

Chapter 2

Waveforms

2.1 Introduction

Waveforms depict the relationship between respiratory parameters and time on a breath-to-breath basis. The three most commonly used signals are pressure (cm H₂O), volume (mL), and flow (mL/s), and these three signals describe the respiratory cycle. Most graphic monitors are now capable of displaying all three waveforms simultaneously; some display only one or two.

When displayed in aggregate, the cyclic phases of respiration can be appreciated. Each waveform has distinct points of initiation of inspiration, peak inspiration, end of inspiration/initiation of expiration, and end of expiration. These are depicted schematically in Fig. 2.1a and actually in Fig. 2.1b.



2.2 Volume Waveform

The volume waveform displays the changes in delivered volume over time. It is determined by integrating the inspiratory and expiratory flow signals. A typical volume waveform is shown in Fig. 2.2. As seen in Fig. 2.2a, the waveform has several reference points. Point A depicts the initiation of inspiration. Point B represents the maximum inspired gas volume. Point C represents the end of inspiration and the start of expiration. Point D depicts end-expiration volume and should be very close to the zero volume line; expired volume is usually a bit less than inspired volume because of air leak around the uncuffed neonatal endotracheal tube. An actual volume waveform is shown in Fig. 2.2b.

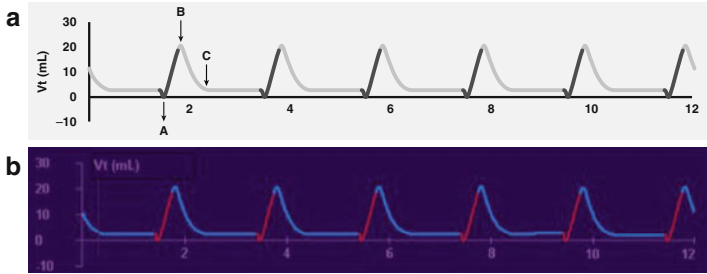


FIGURE 2.2 Volume waveform (**a**, schematic; **b**, actual). Point *A* is the start of inspiration. Point *B* represents the maximum inspired gas volume. Point *C* is the end inspiratory volume

Evaluation of the tidal volume (V_t) waveform may be useful in determining the relative contributions of mechanical and spontaneous breaths during intermittent mandatory or synchronized intermittent mandatory ventilation (SIMV). Figure 2.3 demonstrates this. Note that the larger volume breaths are SIMV, and the smaller breaths, supported only by positive end-expiratory pressure (PEEP), are spontaneous.



FIGURE 2.3 Waveforms obtained during SIMV/pressure support ventilation. Note the relative contributions during SIMV (waveforms connoted by A) and partial pressure support (waveforms connoted by B) in schematic (a) and actual (b) waveforms. In this example, since pressure support is set at 0, we see no pressure deflection (since no positive pressure is being added to support spontaneous breaths) but we do see the flow and volume changes initiated by the patient

2.3 Pressure Waveform

The pressure waveform represents the airway pressure throughout the respiratory cycle (Fig. 2.4). Virtually every newborn requiring conventional mechanical ventilation receives some degree of PEEP. Thus, the waveform at end inspiration or the initiation of inspiration is above the baseline (zero) value. Pressure rises during inspiration, reaching its maximum value, or peak inspiratory pressure (PIP), then declines during expiration to the PEEP level. The area under a single cycle represents the mean airway pressure (mean Paw). The difference between the PIP and the PEEP is referred to as the amplitude or delta P. These are shown schematically (Fig. 2.4a) and actually (Fig. 2.4b).

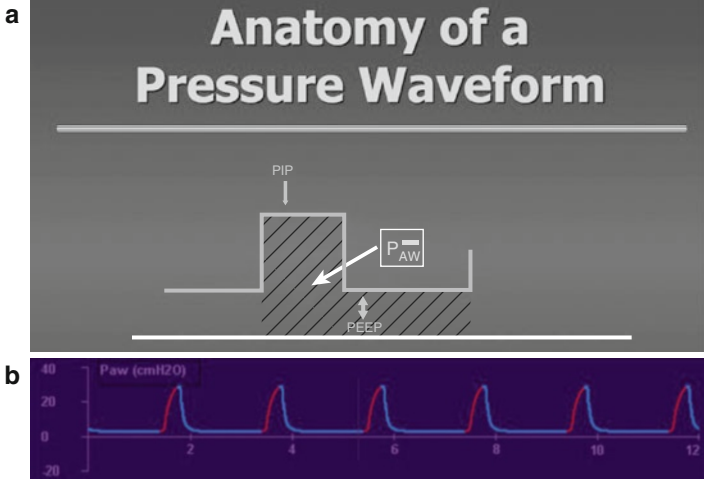


FIGURE 2.4 Schematic representation of the anatomy of a pressure waveform (**a**). The amplitude or ΔP is the difference between the peak inspiratory pressure (PIP) and the baseline pressure, referred to as the positive end-expiratory pressure (PEEP). The mean airway pressure is represented by the area under the curve (*shaded area*) for a single waveform. An actual pressure waveform is depicted in (**b**)

2.3.1 *Plateau Pressure*

If an inspiratory hold is used to prolong the inspiratory time (preventing the exhalation valve from opening), a plateau pressure may develop. This is shown in Fig. 2.5. After reaching the PIP, rather than linearly decreasing to the baseline, it remains constant, creating the plateau, until the hold ends and the exhalation valve opens.

