Components of Conventional Mechanical Ventilation

All mechanical ventilators are basically force generators capable of producing a pressure gradient between the airway opening and the alveoli, allowing gas to flow down that gradient into the lungs, while at the same time improving gas distribution in relation to pulmonary blood flow.[26] Infant ventilators have other capabilities, of course, such as delivering adjustable concentrations of enriched oxygen and a constant, minimal amount of distending airway pressure, or positive end-expiratory pressure (PEEP). But it is the mechanical ventilator's generation of variously configured waveforms of pressure, or applied force, over time and its ability to thereby deliver adjustable volumes of gas per unit time that make mechanical ventilators unique when contrasted with CPAP or extracorporeal membrane oxygenation (see Chapter 13). This unique capability of force generation is essential, even life saving, in providing acute respiratory support to neonates suffering from any form of respiratory distress that compromises their ability to ventilate the lungs.

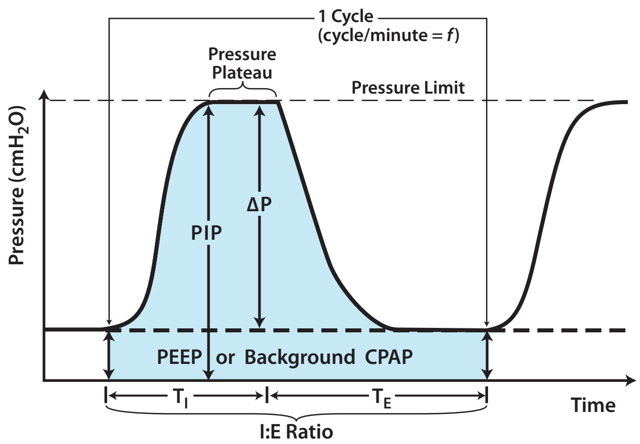
IMV, as the name implies, provides intermittent mandatory positive pressure breaths superimposed on a continuous flow of gas through the ventilator circuit. Prior to development of the Baby Bird ventilator in the early 1970s (conceived by Robert Kirby, an anesthesiologist, with the clinical expertise of Robert deLemos, a neonatologist, but assembled into a workable machine by Jimmy Schultz, a respiratory therapist using components from a Bird Mark V ventilator), any infant on intermittent positive-pressure ventilation (IPPV) who attempted to breathe out of phase with the inspiratory flow cycle of the machine ended up rebreathing exhaled stale gas.[14] With IMV, the constant flow through the circuit provides fresh gas at all times for the infant to breathe; it also provides background CPAP using a flow or threshold resistor, impeding circuit outflow. When the expiratory limb of the circuit is closed completely and then reopened in a repetitive, precisely timed fashion, a predetermined amount of mechanical ventilation is provided to combine with the baby's own spontaneous breathing. Another advantage of IMV comes with weaning, when the number of mandatory breaths provided by the machine can be gradually decreased while allowing the baby's spontaneous breathing to increase.

Positive Pressure Ventilator Classifications

Positive pressure ventilators are most commonly classified according to their method of terminating inspiration and thus are divided into pressure-cycled, volume-cycled, and time-cycled machines.[27–30] Newer ventilators have been introduced that can function as either volume-controlled or pressure-controlled, time-cycled ventilators (Babylog [Dräger Medical Inc., Lübeck, Germany], VIP Bird [Cardinal Health, Dublin, Ohio]). Microprocessors have also been developed that allow ongoing modifications in pressure, flow, and volume throughout the respiratory cycle, making modes such as proportional assist ventilation and respiratory muscle loading possible.[31]

- **Pressure-cycled ventilators** deliver a volume of gas until a preset pressure is reached within the ventilator circuit or patient interface (also lending this type

FIGURE 7-1
Typical pressure waveform generated by a conventional ventilator in IMV mode during a complete respiratory cycle or mandatory breath, superimposed on PEEP, or background CPAP.



