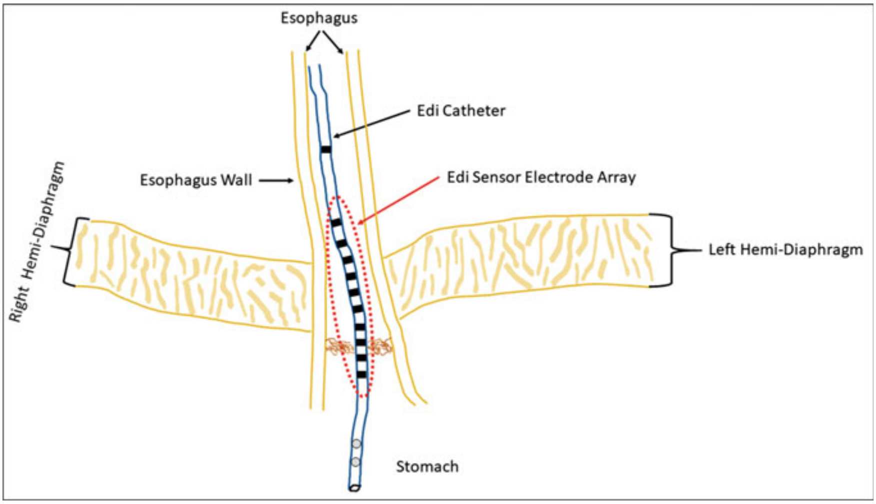


**Fig. 6.10** Illustration demonstrating correct Edi catheter placement via the distal esophagus. The Electrode array is positioned between the left and right hemi diaphragm with distal end located in the stomach

$$Pressure\,Support\,Level = NAVA\,levelxEdi(Peak - Min)$$

where Edi is the strength of the electrical signal in microvolts (μV) and NAVA is the pressure support per μV of Edi. The $Edi_{peak}$ represents the maximal electrical activity of the diaphragm for a particular breath (in μV). The $Edi_{min}$ represents the electrical activity of the diaphragm between inspiratory efforts (in μV). The Edi signal is monitored > 60 times per second the $\text{Edi}_{\text{peak}}$ and $\text{Edi}_{\text{min}}$ are measured at a set interval. The pressure support level provided by the ventilator is set by the NAVA level (set on the ventilator) multiplied by the difference in Edi signals between $\text{Edi}_{\text{peak}}$ and $\text{Edi}_{\text{min}}$ (ΔEdi) as shown in the equation above. For example, if the NAVA level is set to 0.5 μV/cm$H_2O$ and the ΔEdi for a specific breath is 20 μV, the maximum level of support for that breath is 10 cm$H_2O$. NAVA levels are usually set in the range of 0.5–4 cm$H_2O$/μV. Scalar representation of NAVA support is illustrated in Fig. 6.11. With increase in ΔEdi, additional pressure support is provided.

Normal $\text{Edi}_{\text{peak}}$ is 10–15 μV. The goal of NAVA is to provide enough support to normalize diaphragm work by adjusting the NAVA level. A higher NAVA level provides more support while decreasing the NAVA level reduces support. An illustrative example of this is a) if $\text{Edi}_{\text{peak}}$ is consistently above normal range, the patient is working too hard or the ventilator is not providing enough support. In such a case NAVA level should be increased until Edi Peak returns to the normal range. If $\text{Edi}_{\text{peak}}$ is consistently below the goal, the patient is receiving too much support, and the NAVA level should be decreased until the Edi Peak returns to the desired range.

The $\text{Edi}_{\text{min}}$ represents the resting tone of the diaphragm. Normal range for $\text{Edi}_{\text{min}}$ is approximately 2–4 μV. $\text{Edi}_{\text{min}}$ is useful in evaluating whether the PEEP level is