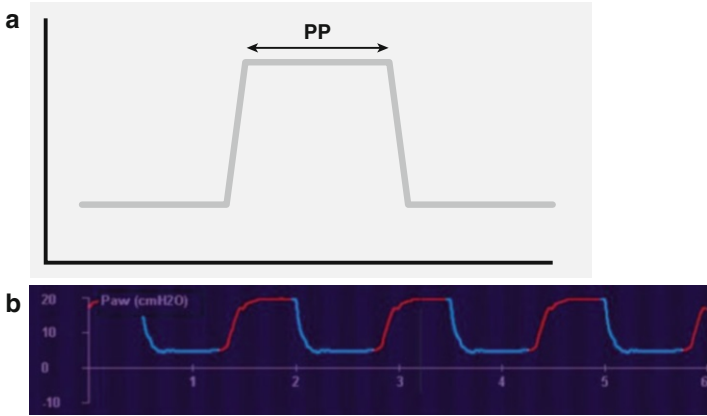


FIGURE 2.5 Plateau pressure. Prolonging inspiratory time by use of an inspiratory hold produces a pressure plateau (PP), demonstrated schematically (a) and actually (b)

2.3.2 *Changes in PIP and PEEP*

Changes in either PIP or PEEP will change the shape of the pressure waveform and alter the delivered mean Paw. Figure 2.6 represents the index ventilator settings, where the PIP is 20 cm H₂O and the PEEP is 5 cm H₂O. Figure 2.7 demonstrates the change when the PIP is increased to 30 cm H₂O. If the PEEP remains unchanged, the amplitude will increase by 10 cm H₂O.

Changes in PIP without concomitant changes in PEEP will alter the amplitude. Here, our initial settings are again PIP 20 cm H₂O and PEEP 5 cm H₂O (Fig. 2.6). When the PEEP is increased to 10 cm H₂O while the PIP is held constant, note how the baseline rises and the difference from PIP to PEEP decreases (Fig. 2.8).

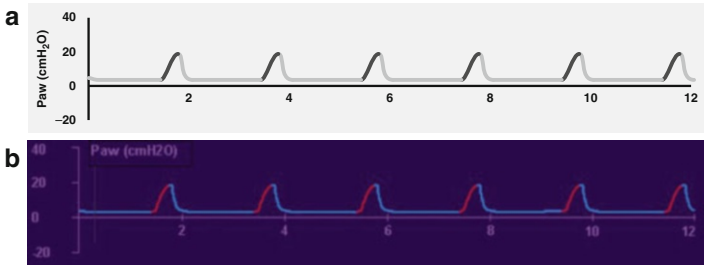


FIGURE 2.6 Index pressure waveform (**a**, schematic; **b**, actual). PIP is 20 cm H₂O, PEEP is 5 cm H₂O

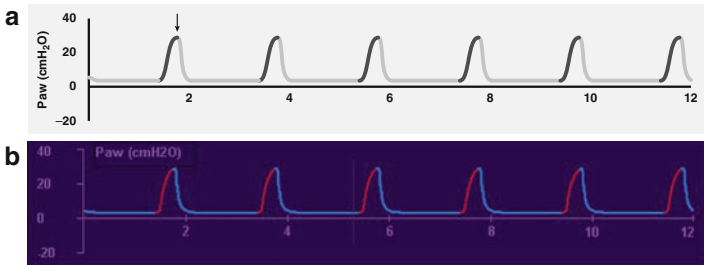


FIGURE 2.7 In this pressure waveform (**a**, schematic; **b**, actual), the PIP has been increased to 30 cm H₂O (*arrow*)

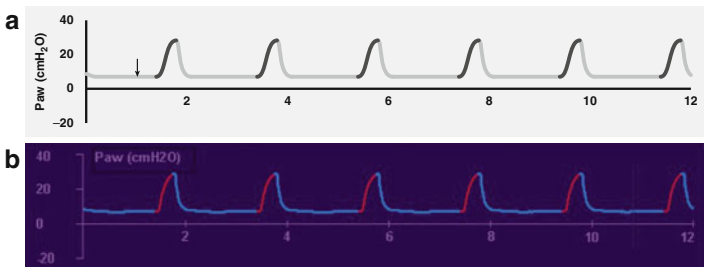


FIGURE 2.8 In this example, the PEEP has been increased from 5 to 10 cm H₂O (*arrow*). Note the rise in the baseline and decrease in the amplitude (**a**, schematic; **b**, actual)

2.3.3 *Change in Inspiratory Time*

Increasing the inspiratory time will increase the duration of positive pressure and will lengthen the inspiratory phase of the pressure waveform. If all other parameters are held constant, the mean Paw will increase (the area under the curve enlarges). Figure 2.9 shows changes in the pressure waveform after increasing the inspiratory time from that seen in Fig. 2.6. Note the increased length of the inspiratory phase of the waveform and the increased area under the curve.

