10 Classification of Mechanical Ventilation Devices

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I. Ventilators, or more precisely, the modes they deliver, can be classified by the variables that are controlled (e.g., pressure or volume), as well as those that start (or trigger), sustain (or limit), and end (cycle) inspiration, and those that maintain the expiratory support (or baseline pressure) (Fig. 10.1). Microprocessor and sensor technology has increased the quality and quantity of ventilator output feedback available. These advances in the technology of targeting schemes warrant further classification.

II. Breath Control Variables. A modality of ventilation can be classified as either a form of pressure control or volume control, meaning that either pressure or volume are used as feedback control variables by the mechanism that controls breath delivery. The theoretical foundation for identifying a control variable is the equation of motion for the respiratory system. A simple version for this purpose (representing a passive patient) is as follows:

$$P_{\text{vent}} = E \times V(t) + R \times \dot{V}(t)$$

where P_{vent} is the pressure generated by the ventilator to drive inspiration, E = elastance ($\Delta P/\Delta V$), $V(t)$ = volume as a function of time (t), and $\dot{V}(t)$ is flow as a function of time. If the ventilator controls the left-hand side of the equation, i.e., the pressure waveform parameters are preset, then the modality is pressure control. This includes modalities for which the peak inspiratory pressure is preset or it is automatically adjusted by the ventilator to be proportional to the patient's inspiratory effort. If the ventilator controls the right hand side of the equation, i.e., both tidal volume and inspiratory flow are preset, then the control variable is volume.

A. Pressure control

To deliver pressure control modes, the ventilator controls the airway pressure waveform by generating: (1) positive airway pressure, making it rise above the body surface pressure (i.e., positive pressure ventilator); or (2) negative airway pressure, making it fall below the body

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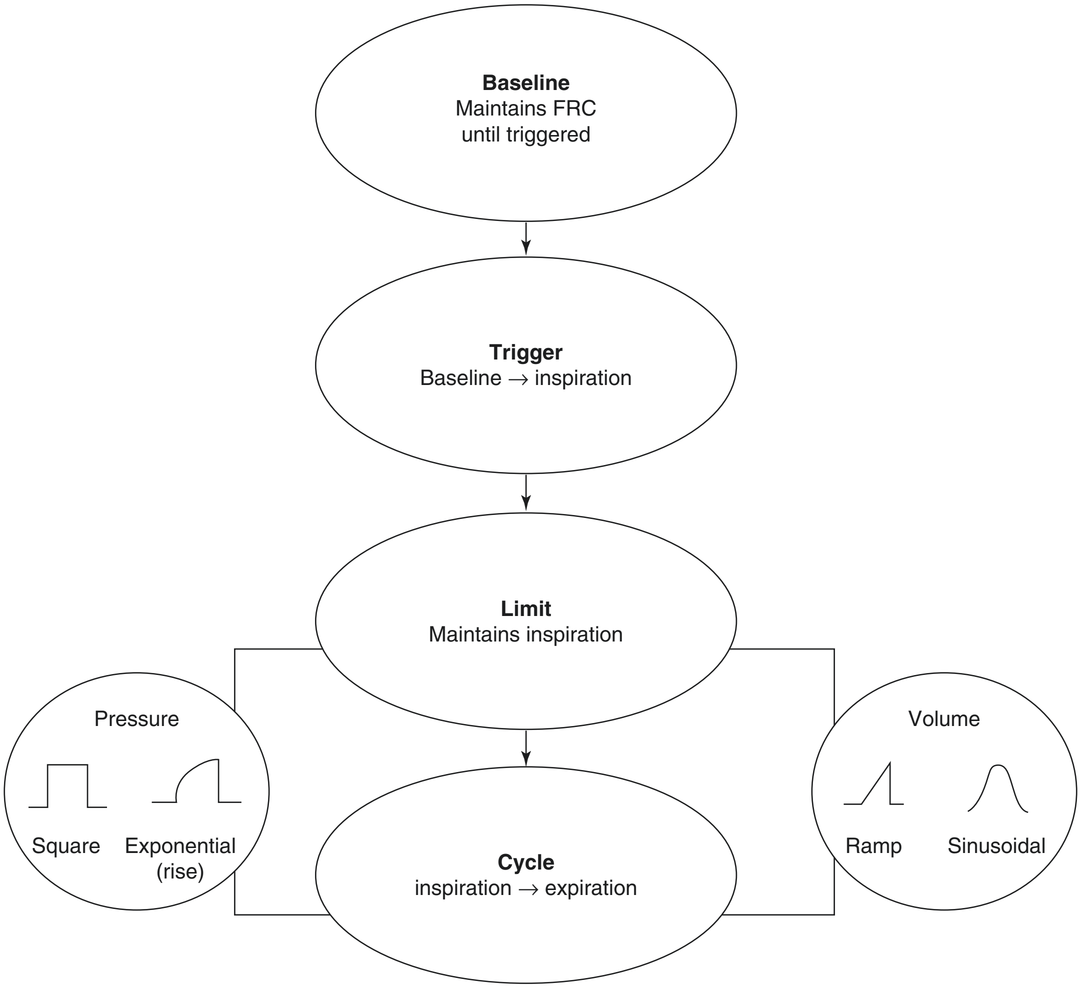