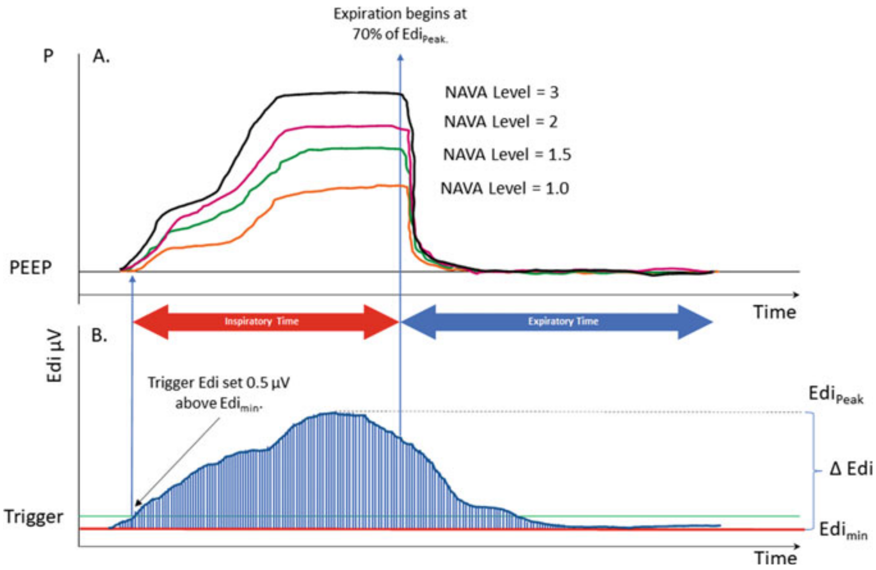


**Fig. 6.11** **a** Pressure over Time illustrating the Pressure wave form increasing with set NAVA Level. **b** Edi Measure over time—Blue line represents individual Edi Measurement associated with pressure support level provided. Green line indicates NAVA trigger level. Red Line is the measured Edi Min

**Table 6.4** Effects of PEEP

| *Beneficial effects* |
|---|
| 1. Recruitment of collapsed alveoli<br>a. Improve lung compliance<br>b. Decrease total dead space<br>c. Decrease venous admixture<br>d. Decrease pulmonary vascular resistance (by improving functional residual capacity) |
| 2. Prevention of airway collapse by decreasing the closing capacity |
| 3. Maintaining stability of alveolar segments<br>a. Shift alveolar fluid into the interstitium (pulmonary edema)<br>b. Prevent crumpling of alveolar walls |
| 4. Reduce work of breathing |
| 5. Stent the airways open (bronchomalacia) |
| 6. Decrease left ventricular afterload (heart failure) |
| *Adverse effects* |
| 1. Over-distention of alveoli<br>a. Increase total dead space<br>b. Decrease lung compliance<br>c. Increase pulmonary vascular resistance<br>d. Increase venous admixture (with heterogenous lung disease) |
| 2. Air-leaks<br>a. Alveolar rupture<br>b. Alveolar rupture |
| 3. Decrease venous return |

adequate. For example, if the Edi min is consistently above the desired range, the resting diaphragmatic tone is too high and may signify an attempt by the patient to maintain end-expiratory lung volume. Increasing PEEP, by increasing the end-expiratory lung volume, might decrease the need for the diaphragm to maintain a high tone. Conversely, if the $\text{Edi}_{\text{min}}$ is consistently below the desired range, the resting tone of the diaphragm is too low and weaning the PEEP should be considered (Table 6.4).

Both $\text{Edi}_{\text{peak}}$ and $\text{Edi}_{\text{min}}$ will vary with patient activity. Any clinical situation resulting in an increased work of breathing will increase the $\text{Edi}_{\text{peak}}$. The clinician should evaluate whether the episode is a result of discomfort (short-term) or clinical decompensation (long-term, with sustained change in vital signs). If the increase in $\text{Edi}_{\text{peak}}$ is sustained, the NAVA level should be increased for additional support. Finally, the patient should be challenged daily to facilitate liberation from the ventilator. Challenging the patient will help identify opportunities for ventilator weaning. Once the patient is stable on a NAVA level of 1, extubation may be considered. Non-invasive NAVA (NIV-NAVA) is a mode that can be used for post-extubation support. However, the greatest barrier to NIV-NAVA is finding an interface device that is well tolerated. NIV-NAVA works well with large leaks as the trigging mechanism is the EMG of the diaphragm.

### 6.5.2 Airway Pressure Release Ventilation

Airway pressure release ventilation (APRV) is a method of mechanical ventilation introduced by Stock and Downs. The original circuit included a CPAP device with unrestricted gas flow allowing spontaneous breathing, and a mechanism to release airway pressure periodically to some desired low pressure. A level of CPAP is provided to keep the lungs open while spontaneous breathing is responsible for maintaining adequate ventilation (Fig. 6.12).