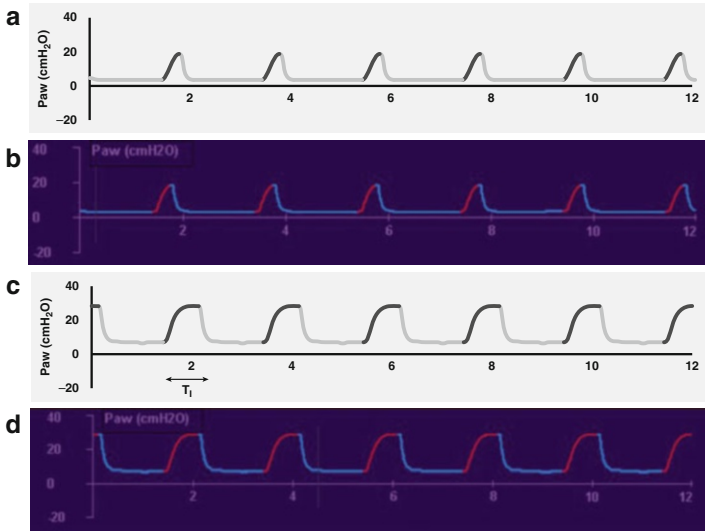


FIGURE 2.9 Increasing the inspiratory time increases the area under the curve, and hence, the mean airway pressure. The upper waveforms (**a**, schematic; **b**, actual) show a PIP of 20, PEEP 5 with a short T_i ; the lower waveforms (**c**, schematic; **d**, actual) show how a longer T_i changes the inspiratory pressure waveform and increases mean airway pressure

2.3.4 *Pressure Overshoot*

Pressure control and pressure support ventilation utilize an accelerating-decelerating inspiratory flow waveform (discussed later). If set too high, it may deliver pressure too rapidly for the patient's need. This creates a condition known as pressure overshoot (sometimes called "ringing"). Figure 2.10 displays this. The pressure waveform exhibits a notch and double peak at PIP. Most ventilators have an adjustable rise time function to respond to this. It is a semi-quantitative means of reducing the inspiratory flow rate.

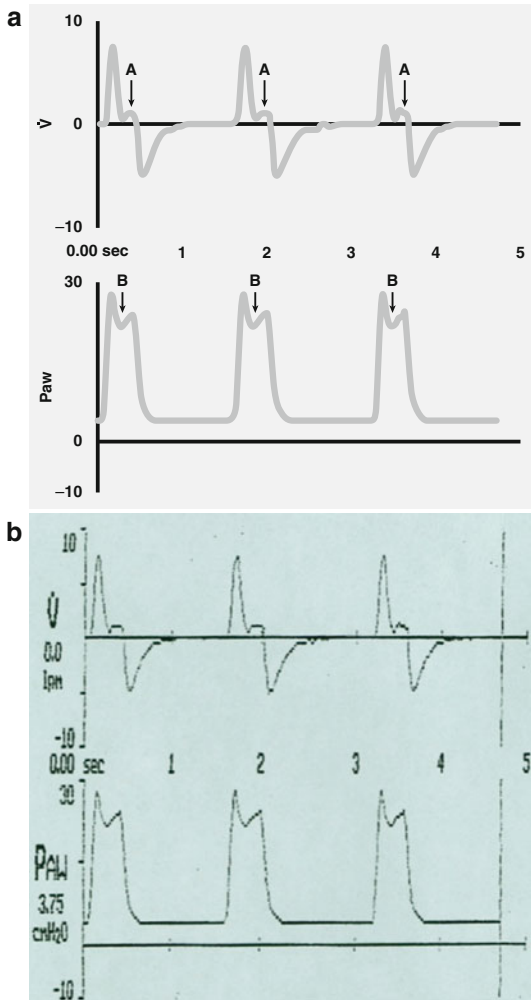


FIGURE 2.10 Pressure overshoot (**a**, schematic; **b**, actual). If the rise time produces an excessive flow rate during pressure control or pressure support ventilation, pressure overshoot, also known as “ringing,” may occur. This can be seen on the flow waveform as a “bump” at the end of inspiratory flow (**A**) and as a notch at the top of the pressure waveform (**B**)

2.4 Flow Waveform

The flow waveform is the most complex because its inspiratory and expiratory phases each have two components. In this waveform, the baseline represents a zero flow state, meaning that no gas is entering or leaving the airway. By convention, anything above the baseline (positive value) represents inspiratory flow (gas flow into the patient), and conversely, anything below the baseline (negative value) represents expiratory flow (gas flow from the patient). The anatomy of a flow waveform during pressure-targeted ventilation is depicted schematically in Fig. 2.11a. Keep in mind that flow is the time rate of volume delivery.