Fig. 10.1 Application of the equation of motion to the respiratory system. A common waveform for pressure and volume control is shown. Pressure, volume, flow, and time are also used as phase variables that determine the characteristics of each ventilator cycle (e.g., baseline pressure, trigger sensitivity, inspiratory time)

surface pressure (i.e., negative pressure ventilator); or (3) proportional airway pressure, making it rise proportional to inspiratory effort as sensed by the ventilator or the diaphragm (e.g., flow or electrical voltage). As the equation of motion above indicates, pressure is the independent variable, while volume and flow are dependent variables whose values are determined by elastance (or compliance) and resistance. Pressure control requires careful attention to changes in compliance through assessments of delivered volumes and chest rise.

B. Volume control

To deliver volume control, the ventilator regulates flow according to a preset value (in a variety of preset flow waveforms) for a preset time, yielding a preset tidal volume. As the equation of motion indicates, flow and volume (as it is the integral of flow) are the independent variables, and hence airway pressure depends on elastance (or compliance) and resistance. Control of tidal volume can be useful in circumstances of rapidly changing lung mechanics. Volume control is reliant upon the accuracy of flow sensors and requires careful attention to changes in chest rise and delivered pressures.

C. Time control

There are modalities of ventilation for which neither pressure nor flow/volume are preset. All that is preset are the inspiratory and expiratory times. Hence, we say the control variable is time and the modality is a form of time control (vs volume or pressure control). High-frequency oscillatory ventilation and intrapulmonary percussive ventilation are examples of modalities classified as time control.

III. Cycle Control Variables

The ventilatory cycle has four phases: (1) the change from expiration to inspiration (trigger); (2) inspiratory limit; (3) the change from inspiration to expiration (cycle); and (4) expiration (baseline pressure) (Fig. 10.2). With spontaneous breaths, the cycle is determined by the patient independent of any ventilator settings. Spontaneous breaths may be assisted (as in pressure support) or unassisted. With mandatory breaths, the entire cycle is determined by the ventilator independent of the patient. A mandatory breath is by definition assisted.

A. Trigger

1. Inspiration begins when one or more monitored variables in the equation of motion (i.e., pressure, volume, flow, and time) reach a preset threshold.
2. Trigger events may be either patient-initiated (spontaneous) or ventilator-initiated (mandatory).
3. The most common trigger variables are time (i.e., after a pre-defined time, the ventilator is triggered to start inspiration as in intermittent mandatory ventilation) and flow (i.e., when a pre-defined flow is detected, the ventilator is triggered to assist). Pressure may also be used as a trigger (i.e., when an inspiratory effort is detected as a change in the end expiratory pressure, the ventilator is triggered to start inspiration, as in patient-triggered ventilation). Flow-

