Expert Review of Respiratory Medicine

ISSN: 1747-6348 (Print) 1747-6356 (Online) Journal homepage: http://www.tandfonline.com/loi/ierx20

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To cite this article: Robert L Chatburn (2010) Understanding mechanical ventilators, Expert Review of Respiratory Medicine, 4:6, 809-819, DOI: 10.1586/ers.10.66

To link to this article: http://dx.doi.org/10.1586/ers.10.66

Published online: 09 Jan 2014.

EXPERT REVIEWS

Understanding mechanical ventilators

Expert Rev. Resp. Med. 4(6), 809–819 (2010)

Robert L Chatburn

Cleveland Clinic, Respiratory Therapy Department, M56, 9500 Euclid Avenue, Cleveland, OH 44195, USA
Tel.: +1 216 445 1424
chatbur@ccf.org

The respiratory care academic community has not yet adopted a standardized system for classifying and describing modes of ventilation. As a result, there is enough confusion that patient care, clinician education and even ventilator sales are all put at risk. This article summarizes a ventilator mode taxonomy that has been extensively published over the last 15 years. Specifically, the classification system has three components: a description of the control variables within breath; a description of the sequence of mandatory and spontaneous breaths; and a specification for the targeting scheme. This three-level specification provides scalability of detail to make the mode description appropriate for the particular need. At the bedside, we need only refer to a mode briefly using the first or perhaps first and second components. To distinguish between similar modes and brand names, we would need to include all components. This taxonomy uses the equation of motion for the respiratory system as the underlying theoretical framework. All terms relevant to describing modes of mechanical ventilation are defined in an extensive appendix.

Keywords: adaptive control • breathing pattern • equation of motion • feedback control • mechanical ventilation • mechanical ventilator • modes of ventilation • targeting schemes • taxonomy

The problem

Physicians are at a disadvantage in learning about mechanical ventilation. No formal training is provided on this subject in medical schools in the USA. Physicians learn about ventilators during their residencies, and invariably they are exposed to a very small subset of all the commercially available devices. For example, in the most recent edition of *Mosby's Respiratory Care Equipment* [1], 49 ventilators are listed along with descriptions of 54 unique names for modes of ventilation. Even respiratory therapists, who, in the USA, spend 2–4 years studying respiratory care equipment, are never exposed to all of these ventilators and modes in school or on the job. The result of this inequity between educational supply and demand can be surmised from this quote:

"Health Devices has repeatedly stressed the need for users to understand the operation and features of ventilators, regardless of whether they will be used to ventilate neonatal/pediatric or adult patients. The fact that ventilators are such an established technology by no means guarantees that these issues are clearly understood … we continue to receive reports of hospital staff misusing ventilators because they're unaware of the devices' particular operational considerations" [101].

Today, state-of-the-art mechanical ventilators may have as many as 24 modes, some of which may even employ computerized artificial intelligence. Yet, we lack a standardized classification system sufficient to describe this technological complexity. Despite repeated attempts, no official controlled vocabulary or taxonomy of mechanical ventilation exists either among healthcare organizations or manufacturers. On the contrary, manufacturers have exacerbated the problem by coining a plethora of names for modes and how they work in an effort to create product differential and increase sales. Thus, the 54 modes referred to above are indeed not 54 unique modes but just unique names. As a result of not having a standardized taxonomy, four major problems accrue: published studies of mechanical ventilation are hard to interpret and compare; there is little consistency among educational programs regarding how ventilators work; clinicians do not have the time or educational resources to develop adequate skills with all modes on all ventilators they may encounter, making optimal ventilator management unattainable; and manufacturers can no longer easily communicate with prospective clients, thus limiting the effectiveness of both sales and training, which in turn, exacerbates the other problems.

Notwithstanding the aforementioned issues, much has been written on the subject of ventilator and mode classification [2–17]. The purpose

 10.1586/ERS.10.66 ISSN 1747-6348

of this article is to summarize the previous literature and present a simplified approach to understanding the basic capabilities of modes of ventilation.

Key concepts for understanding ventilators

Clinicians and authors alike have used a variety of common terms without explicit definitions. Thus, the first step in developing an understanding of the subject is to make some key constructs explicit. The general concepts are described below and specific definitions are provided in the Appendix [18].