There are two major ways in which inspiratory flow can be delivered to the patient, variable or constant (continuous) flow. Variable flow is utilized in pressure control and pressure support ventilation. As inspiration begins, there is a sharp upward rise, or acceleration, in inspiratory flow. At its maximal value, it is referred to as peak inspiratory flow. This is the fastest rate at which gas enters the airway. Thereafter, flow decelerates to the baseline value, reaching zero when the lungs are filled and no further gas enters the airway. Even though the slope (direction) of the decelerating phase differs

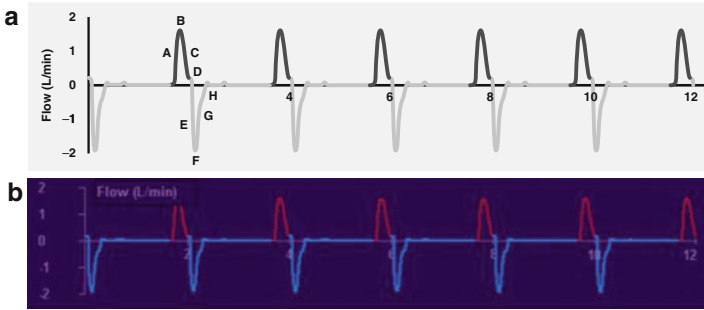


FIGURE 2.11 Anatomy of a flow waveform (**a**, schematic; **b**, actual). As the breath begins, there is an acceleration of inspiratory flow from the zero flow baseline (*A*) to its maximal value, the peak inspiratory pressure (*B*). Flow then decelerates (*C*) back to the zero flow baseline, where inspiration ends (*D*). Flow then reverses in expiration, as gas flow out of the airway accelerates (*E*), reaches its peak expiratory flow rate (*F*), then slows (decelerates) (*G*) until flow ceases at end-expiration (*H*). Thus, there are four phases- accelerating inspiratory flow, decelerating inspiratory flow, accelerating expiratory flow, and decelerating expiratory flow

from the accelerating phase, both are above the baseline and represent gas flow into the patient, but at different rates. Note that the time from one zero flow state to the next defines the inspiratory time. When a continuous inspiratory flow modality, such as volume control, is used, the inspiratory flow accelerates to a peak level and then is held constant for the duration of inspiration, decelerating only after the exhalation valve opens. This creates a characteristic “square” waveform.

The expiratory phase of the flow waveform is similar, but in the opposite direction. As expiration begins, there is a rapid acceleration of expiratory flow, and the most rapidly moving gas from the airway is seen at the peak expiratory flow rate (the deepest negative deflection). This is followed by a deceleration of expiratory flow until the lung is emptied to functional residual capacity and a zero flow state is achieved. Again, although the direction of the accelerating and decelerating components is different, they are both below the baseline (negative) and both represent expiratory flow. The distance between the zero flow states represents the expiratory time. An actual flow waveform during pressure control ventilation is depicted in Fig. 2.11b. Note the sharply accelerating inspiratory flow, peak inspiratory flow, decelerating inspiratory flow, and zero flow at end-inspiration. Expiration then ensues, with accelerating expiratory flow, peak expiratory flow, and decelerating expiratory flow. The expiratory phase ends at a zero flow state.

Figure 2.12 shows a flow waveform during volume control ventilation. The accelerating inspiratory flow peaks and then is held constant (continuous) until inspiration ends, creating a square waveform.

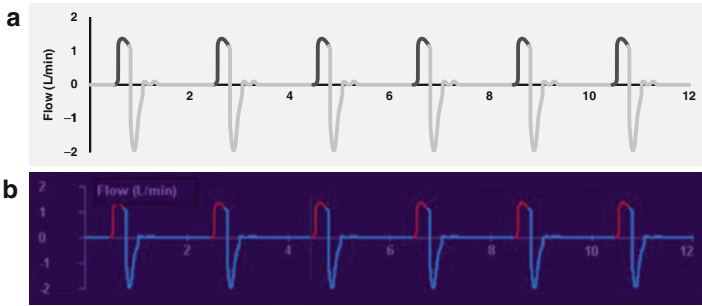


FIGURE 2.12 Flow wave form during volume control ventilation (**a**, schematic; **b**, actual). Inspiratory flow is continuous, rather than variable, and produces a characteristic “square” waveform

2.4.1 *Increased Expiratory Resistance*

Increased expiratory resistance will decrease expiratory gas flow. This results in a longer time for the lung to empty and is depicted graphically by either shallow accelerating expiratory flow and decreased peak expiratory flow rate, a longer time to return to baseline during decelerating expiratory flow, or both. These changes are shown in Fig. 2.13. Note the shallow accelerating expiratory flow with decreased peak expiratory flow and the prolonged time to return to the baseline during decelerating expiratory flow.