Key: CPAP = continuous positive airway pressure; PEEP = postiive end-expiratory pressure; PIP = peak inspiratory pressure; ΔP = airway pressure gradient; T_I = inspiratory time; T_E = expiratory time
Mean airway pressure is the solid blue area under the curve.

of machine the name *pressure-preset ventilator*). The delivered volume from the machine is determined by the rate of internal gas flow (a control setting) and the duration of inspiration. Although the peak pressure delivered to the infant remains constant, the actual volume of gas delivered to the alveoli is variable, depending on: (1) the compliance of the ventilator circuit, including the humidifier; (2) the compliance of the infant's lungs; (3) the resistance to gas flow through the circuit, endotracheal (ET) tube, and the infant's airways; and (4) the presence or absence of air leakage around the ET tube.[10] Thus, the volume of gas delivered to the patient on inspiration may vary tremendously from breath to breath. In cases of sudden decreases in lung compliance (e.g., development of a pneumothorax) or increases in upper airway resistance (e.g., mucus plugging), preset cycling pressure will be reached prematurely, shutting off inspiration and shortening "time-of-flow" to the point of causing ineffective alveolar ventilation (even though the infant is receiving "controlled" mechanical ventilation).

- **Volume-cycled ventilators** deliver a constant tidal volume of gas from the machine into the patient circuit during the inspiratory phase, regardless of the pressure generated, unless pressure limits are set. Inspiration is terminated when a preset volume has been delivered, lending this type of machine the name *volume-preset ventilator*. The relative distribution of that volume into the circuit, humidification apparatus, and patient tubing versus the volume actually delivered to the patient's alveoli depends on the relative compliance and resistance of the circuit versus that of the infant's upper airway and lungs. In cases of nonhomogeneous lung disease, portions of the lung that are obstructed or atelectatic require higher opening pressure. With volume preset ventilators, most of the volume reaching the lung is preferentially delivered to areas of the lung that are open, resulting in an increased potential for overdistention. Furthermore, because the preset volume is delivered into the patient circuit irrespective of the pressure it takes to deliver it, the first place a sizable portion of the inspiratory gas flow may escape is out of a leak around the ET tube (i.e., taking the path of least resistance).
- **Time-cycled ventilators** utilize electronic timers to terminate the machine's inspiratory phase. Time-cycled ventilators may be pressure limited; but unlike with pressure-cycled machines, gas flow to the patient does not cease when the preset pressure is reached. Rather, flow tapers off to hold the preset peak pressure steady (forming a pressure plateau, as shown in Figure 7-1, at the preset peak pressure and pressure limit). Any excess flow, which otherwise would drive pressure over the preset limit, is simply vented from the circuit. The volume actually delivered to the patient by time-cycled machines depends again on compliance and resistance factors, as well as on the chosen inspiratory time, gas flow rate, and preset pressure limit.[30] Actual volume delivered to the infant's lungs using time-cycled ventilators has been shown to be more consistant than that provided by pressure-cycled ventilators, and the performance of time-cycled machines is comparable to that of volume-cycled machines in this regard.[28]

Knowing how the various types of infant ventilators apply pressure and deliver volume, and especially understanding how the machine(s) you employ perform these tasks, is the first step toward applying safe and effective mechanical ventilation in IMV mode (or any other ventilation mode) to newborn infants. The second step is gaining a working knowledge of the various components of the positive pressure force an infant ventilator delivers and learning how to adjust these ventilator control settings (variables) to allow additional gas flow per unit time in support of the infant's own spontaneous breathing and achievement of adequate gas exchange.