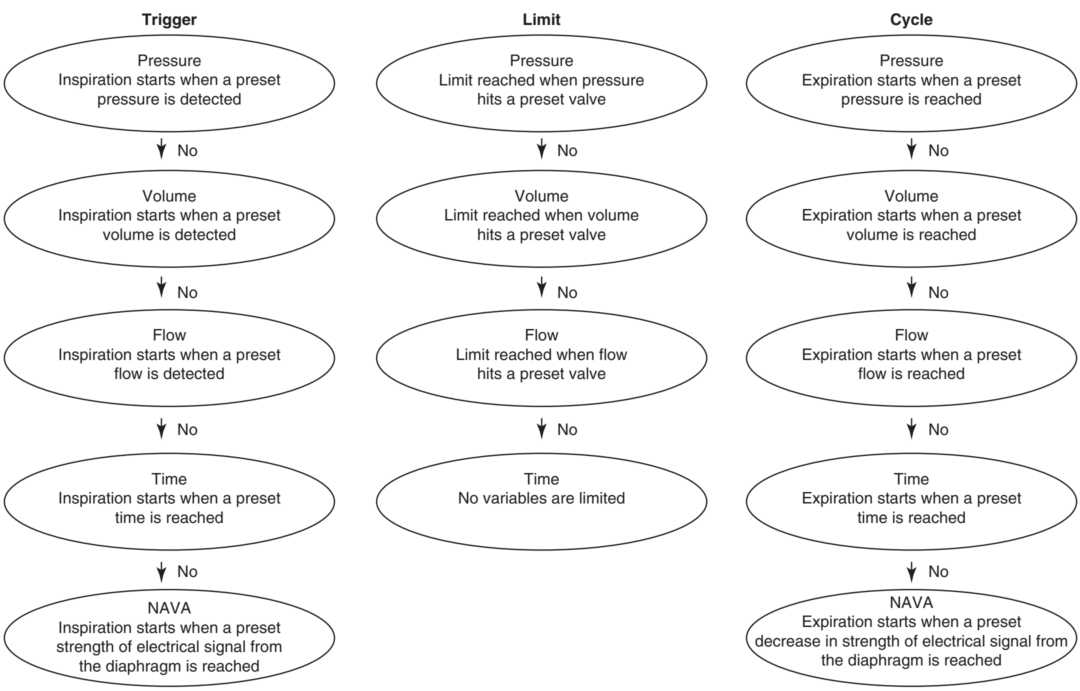

Fig. 10.2 Criteria for determining the phase variables during a ventilator-supported breath. This emphasizes that each control variable may have a different set of control and phase variables, depending on the mode of ventilation desired

triggering involves less patient effort and is more commonly used in infant ventilators. Neurally adjusted ventilatory assist (NAVA) triggers a ventilator breath by monitoring electrical signals from the diaphragm. NAVA is becoming more common as a trigger variable in infants.

B. Limit
   1. Pressure, volume, and flow increase during inspiration.
   2. A limit variable restricts the inspiratory increase to a preset value but does not limit the duration.
   3. Many modes delivered by neonatal ventilators are pressure-limited.

C. Cycle
   1. Inspiration stops (or is cycled off) when a monitored variable reaches a preset threshold.
   2. Cycling events may be either patient-initiated (i.e., by detecting changes in flow, pressure, or electrical signals from the diaphragm) or ventilator-initiated (i.e., based on the set inspiratory time or cycle time).
   3. Many neonatal ventilators, including high-frequency ventilators, are time-cycled (ventilator-initiated).

D. Baseline

E. The baseline variable maintains expiratory pressure and expiratory lung volume (e.g., positive end expiratory pressure on conventional ventilators or mean airway pressure on high-frequency oscillators).

IV. Targeting Variable

A target is a predetermined goal of ventilator output. The targeting variable describes the relationship between the selected ventilator settings and the ventilator output as detected by feedback control systems. Targets can be set between-breaths (i.e., end-tidal CO_2) or within-breaths (i.e., tidal volume). Within each ventilatory modality, there are also several targeting schemes that can be distinguished although some ventilators use more than one targeting scheme. The currently available targeting variables and their abbreviations (in parentheses) are as follows:

A. Set-point (s)

Operator sets all the parameters of the pressure wave form or volume and flow waveforms. This is the most common modality used in pressure control and time control ventilation.

B. Dual (d)

Switches between volume control and pressure control during a single inspiration.

C. Servo (r)

Ventilator output (pressure or volume) automatically follows a varying input (inspiratory effort). This is the modality used by NAVA and proportional assist.

D. Adaptive (a)

Ventilator automatically sets one target (pressure) in order to achieve another monitored target (volume). This is the most common modality used in volume control ventilation.

E. Bio-variable (b)

Ventilator randomly selects inspiratory pressure or volume to mimic the variability of normal breathing.