2.4.2 *Gas Trapping*

Gas trapping occurs when the expiratory flow is less than the inspiratory flow, resulting in more gas entering than leaving the lung. This is a potentially dangerous situation that can lead to alveolar rupture and air leak. Prior to the advent of real-time graphics, clinicians were usually aware of gas trapping only after the air leak had occurred. Now, careful observation of the flow waveform can detect this condition, allowing time to avoid its consequences.

In the panel shown in Fig. 2.14, note that in each flow waveform, the decelerating expiratory component never reaches the baseline (zero flow state) before the subsequent breath is initiated and the accelerating inspiratory flow occurs. Possible adjustments might include decreasing the ventilator rate, decreasing the flow rate, shortening the inspiratory time, or increasing the PEEP, depending upon the clinical condition, ventilator modality, and underlying pathophysiology.

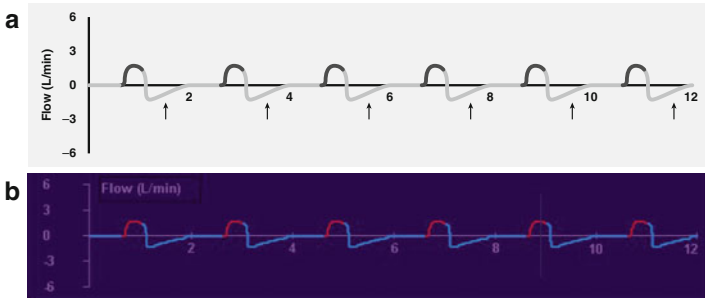


FIGURE 2.13 Flow waveform depicting increased expiratory resistance (**a**, schematic; **b**, actual). Note the decreased slope and increased time for the decelerating portion of the expiratory flow to return to the baseline (*arrows*)

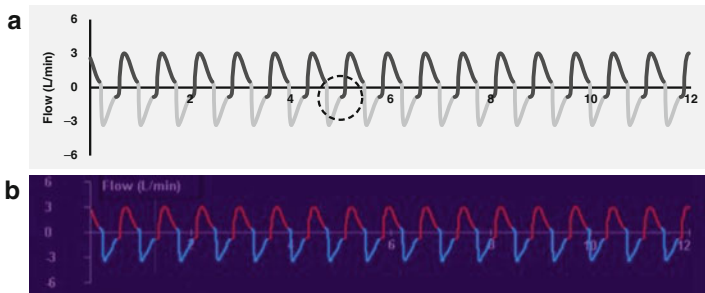


FIGURE 2.14 Gas trapping (**a**, schematic; **b**, actual). Note that the expiratory flow fails to reach the baseline (zero flow state) before the next breath is initiated (*circle*)

2.4.3 *Cycling Mechanisms*

Cycling refers to the mechanism that transitions inspiration to expiration and expiration to inspiration. For decades, neonatal ventilators offered only time as the cycling mechanism. The clinician chose an inspiratory time or an inspiratory:expiratory ratio. The exhalation valve would close and pressure and flow would be delivered until the exhalation valve opened at the end of the inspiratory time. During time cycling (Fig. 2.15), note that the inspiratory time is identical for each breath and that there may be a prolongation of the zero flow state at the end of inspiration if all of the breath conditions (such as peak pressure) have been met prior to the completion of the inspiratory time.

The advent of microprocessor-controlled ventilation offered new cycling mechanisms, particularly flow-cycling of neonatal patients. Flow-cycling can be applied to pressure-targeted modalities, such as pressure-limited ventilation, pressure control ventilation, and pressure support ventilation.

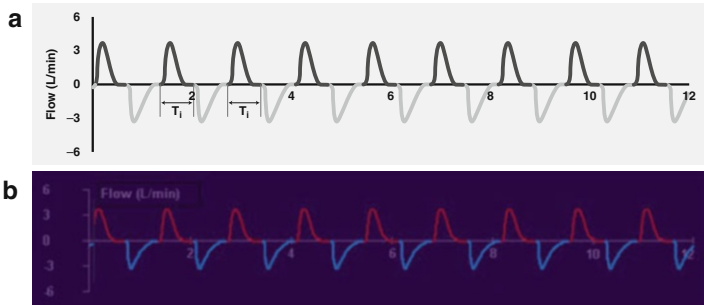


FIGURE 2.15 Time cycling (**a**, schematic; **b**, actual). For each breath, inspiration lasts for a set period of time until the exhalation valve opens. Note that there may be no flow going into the airway at end-inspiration (*arrows*)