In modern ventilators that provide APRV, there are 4 major variables that determine an APRV breath. These are $P_{high}$, $P_{low}$, $T_{high}$, and $T_{low}$. $P_{high}$ is defined as the pressure limit of the triggered mandatory breath and $T_{high}$ is the duration that $P_{high}$ is maintained. $P_{low}$ is the release pressure and $T_{low}$ is the time of the pressure release (Fig. 6.8). The top panel of Fig. 6.8 shows the ventilator settings with no spontaneous breathing. With no spontaneous breathing, this mode of ventilation is Pressure-Control CMV with inversed I:E ratio. The bottom panel of Fig. 6.8 shows the same ventilator settings but with spontaneous breathing occurring both during $P_{high}$ and during $P_{low}$. The mandatory breaths applied by APRV are time-triggered, pressure-targeted, time-cycled breaths. The advantage of APRV in parenchymal lung disease is lung recruitment and improvement in gas exchange with much lower peak alveolar pressures.

APRV is currently seldom used as a primary mode of ventilation when the patient is intubated and initially placed on mechanical ventilation. It is often used after a period of conventional mechanical ventilation. The initial level of $P_{high}$ can be one to provide a mean airway pressure 3–6 cm of $H_2O$ above the conventional ventilation. Subsequent adjustments can be made based on level of chest expansion (visually as well as on a chest radiograph) and by gas exchange parameters. There are two methods to set the $P_{low}$ value. One method is a fixed value similar to PEEP. The second method is to set the $P_{low}$ to be zero; this is usually combined with

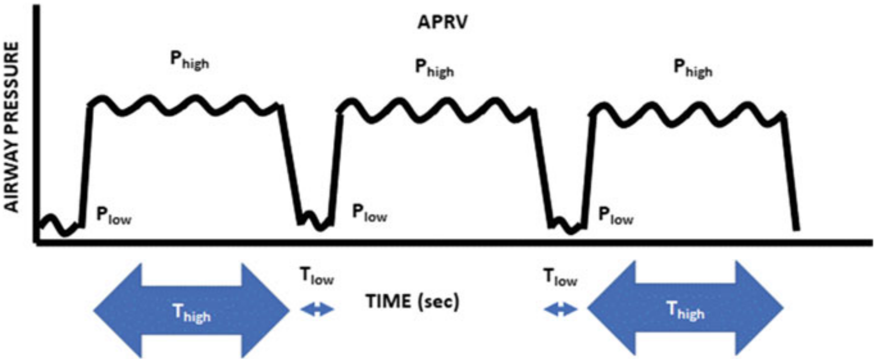


**Fig. 6.12** Airway Pressure Release Ventilation. $P_{high}$ is the pressure limit of the ventilator breath, $P_{low}$ is the release pressure, $T_{high}$ is the duration that $P_{high}$ is maintained and $T_{low}$ is the duration of $P_{low}$. Note that spontaneous breaths (waveform) occur both during $P_{high}$ and $P_{low}$

setting the $T_{low}$ to terminate when the expiratory flow rate decreases to a predetermined value, usually 30% of the peak expiratory flow. When $T_{low}$ terminates before the expiratory flow reaches zero flow, pressure in the alveoli is positive and prevents de-recruitment. This is similar to the auto-PEEP concept with lower airway obstruction. The degree of ventilatory assistance provided by APRV will be determined by the difference between $P_{high}$ and the pressure in the lungs at the end of $T_{low}$, frequency of pressure release, the duration of pressure release, the patient's lung-thorax compliance, and flow resistance in the patient's airways. With APRV, minute ventilation occurs with both spontaneous breaths and the periodic inflation and deflation that occur with the two levels of airway pressure. Gas exchange can occur throughout the respiratory cycle. Inspiratory demand flow during spontaneous breathing.

Only 2 parameters are usually used to wean patients from APRV. One is $P_{high}$ and the other is the ratio between $T_{high}$ and $T_{low}$. Decreasing $P_{high}$ will decrease the tidal volume and mean airway pressure and is akin to weaning CPAP. Increasing the ratio between $T_{high}$ and $T_{low}$ decreases the frequency of pressure release and the minute ventilation provided by the ventilator. Patients can be either switched to conventional ventilation or by simply lowering $P_{high}$ to CPAP breathing.