Managing Mechanical Ventilation

A graph displaying how the pressure waveform generated during a mandatory breath is altered when ventilator settings are adjusted in one direction or the other provides a useful visual reference to help clinicians keep all the components and variables straight. Figure 7-1 depicts a typical pressure waveform generated by a conventional ventilator in IMV mode during a complete respiratory cycle or mandatory breath, superimposed on background CPAP, or PEEP. The discussion that follows individually addresses the pressure components (PIP and PEEP), time intervals (inspiratory and expiratory time [T_I and T_E]), timing derivative (inspiratory:expiratory [I:E] ratio), airway pressure gradient (ΔP), and pressure composite (mean airway pressure [Paw]), all of which are graphically illustrated in Figure 7-1.

Peak Inspiratory Pressure

Peak inspiratory pressure PIP is the maximum level of pressure generated during the inspiratory phase of the ventilator cycle, signified graphically as the apex of the pressure waveform shown in Figure 7-1. The higher the PIP setting on a time-cycled, pressure-limited ventilator, the more gas delivered to the patient (all other determining factors being equal). The difference between PIP and PEEP, known as the airway pressure gradient (ΔP), is the primary determinant of the tidal volume delivered by a pressure-limited ventilator.[31]

To select an appropriate PIP, the clinician must consider the infant's gestational age, weight, lung compliance and resistance, and the type and severity of the disease process. The safest PIP setting is the lowest level needed to achieve adequate ventilation. When treating respiratory failure caused by RDS, initial PIP settings may range between 18 and 24 cmH_2O. Opening or reopening areas of collapsed lung requires PIP levels that exceed the lung unit's critical opening pressure. However, when PIP levels approach 25 cmH_2O on conventional or rapid-rate IMV, it is time to consider switching to a high-frequency mode of ventilation (see Chapter 12).

Positive End-Expiratory Pressure or Background CPAP

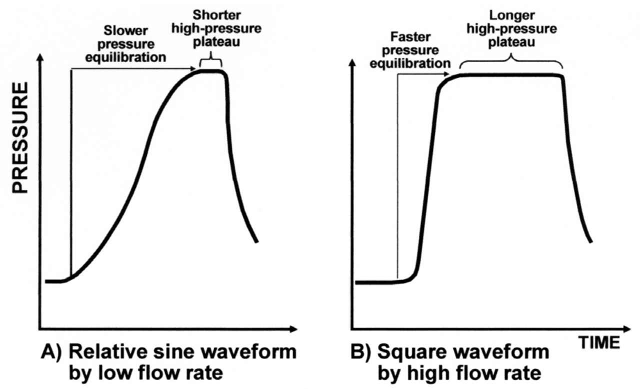
PEEP is the residual positive pressure remaining in the patient circuit at the end of expiration, even when there is no flow in the circuit between positive pressure breaths during intermittent IPPV. When dealing with IMV, however, PEEP is better conceived as *background CPAP*.[32] That is because the same continuous flow of fresh gas through the circuit that distinguishes IMV from IPPV also produces the back pressure against which the baby exhales, just as when an infant is attached to any CPAP apparatus and is breathing spontaneously. The pneumatic-splinting effect of background CPAP (or PEEP) during IMV prevents collapse of alveoli at end expiration (discussed later in this chapter in the section on the Laplace relationship).

As is the case for PIP, the selection of an appropriate PEEP depends on the size of the patient and the underlying disease process. Although PEEP contributes greatly to the maintenance of normal lung volume, it is probably not reasonable to assume it contributes much to lung volume recruitment.[33] The levels of background CPAP commonly used during IMV (i.e., 4–6 cmH_2O) are well below the critical opening pressure of most atelectatic alveoli, although partially collapsed units may respond to noninvasive CPAP if it is applied relatively early in the course of RDS.