Flow-cycling takes advantage of the natural pattern of breathing by focusing on the baby's inspiratory flow (Fig. 2.16). As a breath is delivered, the ventilator notes the peak inspiratory flow rate. The inspiratory flow rate then decelerates, but before it completely reaches the zero flow state, the exhalation valve will open, discharging the remainder of inspiratory flow. The exact point at which this happens is determined by both the specific ventilator algorithm and the clinician-chosen termination point. Generally, this is at 5–25 % of the peak inspiratory flow rate. There are two major advantages to flow-cycling. First, it theoretically enables 100 % synchrony between the baby and the ventilator because the baby both initiates and terminates the breath (the effect of lag time between the actual patient effort, the onset of flow, and signal transfer time may still result in imperfectly triggered breaths). Second, it prevents gas trapping and the inversion of the inspiratory:expiratory ratio during patient-triggered ventilation. During time-cycled, patient-triggered ventilation, because the inspiratory time is fixed, the faster a baby breathes, the shorter will be the expiratory time and the greater the ratio will be. At very rapid rates, the risk of gas trapping increases. If flow-cycling is used, the ratio will be preserved because each breath will be terminated at a percentage of the peak inspiratory flow rate, thus shortening inspiration.

Flow-cycling is used in conjunction with time-cycling, in that a breath will be terminated by whichever condition occurs first. In pressure support ventilation, the inspiratory time is a “time limit,” which cannot be exceeded.

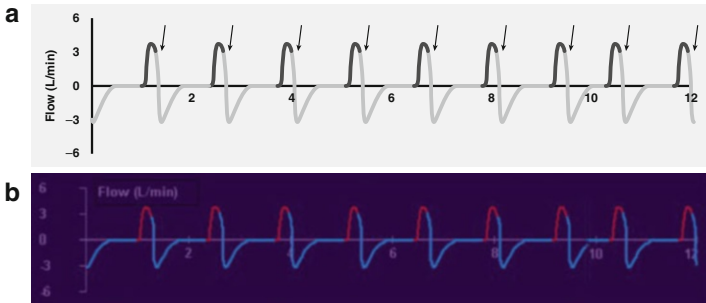


FIGURE 2.16 Flow cycling (**a**, schematic; **b**, actual). During flow cycled breaths, inspiration ends when inspiratory flow has decelerated to a small percentage of the peak inspiratory flow rate, and the breath cycles directly into expiration (*arrows*)

2.4.4 *Endotracheal Tube Leaks*

Because cuffed endotracheal tubes are not used in newborns, there will almost always be some degree of leak around the endotracheal tube. Most of this occurs during inspiration when pressure is higher. Although leaks are easiest to recognize on the V_t waveform (Fig. 2.17) or the pressure-volume and flow-volume loops (see later), their importance can be seen by examining their effect on the flow waveform during flow-cycling.

A significant leak may divert gas flow, such that the decelerating inspiratory flow may never reach the termination point. The breath will then be time-cycled, but often with inadequate pressure or volume delivered to the baby.

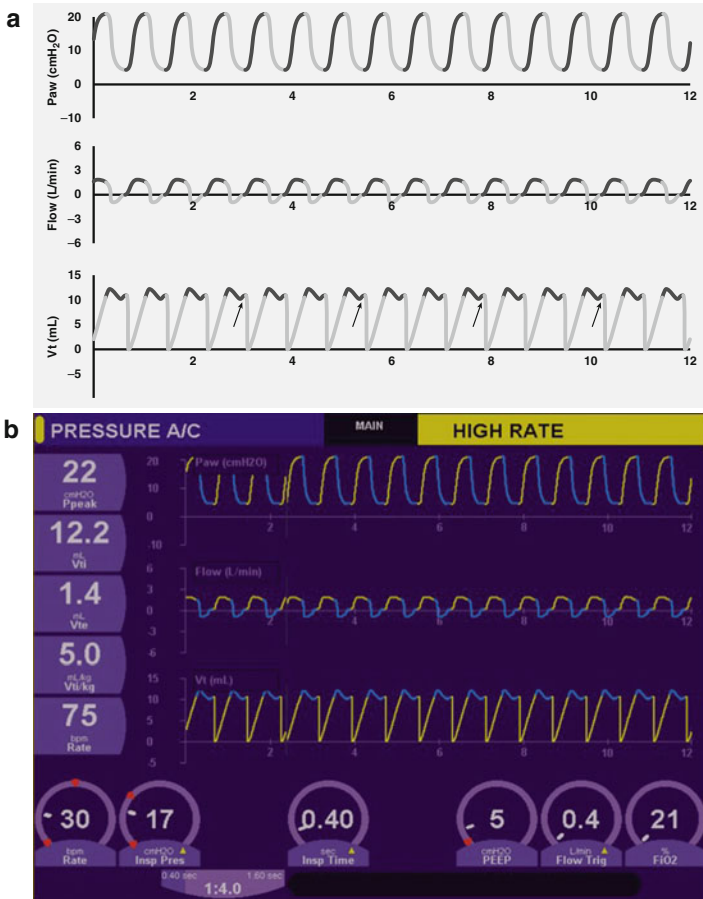


FIGURE 2.17 Large endotracheal tube leak (**a**, schematic; **b**, actual). The flow waveform, shown in the middle panel, has virtually no expiratory component. The volume waveform, in the lower panel, shows almost no expired volume (the actual end of the expiratory volume waveform is shown by the *arrows* in the schematic, and by the short blue line in the actual tracing) which is followed by a reset artifact (yellow colored line dropping to the zero baseline). This also results in auto-cycling, with a rate of 75