## 6.6 High Frequency Ventilation

### 6.6.1 *Definitions and Description*

High-frequency ventilation (HFV) refers to diverse modes of ventilation characterized in general by supra-physiologic ventilatory frequencies (>60/min) and low tidal volumes. Commonly used high frequency modes described below are high frequency oscillatory ventilation (HFOV) and high frequency jet ventilation (HFJV) (Table 6.5).

The exact mechanism of gas transport in HFV is not fully elucidated. It is possible that each mode of ventilation may have differing mechanisms of gas flow from the proximal airway to the alveoli. The mechanisms include increased gas mixing with agitation of the airway gas, accelerated axial dispersion, increased collateral flow through pores of Kohn, intersegmental gas mixing or Pendelluft phenomenon, Taylor dispersion, asymmetrical gas flow profiles, and gas mixing within the airway due to the nonlinear pressure-diameter relationship of the bronchi.

**Table 6.5** Commonly used types of high frequency ventilation

| | HFJV | HFO |
|---|---|---|
| Usual rate | 240–660 | 300–900 |
| Vt/kg | 2–4 | 1–3 |
| Exhalation | Passive | Active |
| Entrainment | Yes | Yes |

### 6.6.2 High Frequency Oscillatory Ventilation

HFOV refers to ventilation at frequencies of 170–900 (2.8–15 Hz) cycles per minute, with an alternating positive and negative pressure in the airway. This oscillatory pressure may be produced by a piston pump or a diaphragm with tidal volumes of 1–3 ml/kg. HFOV systems widely used are the Viasys Critical Care 3100A and 3100B ventilators. The main difference between these two ventilators is the age range each of them supports. The 3100A is designed to support HFOV in neonates and small children. The 3100B is designed to support older children and adults weighing more than 35 kg. Input power for both the ventilators requires two pneumatic gas sources and one electrical source. The first pneumatic connection through a blender determines the $FiO_2$ delivered to the patients. The second pneumatic connection is for cooling the oscillator. The drive mechanism is a square-wave driver which has an electric linear motor and a piston. The stroke of the piston (both positive and negative) determines the amplitude. The position of the piston determines the mean airway pressure of the circuit.

The main controls in HFOV are mean airway pressure, oscillatory pressure amplitude/power, bias flow, frequency, and inspiratory time. With piston-driven oscillators, the piston position should be centered which can be controlled using a knob. Mean airway pressure determines the mean lung volume of the lung. Oscillatory amplitude is the total change in pressure around the mean airway pressure produced by forward and backward displacement of the piston. The pressures developed in the patients' airways are considerably dampened due to the impedance of the endotracheal tube. The pressure profile is further dampened progressively in the distal airways due to the impedance of the proximal airways. If the oscillatory frequency approaches the natural resonant frequency of the lung and airways, there may be amplification of the pressure waves developed in the airways. The oscillatory amplitude determines the volume displacement with each stroke of the piston. For a given amplitude, a lower frequency will result in less attenuation of pressures along the airways and improve gas exchange. Inspiratory time is generally controlled at 33% of the total cycle time. The absolute inspiratory time is thus inversely proportional to the frequency. Bias flow is a continuous flow of fresh humidified gas and allows replenishing oxygen and removing carbon dioxide from the circuit. Determinants of oxygenation during HFOV are mean airway pressure and $FiO_2$. Minute ventilation during HFOV is directly proportional to the frequency and the square of the tidal volume. Tidal volume is determined by the amplitude and the duration of each stroke. With increased frequency, the time for each stroke is reduced, decreasing the tidal volume. When the ventilatory frequency is decreased, the time for each stroke is increased thus increasing the tidal volume. The primary determinant of ventilation is oscillatory amplitude which is adjusted by the power setting. Decreasing the frequency to reduce pressure attenuation will increase the tidal volume per breath and improve ventilation. But such a maneuver may increase the pressure changes in the alveoli which may not be desirable.