T_I, T_E, and I:E Ratio

T_I (or I-time), T_E (or E-time), and I:E ratio are fairly self-explanatory control variables. They do require attention, however, because they may be set differently on different infant ventilators and because either T_I or I:E ratio must be repeatedly adjusted as the ventilator rate is changed. When using a time-cycled machine, the T_I is selected along with the rate, and the combination of these two variables automatically determines the T_E and the I:E ratio. The usual setting range for T_I is 0.3–0.5 second, for T_E, 0.6–1.2 seconds, and for I:E ratio, 1:2–1:3. Both slow-rate, long T_I (or reverse I:E ratio) IMV and rapid-rate, short T_I IMV (sometimes called high-frequency mechanical ventilation or high-frequency positive pressure ventilation) have been used as alternative modes for treatment of RDS because both allow PIP (thought to be the major culprit in producing barotrauma and subsequent bronchopulmonary dysplasia) to be reduced.[17,34,35] However, if not administered with extreme precision and timing, especially in the recovery phase of RDS, both modalities can result in problems with insufficient time for exhalation. Without enough time to exhale, air trapping,

FIGURE 7-2
Effects of low versus high ventilator flow rates on pressure waveforms.



Adapted from: Spitzer AR, and Clark RH. 2011. Positive-pressure ventilation in the treatment of neonatal lung disease. In *Assisted Ventilation of the Neonate,* 5th ed., Goldsmith JP, and Karotkin EH, eds. Philadelphia: Saunders, 167. Reprinted by permission.

inadvertent PEEP, lung overexpansion, volutrauma, air leak, diminished pulmonary capillary blood flow with increased intrapulmonary shunting, reduced venous return and cardiac output, and increased risk for intraventricular hemorrhage can occur.[36] This unfortunate sequence is discussed further later in this chapter under the headings **Mean Airway Pressure, Controlling Blood Gases during IMV, Compliance,** and **Time Constants.**

Airway Pressure Gradient

The airway pressure gradient is the difference between PIP and PEEP (i.e., PIP – PEEP = ΔP) and represents the pressure gradient between the machine and the patient's lower airway or the gradient down which all air flows to the patient's lungs during inspiration. If there is no difference in pressure between the outside air (i.e., the patient circuit if the infant is on a ventilator) and the alveoli, the result is no airflow. ΔP represents the main motor for bulk flow ventilation of the type generated by conventional mechanical ventilation. ΔP exactly parallels pulse pressure in blood pressure measurements: Pulse pressure is the difference between systolic and diastolic blood pressures and largely determines stroke volume. Just as stroke volume multiplied by heart rate yields cardiac output, so ΔP multiplied by ventilator rate approximates alveolar ventilation. That is because the inspiratory volume delivered by the machine roughly equals tidal volume (V_T), and V_T minus dead-space volume multiplied by breathing rate determines minute volume, or alveolar ventilation. The contribution of ΔP to alveolar ventilation becomes even more important during high-frequency ventilation, where V_T is exponentially related to minute ventilation or CO_2 excretion per unit time (see Chapter 12).

Mean Airway Pressure

Mean airway pressure (or Paw) defines the mean pressure delivered to the proximal airways from the beginning of one inspiration to the beginning of the next, averaged over a series of respiratory cycles. Paw is determined by calculating the area beneath the pressure curves of both inspiration and expiration and then dividing that area by its appropriate time interval.[37] Paw is represented diagrammatically by the total area beneath the pressure waveform (see Figure 7-1) and is monitored electronically by integration of repeated airway pressure measurements made multiple times per second throughout a number of cycles. Thus, Paw is the composite measure of all pressures transmitted to the airways by a mechanical ventilator.[38] Paw is not a variable that can be set on a conventional ventilator. Rather, it is determined by the PIP, PEEP, I:E ratio, and flow.