2.4.5 *Auto-cycling (Auto-triggering)*

Auto-cycling (also referred to as auto-triggering) may occur during flow-triggered ventilation if the ventilator interprets an aberrant flow signal as patient effort. This can happen if there is a leak that exceeds the trigger threshold, and it may occur anywhere in the path of gas flow (e.g., ventilator circuit, humidifier, endotracheal tube). It may also occur from excessive condensation in the ventilator circuit (“rainout”). As this fluid shifts back and forth during ventilator cycling, it may create a flow change sufficient to trigger the ventilator. When auto-cycling occurs, there may be rapid delivery of mechanical breaths, inducing hypocapnia as well as the risk of lung injury.

Figure 2.18 shows a flow waveform panel during auto-cycling. It may be distinguished from rapid breathing that is actually patient-initiated. During some types of auto-cycling, all of the breaths are identical—there is no variation in their rate or periodicity. For others, such as the movement of water in the tubing, the rate may vary and be more challenging to identify. Even a rapidly breathing baby will show some variation in the rate of breathing and the appearance of the flow waveform.

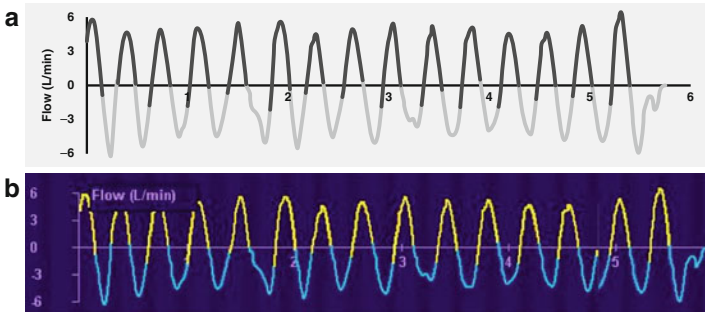


FIGURE 2.18 Another example of auto-cycling (**a**, schematic; **b**, actual). Significant leaks during flow-triggered ventilation may reach the assist sensitivity threshold and result in repetitive delivery of mechanical breaths. Note the relative uniformity of the breaths, which helps to distinguish this from just rapid breathing, where there will be some variability

2.4.6 *Flow Rate and the Shape of the Flow Waveform*

The manner in which flow is delivered to the patient will determine its shape. Inspiratory flow may be continuous, as in pressure-limited ventilation or volume control ventilation, or it may be variable, as in pressure control or pressure support ventilation.

Continuous flow in pressure-limited ventilation produces a sinusoidal flow waveform with a rounded contour. This is shown in Fig. 2.19.

Continuous flow during volume ventilation produces a square flow waveform (Fig. 2.20). Flow accelerates at the initiation of inspiration but is held constant until inspiration ends.

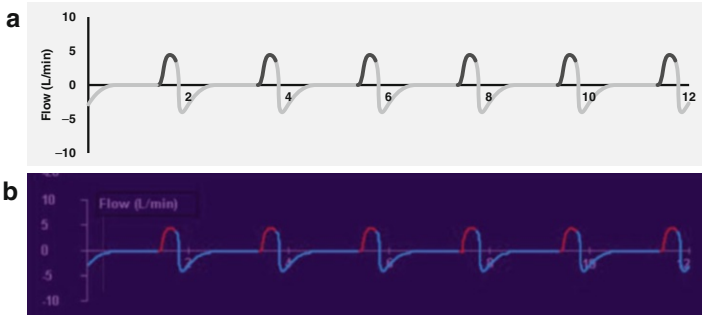


FIGURE 2.19 Pressure limited ventilation (**a**, schematic; **b**, actual). Continuous inspiratory flow produces a more sinusoidal flow waveform

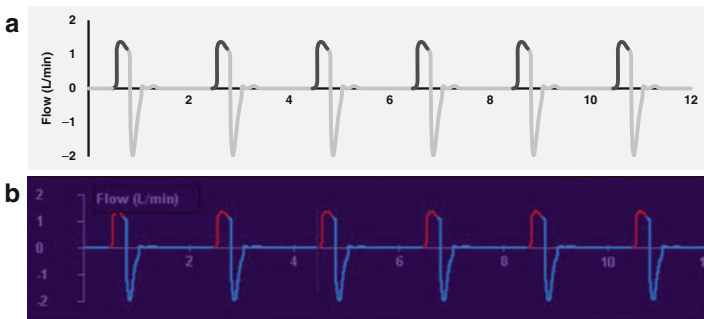


FIGURE 2.20 Volume control ventilation (**a**, schematic; **b**, actual). Constant inspiratory flow produces a square flow waveform

Variable inspiratory flow produces a waveform that rapidly accelerates and peaks then decelerates (Fig. 2.21). It is used in pressure control and pressure support ventilation and is typically “spiked.” Although its shape is determined primarily by the ventilator algorithm, it may be modulated through a feature known as rise time. Figure 2.22 shows a flow waveform has been modulated by adjusting the rise time, decreasing the inspiratory flow rate, and producing a less spiked shape.