Optimization of HFOV

HFOV may be considered when the mean airway pressure during conventional mechanical ventilation is around 20 cm $H_2O$. The most common strategy when HFOV is initiated is to set the mean airway pressure to be about 2–5 cm higher than that with conventional ventilation. Amplitude is set by adjusting the power control while observing for adequacy of chest wall vibrations. There are many ways to recruit the lung and optimize HFOV settings. The most common method of alveolar recruitment is incremental increase in mean airway pressure followed by arterial blood gases to determine whether further increase in mean airway pressure is warranted. An optimal recruitment would be manifested by an increase in lung volume on a chest x-ray, and improved oxygenation and ventilation. Adequacy of lung recruitment is usually verified by ensuring that both hemidiaphragms are displaced to the level of the 9th posterior rib on a chest radiograph. Once sufficient recruitment has been achieved, $FiO_2$ should be decreased. The goal for oxygenation is to employ a mean airway pressure that will allow reduction of $FiO_2$ to at least 0.6 while maintaining an arterial oxygen saturation of at least 90%. This may require titration of the mean airway pressure from the initial setting. Once an appropriate degree of lung inflation and patency of the endotracheal tube are verified, ventilation needs to be addressed. Arterial $PaCO_2$ can be maintained at the desired level by changing the amplitude or frequency. Ventilation is increased by an increase in amplitude and a decrease in frequency. It is also important to deflate the cuff of the endotracheal tube, if a cuffed tube is used. Increasing the inspiratory time is a less effective strategy to improve carbon dioxide elimination.

Weaning from HFOV to Conventional Ventilation

Once the mean airway pressure is below 20 cm $H_2O$, the patient may be placed on conventional mechanical ventilation. The rule of thumb is to employ the same mean airway pressure (MAP) as HFOV and make adjustments based on the gas exchange. Most modern ventilators display the approximate MAP values. $FiO_2$ would be the same as in HFOV and the ventilator rate would be one appropriate for age and adjusted based on gas exchange. An $ETCO_2$ monitor would be very helpful in adjusting the rate when the patient is switched from HFOV to conventional ventilation.

### *6.6.3 High Frequency Jet Ventilation*

High frequency jet ventilation (HFJV) refers to delivery of inspiratory gases through a jet injector at a high velocity into the trachea at a rate of 240–660 cycles per minute. Along with these tiny high velocity jets, additional air from the bias flow is entrained to generate tidal volumes of 2–4 mL/kg. The main indications for HFJV are (1) as a means to support gas exchange in patients with severe parenchymal lung disease, and (2) management of bronchopleural fistula.

Special endotracheal tubes were required for jet ventilation necessitating reintubation which may be hazardous in severe respiratory failure. Adapters with a side port are now available to fit an already present ET tube to deliver jet ventilation without the need for reintubation. These adapters also provide a port to monitor proximal pressures delivered by HFJV. As in HFOV, these pressures are attenuated lower down in the airways and alveoli. The mechanisms involved in gas transport during HFJV are complex and include Taylor dispersion, accelerated axial dispersion, increased collateral flow through pores of Kohn, intersegmental gas mixing or Pendelluft phenomenon, asymmetrical gas flow profiles, and gas mixing within the airway due to the nonlinear pressure-diameter relationship of the bronchi. A conventional ventilator is used in tandem to provide PEEP and sigh breaths. Administration of sigh breaths is important to recruit the lungs and maintain lung volume. Sigh breaths should be at such inflation pressure (lower than the HFJV PIP) so as to not hinder the delivery of the jet pulses. Exhalation on HFJV is passive from elastic recoil.

There are 3 parameters that can be set: PIP, Jet valve time and Rate. The desired level set for PIP is accomplished by automatic adjustment of the internal machine servo pressure. If PIP falls below the desired level (e.g., improved compliance/resistance), the machine raises the servo pressure to raise the PIP. Conversely, the servo pressure is decreased if the PIP rises (worsening compliance/resistance) to bring the PIP down to the desired level. Changes in servo pressure level for a desired PIP are thus important indicators of the respiratory compliance/resistance. The jet valve time is set at 0.02 s. This refers to the time the jet valve is opened to generate pulses of jet that are delivered to the patient. It is nearly equivalent to $T_i$. Increasing the jet valve time improves tidal volume but carries the risk of decreasing the exhalation time resulting in air trapping. The rate is generally set at 420/min. Decreasing the rate results in an increase in the exhalation time allowing greater alveolar emptying but decreasing minute ventilation. Increasing the rate will decrease the exhalation time and may result in air trapping.