The ideal Paw can be defined, but only for the individual patient, given the fact that results are largely dependent on the type and severity of the disease process being treated.[37] The less compliant or stiffer the lungs, the higher the level of Paw the patient can tolerate without adverse cardiovascular effects. This is true because lungs with low compliance allow less transmission of airway pressure to the capillary bed on the outside walls of the alveoli and to the interstitial, interpleural, or intrathoracic spaces. Finding the optimal Paw is similar to finding optimal PEEP when treating adults with IPPV.[39] In both cases, the clinician seeks out the maximum level of PEEP or Paw that yields improving values for lung mechanics (e.g., lung compliance) and gas exchange (e.g., PaO_2, $PaCO_2$) without causing significant deterioration in measured cardiovascular parameters (such as central venous pressure and/or cardiac output). Paw is the major determinant of oxygenation when applying all modalities of mechanical ventilation (including IMV) to most forms of neonatal lung disease. Paw levels above 11–12 cmH_2O while on IMV are generally considered an indication to switch to a high-frequency mode of ventilation where higher levels of Paw can be more safely applied.

Flow Rate

In most ventilators capable of delivering IMV, flow rate is the rate of continuous gas flow through the patient circuit and also what determines inspiratory flow rate during mandatory breaths. Flow rate determines the ability of the ventilator to deliver the set PIP, I:E ratio, and respiratory rate.[31] Flow rates may be categorized as either low flow (0.5–3 liters/minute) or high flow (4–10 liters/minute or more).[29] When IMV is being applied to infants, the circuit flow rate is usually set somewhere between 4 and 10 liters/minute.[29] The minimal acceptable flow rate is considered to be at least two times an infant's minute ventilation, or two times 210 mL/kg/minute.[40] With a low flow rate (Figure 7-2A), it takes longer to reach pressure equilibration at the set PIP. If the flow rate is too low relative to minute ventilation, dead space ventilation and CO_2 levels increase because effective airway opening pressure is not being adequately maintained.[29] At the other extreme, flow rates as high as 10 to 12 liters/minute find use in delivering high levels of PIP, in producing a waveform resembling a square wave (Figure 7-2B), when reversing the I:E ratio, or when delivering high-pressure, rapid-rate IMV. In these cases, the high inspiratory flow rate allows for quick delivery of the volume needed to reach the preset PIP (i.e., quick equilibration of PIP between the circuit and the baby's alveoli). Be aware, however, that forcing high-pressure gas into noncompliant lungs is a setup for barotrauma, overdistention of the more compliant terminal gas-exchange units (i.e., the respiratory bronchioles and alveolar ducts), and volutrauma in premature babies with RDS. Slower flow rates generate less turbulence and a waveform that more resembles a sine wave (Figure 7-2A), thereby better mimicking the normal infant respiratory pattern and providing a smoother, gentler increase in pressure during inspiration.[28]

Ventilator Rate or Frequency

Ventilator rate, or frequency, refers to the number of breaths delivered per minute by the ventilator during IMV (the baby's spontaneous breaths are not included). Along with inspiratory volume (or V_T if one subtracts anatomic dead space), ventilator rate is a primary determinant of alveolar ventilation during conventional mechanical ventilation. IMV can be classified as slow rate (<40 breaths per minute), medium rate (40–60 breaths per minute), and rapid rate (>60 breaths per minute).[29] As a rapid-rate IMV range is reached or exceeded, during use of a conventional ventilator, the following changes can be anticipated in the pressures generated, volumes delivered, and other ventilator-control variables:[41,42]

1. Paw increases.
2. If the ventilator rate is increased markedly while the I:E ratio is kept constant, the preset PIP may not be reached because the marked increase in ventilator rate may shorten T_I to the point at which it is insufficient to permit achieving the preset PIP level.
3. If T_I is left unchanged, the I:E ratio will be reversed because T_E will become progressively shorter. Eventually, this will prevent complete emptying of the last breath delivered before the next mandatory breath comes in.
4. Once the rate exceeds 25–30 breaths per minute when using most conventional ventilators, inspiratory volume delivered to the circuit (and therefore V_T) will progressively decrease.
5. Minute volume (and therefore alveolar ventilation) will continue to increase, but only up to a rate of about 75 breaths per minute. At higher rates, both minute volume delivered and the patient's alveolar ventilation actually fall off. Thus, rate increases beyond 75 breaths per minute are counterproductive when using conventional ventilators at unconventional rates.