Mandatory versus spontaneous breath

Every ventilator operator's manual uses the terms mandatory and spontaneous in describing modes, but none of them give adequate (if any) definitions. While there are any number of rational definitions for these terms, there is only one set that allows for a consistent classification of all current and any conceivable future modes of ventilation. This is critical because these definitions are the very foundation of any mode description. Simply put, a spontaneous breath is one for which inspiration is both started (triggered) and stopped (cycled) by the patient. If inspiration is either triggered or cycled by the machine, the breath is classified as mandatory. Although many people associate the term 'spontaneous breath' with breaths unassisted by the ventilator, there is no logical reason to associate mechanical assistance with the terms spontaneous versus mandatory. Indeed, there is no need to even associate the definition of spontaneous, as given here, to patients connected to ventilators. Therefore, spontaneous breaths may be assisted or unassisted, but mandatory breaths by definition are assisted.

Control

The meaning and importance of this word have evolved radically over time as have ventilators themselves. The problem is that the focus of the meaning has shifted subtly from patient physiology to machine function. A prime example is the use of the word control as in 'assist/control' versus 'volume control of inspiration'. The term assist/control focuses on the patient's neurological control of breathing, and refers to a mode in which the ventilator may either 'control' the breathing pattern by triggering inspiration as a substitute for the patient's own neurological control or 'assist' the patient's inspiratory effort after he/she has triggered inspiration. These definitions date back over 30 years [19] to a time when ventilator capabilities were primitive by today's standards. By contrast, the phrase volume control of inspiration focuses on the ventilator's mechanical operation and refers to how the ventilator shapes the breath regardless of how it has been triggered. Ventilators have evolved over at least five generations [20] in the span of a single human generation. As a result, many people who have been in the field for a long time still cling to the older, patient-centric view of the word control and thus fail to appreciate the implications and utility of the machine-centric view. Manufacturers feel compelled to perpetuate this inertia because many of these same people make the purchasing decisions. The result is that the term assist/control continues to be associated with mode selection on new ventilators, even though the meaning of the term has changed from its historical roots to the point of virtual uselessness. Originally, assist/control meant volume-controlled continuous mandatory ventilation (CMV). Now it can also refer to pressure control. In fact, the term assist/control only means that a breath may be either machine or patient triggered and thus technically does not distinguish CMV from intermittent mandatory ventilation (IMV). The term could apply to any of a large number of new modes, and thus offers little of its former descriptive utility. The most practical uses for the word control are to describe how the ventilator manages pressure, volume and flow delivery within a breath, or to describe how it manages the sequence of mandatory and spontaneous breaths to create specific breathing patterns.

Equation of motion

The interaction between the patient and ventilator during inspiration (and expiration) in terms of pressure, volume, flow and the time course of these variables is complex. Yet these variables can be adequately represented by a mathematical model called the equation of motion for the respiratory system [20–24]. The simplest version of this model assumes that the complicated respiratory system can be modeled as a single resistance (representing the artificial and natural airways) connected in series with a single compliance (representing lung and chest wall compliance):

$$\Delta P_{TR} + \Delta P_{mus} = EV + R\dot{V}$$

This equation says that the change in transrespiratory system pressure (ΔP_{TR}, i.e., the 'airway' pressure read on a ventilator) works in concert with the patient's muscle pressure (ΔP_{mus}) to generate inspiratory volume (V) and flow ($\dot{V}$) against the loads (pressures) created by elastance (E) and resistance (R; i.e., elastic load is EV and resistive load is $R\dot{V}$).

This model has two main functions in the study of mechanical ventilation: to calculate the clinically relevant lung mechanics parameters of resistance and compliance (reciprocal of elastance) given information about pressure, volume and flow; and to predict pressure, volume and flow given values for resistance and compliance. The first application is widely implemented on newer ventilators to monitor the patient's course during changing pathology or in response to treatment. The second application is the very basis of ventilator control theory and thus a key component of the proposed mode classification system. Indeed, the equation shows that for any mode, only one variable (i.e., pressure, volume or flow) can be controlled at a time, greatly simplifying our understanding of ventilator operation. We can simplify matters even more by recognizing that volume and flow are inverse functions (i.e., flow is the derivative of volume as a function of time and volume is the integral of flow) such that we only need to speak about pressure versus volume control. It is quite possible to have a very good clinical understanding of patient–ventilator interaction with nothing more than a conceptual (i.e., nonmathematical) appreciation of this model.

Mode

Perhaps no other word in the mechanical ventilation lexicon is more used and less understood than 'mode'. Intuitively, a mode of ventilation must refer to a predefined pattern of interaction between the patient and the ventilator. To be specific, the pattern of interaction is the breathing pattern. Even more specifically, the breathing pattern refers to the sequence of mandatory and spontaneous breaths. Thus, a mode description reduces to a specification of how the ventilator controls pressure, volume and flow within a breath along with a description of how breaths are sequenced. Indeed, a complete mode description should have three basic components: the control variable, the breath sequence and the targeting scheme. The outline in Box 1 defines the classification scheme proposed for modes of mechanical ventilation. Specific terms used in the outline are defined in the Appendix. As mentioned previously, the scheme is scalable in that a mode may be described in increasing detail using one, two or all three levels as appropriate for the situation. The following are some specific guidelines for implementation.