F. Optimal (o)

Ventilator automatically adjusts the targets of the ventilatory pattern to either minimize or maximize a monitored target (e.g., work of breathing).

G. Intelligent (i)

Ventilator automatically adjusts the targets of the ventilatory pattern using artificial intelligence programs.

V. Ventilatory Mode Classification

A. Because neonatal ventilators now offer dozens of modes and sometimes different names for similar modes, it is helpful and necessary to have a classification system (taxonomy) to understand ventilator modes and capabilities. Modes are classified using three basic characteristics (Fig. 10.3). First is the control variable (i.e., pressure-control or volume control as described above). Second is the cycle variable or pattern of mandatory and/or spontaneous breaths. If all breaths are mandatory, we say the breath sequence is continuous mandatory ventilation (CMV). If spontaneous breaths are possible between mandatory breaths, the sequence is intermittent mandatory ventilation (IMV). Finally, if all breaths are spontaneous, the sequence is continuous spontaneous ventilation (CSV) (Table 10.1). The third component of this classification system is the targeting variable (as described above), which adds detail that allows us to distinguish between similar modes. Thus, to classify a mode, we specify the control variable, the cycle variable, and the targeting variable.

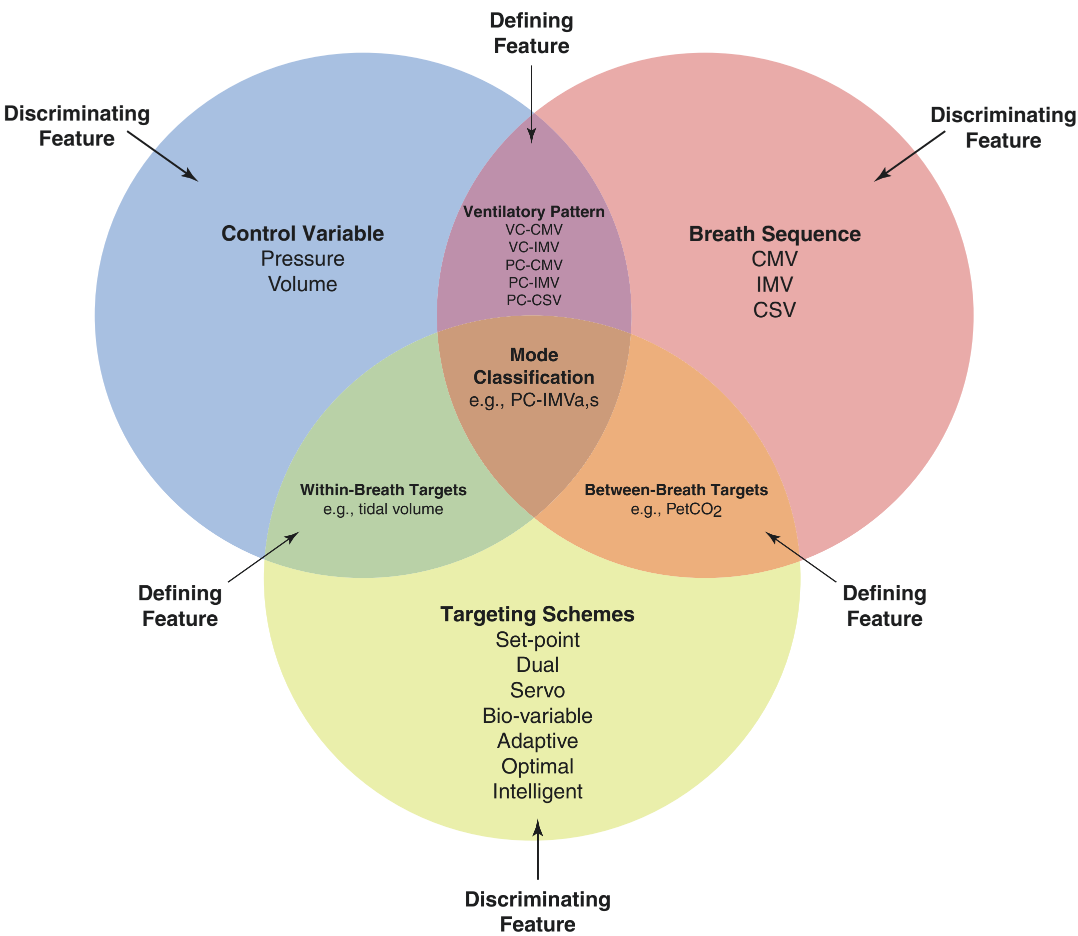

Fig. 10.3 Venn diagram illustrating how the mode taxonomy can be viewed in terms of discriminating features and defining features. (From Chatburn RL, El-Khatib M, Mireles-Cabodevila E. A taxonomy for mechanical ventilation: 10 fundamental maxims. Respir Care. 2014;59(11):1747–63, with permission from the American Academy of Respiratory Care). CMV, conventional mandatory ventilation; IMV, intermittent mandatory ventilation; CSV, continuous spontaneous ventilation; VC, volume control; PC, pressure control; $P_{et}CO_2$, end-tidal partial pressure of carbon dioxide; a, adaptive targeting; s, set-point targeting

Table 10.1 Targeting schemes

Name	Abbreviation	Description	Advantage	Disadvantage	Example mode name
Set-point	s	The operator sets all parameters of the pressure waveform (pressure control modes) or volume and flow waveforms (volume control modes)	Simplicity	Changing patient condition may make settings inappropriate.	Volume control continuous mandatory ventilation
Dual	d	The ventilator can automatically switch between volume control and pressure control during a single inspiration	Can adjust to changing patient condition and assure either a preset tidal volume or peak inspiratory pressure, whichever is deemed most important	Complicated to set correctly and needs constant readjustment.	Volume control
Servo	r	The output of the ventilator (pressure/volume/flow) automatically follows a varying input.	Support by the ventilator is proportional to inspiratory effort.	Requires estimates of artificial airway and/or respiratory system mechanical properties	Proportional assist ventilation plus