The parameters that are monitored during HFJV include PIP, $\Delta P$, PEEP, MAP, and servo pressure. PEEP is adjusted through the conventional ventilator. $\Delta P$ refers to the difference between PIP and PEEP and it is responsible for generating $V_t$. MAP can be adjusted by adjusting the PEEP. The servo pressure, measured in PSI, is an indicator of the internal system pressure that is necessary to generate the desired PIP. Larger patients and those with compliant (and low resistant) lungs will need a higher servo pressure.

### 6.6.4 Clinical Applications

Both modes of high frequency ventilation have been used to treat severe respiratory failure due to parenchymal lung disease where the major pathophysiology includes atelectasis, intrapulmonary shunting, ventilation-perfusion mismatching and decreased compliance.

All three modes of high frequency ventilation have been reported to improve oxygenation with adequate recruitment of the lung. HFJV is particularly useful with air leaks, especially bronchopleural fistula that precludes use of high airway pressures. HFJV has been successful in supporting gas exchange in patients with bronchopleural fistula while keeping the fistula flow to be low.

HFJV is especially suited for patients who have a significant component of intrathoracic airway obstruction in addition to their alveolar-interstitial pathology. Figure 6.13 shows comparison of HFOV and HFJV in a patient with airway obstruction. The top panel shows the lung and airway pressures during HFOV. A large proportion of the negative pressure generated during active exhalation is transmitted to the site of obstruction while the pleural and alveolar pressure remains positive. This creates an excessively high transmural pressure favoring dynamic airway collapse and airway obstruction exacerbating the already existing hyperinflation and air trapping. The bottom panel shows the same patient with HFJV. Since exhalation is passive, intraluminal pressure does not fall below PEEP. The

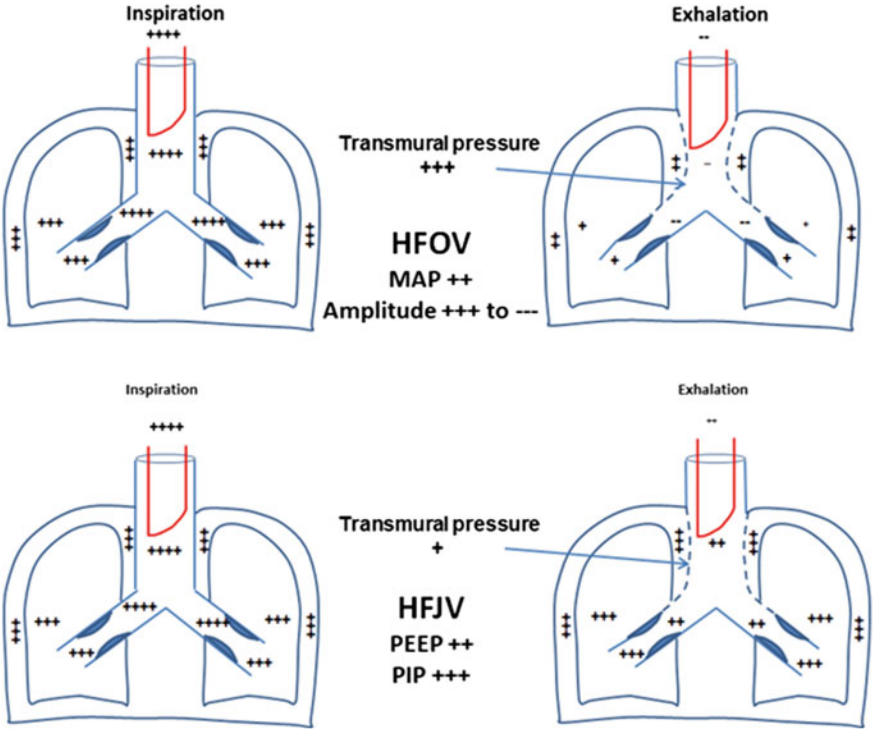


**Fig. 6.13** Transmural pressures in the airways in a patient with lower airway obstruction with HFOV (top panel) and HFJV (bottom panel). During exhalation, the proximal airway pressure during HFOV is negative compared to intrathoracic pressures beyond the obstruction causing dynamic airway collapse. In HFJV, the intraluminal pressure doesn't fall below the PEEP. The transmural pressure during exhalation resulting in airway collapse is not as high in HFJV as in HFOV

transmural pressure favoring airway collapse is not as strikingly elevated as in HFOV. HFJV may therefore be a preferred option compared to HFOV in management of patients with obstructive airway disease such as bronchiolitis.

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