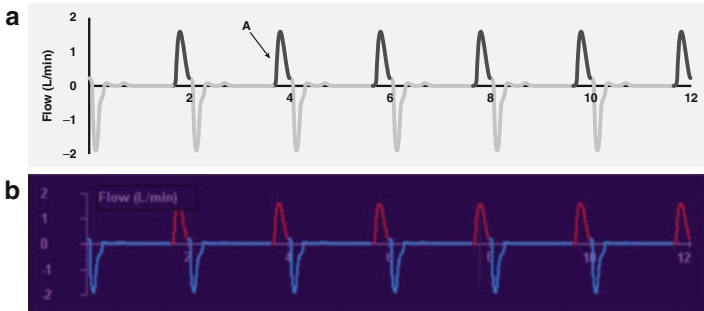


FIGURE 2.21 Pressure control or pressure support ventilation (**a**, schematic; **b**, actual). Variable inspiratory flow produces a rapidly accelerating (*A*) and decelerating inspiratory flow waveform, sometimes referred to as a “spike” waveform

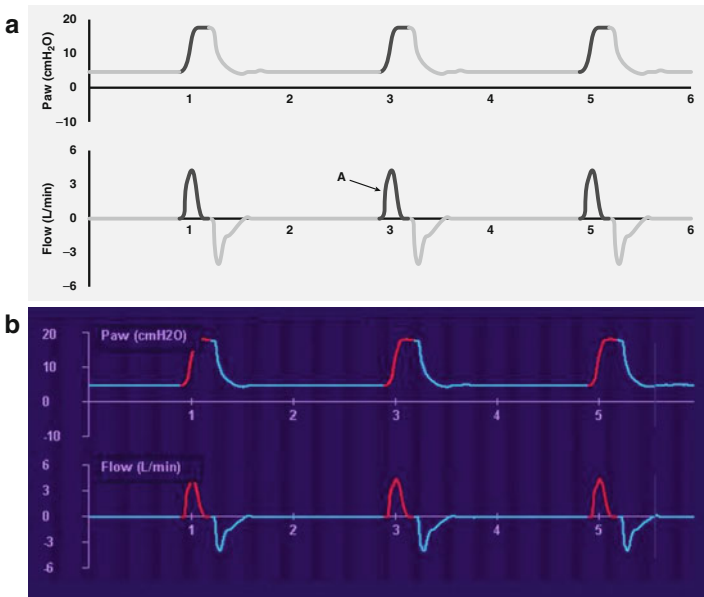


FIGURE 2.22 Adjustment of rise time modulates the inspiratory flow rate during pressure control or pressure support ventilation (**a**, schematic; **b**, actual). Note that the slope of the accelerating inspiratory flow (*A*) is less than in Fig. 2.21

2.4.7 *Spontaneous Breath*

Figure 2.23 demonstrates a spontaneous breath from a baby not receiving any ventilatory support. It has been included to demonstrate differences between spontaneous and assisted breathing. Note the much more rounded contour and return to baseline.

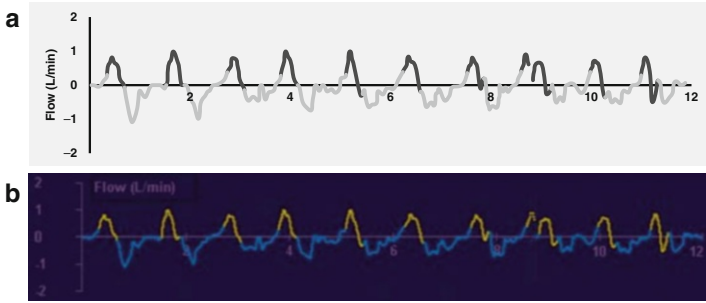


FIGURE 2.23 Spontaneous breathing (**a**, schematic; **b**, actual). The baby is not receiving any ventilatory support. The breaths show significant variability

Suggested Reading

Becker MA, Donn SM. Real-time pulmonary graphic monitoring. *Clin Perinatol*. 2007;34:1–17.

Bhutani VK, Benitz WE. Pulmonary function and graphics. In: Goldsmith J, Karotkin E, editors. *Assisted ventilation of the newborn*. 5th ed. Philadelphia: Saunders; 2011. p. 306–20.

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