Adaptive	a	The ventilator automatically sets target(s) between breaths in response to varying patient conditions	Can maintain stable tidal volume delivery with pressure control for changing lung mechanics or patient inspiratory effort	Automatic adjustment may be inappropriate if algorithm assumptions are violated or they do not match physiology	Pressure regulated volume control
Bio-variable	b	The ventilator automatically adjusts the inspiratory pressure or tidal volume randomly	Simulates the variability observed during normal breathing and may improve oxygenation or mechanics	Manually set range of variability may be inappropriate to achieve goals.	Variable pressure support
Optimal	o	The ventilator automatically adjusts the targets of the ventilatory pattern to either minimize or maximize some overall performance characteristic (e.g., work rate of breathing)	Can adjust to changing lung mechanics or patient inspiratory effort	Automatic adjustment may be inappropriate if algorithm assumptions are violated or they do not match physiology	Adaptive support ventilation
Intelligent	I	Targeting scheme that uses artificial intelligence programs such as fuzzy logic, rule based expert systems, and artificial neural networks	Can adjust to changing lung mechanics or patient inspiratory effort	Automatic adjustment may be inappropriate if algorithm assumptions are violated or they do not match physiology	SmartCare/PS IntelliVent-ASV

Adapted from Chatburn RL, El-Khatib M, Mireles-Cabodevila E. A taxonomy for mechanical ventilation: 10 fundamental maxims. Respir Care. 2014;59(11):1747–63, with permission from the American Academy of Respiratory Care. PS, pressure support; ASV, adaptive support ventilation

B. For example, the most common mode of ventilation used among neonates has historically been called “time-cycled pressure-limited.” Formally, this was classified as pressure control intermittent mandatory ventilation with set-point targeting, appreciated as PC-IMVs. More recently, the commonly used “synchronized intermittent mandatory ventilation + pressure support” is classified as PC-IMVs. Using the above classification system, high-frequency oscillatory ventilation would be classified as time control continuous mandatory ventilation with set-point targeting or TC-CMVs, and high-frequency jet ventilation would be classified as pressure control continuous mandatory ventilation with set-point targeting or PC-CMVs. NAVA ventilation may be classified as pressure control continuous spontaneous ventilation with servo targeting or PC-CSVr. “Patient-triggered ventilation” or “assist control” can use either pressure or volume control and is classified as continuous mandatory ventilation with either set-point (PC-CMVs) or adaptive targeting (VC-CMVa) respectively. “Volume guarantee” or “pressure regulated volume control” may be classified as pressure-control intermittent mandatory ventilation with both adaptive and set-point targeting or PC-IMVa,s.

Suggested Reading

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