Control variable

As it relates to mechanical ventilation, volume control means that inspired volume, as a function of time, is predetermined before the breath begins. By contrast, pressure control means that inspiratory pressure as a function of time is predetermined. 'Predetermined' in this sense means that either pressure or volume is constrained to a specific mathematical form (e.g., constant or time varying such as a ramp or sinusoid). The control variable is the variable that the ventilator uses as a feedback signal to control inspiration (i.e., pressure, volume, flow and sometimes time). One way to view this is that for simple volume and pressure control modes, if the peak inspiratory pressure remains constant as the load experienced by the ventilator changes, then the control variable is pressure. If the peak pressure changes as the load changes but tidal volume remains constant, then the control variable is volume. Volume control implies flow control and vice versa, but it is possible to distinguish the two on the basis of which signal is used for feedback control. Some primitive ventilators cannot maintain either constant peak pressure or tidal volume and thus control only inspiratory and expiratory times (i.e., they may be called time controllers).

Box 1. A three-level mode classification scheme.

- Control variable
  - Volume
  - Pressure
- Breath sequence
  - Continuous mandatory ventilation
  - Intermittent mandatory ventilation
  - Continuous spontaneous ventilation
- Targeting scheme
  - Set-point
  - Auto-set-point
  - Servo
  - Adaptive
  - Optimal
  - Intelligent control

Adapted with permission from [18].

Breath sequence

The abbreviation CMV has been used to mean a variety of things by ventilator manufacturers. The most logical usage in this classification system is to represent CMV as part of a continuum from full ventilatory support to unassisted breathing. The abbreviation IMV has a long history of consistent use to mean 'intermittent mandatory ventilation' (i.e., a combination of mandatory and spontaneous breaths). However, the development of the 'active exhalation valve' and other innovations has made it possible for the patient to breathe spontaneously during a mandatory breath. This is primarily a feature used to help ensure synchrony between the ventilator and patient in the event that the mandatory breath parameters (e.g., preset inspiratory time, pressure, volume or flow) do not match the patient's inspiratory demands. This blurs the historical distinction between CMV and IMV. The key difference now between CMV and IMV is that with CMV, the clinical intent is to make every inspiration a mandatory breath, whereas with IMV the clinical intent is to partition ventilatory support between mandatory and spontaneous breaths. This means that during CMV, if the patient makes an inspiratory effort after a mandatory inspiration cycles off, another mandatory breath is triggered. Thus, if the operator decreases the ventilatory rate (often considered to be a safety 'backup' rate in the event of apnea), the level of ventilatory support is unaffected so long as the patient continues triggering mandatory breaths at the same rate (i.e., each breath is assisted to the same degree). With IMV, the rate setting directly affects the number of mandatory breaths and hence the level of ventilatory support (assuming that spontaneous breaths are not assisted to the same degree as mandatory breaths; originally, spontaneous breaths could not be assisted during IMV). CMV is normally considered a method of full ventilatory support while IMV is usually viewed as a method of partial ventilatory support (e.g., for weaning). Thus, for classification purposes, if spontaneous breaths are not allowed between mandatory breaths the breath sequence is CMV, otherwise the sequence is IMV. Given that almost every ventilator may be patient triggered, it is no longer necessary to add an S (as in SIMV) to designate synchronized IMV (i.e., the patient may trigger mandatory breaths). Such usage was important in the early days of mechanical ventilation but is an anachronism now.

There has been no consistent abbreviation to signify a breathing pattern composed of all spontaneous breaths. However, the logical progression would be from CMV to IMV to continuous spontaneous ventilation (CSV).

Targeting scheme

The targeting scheme type is a categorization of the feedback control function of the ventilator. As shown in Box 1, six different systems are commercially available. These targeting schemes are defined in Table 1 and again in the Appendix. Specifying the targeting scheme allows us to go beyond the five basic ventilatory patterns to distinguish between modes that look nearly identical on a graphics monitor and present conceptual problems when trying to differentiate them. For example, it might be difficult to appreciate the difference between pressure support

Table 1. Targeting schemes used in current mechanical ventilators.

Targeting scheme	Characteristics	Example mode description	Example mode name	Example ventilator
Set-point	The output of the ventilator automatically matches a constant operator preset input value. Multiple set-points are possible	Mandatory breaths are pressure controlled and time cycled according to the operator set values for peak inspiratory pressure and frequency	PC-IMV	Bird V.I.P.
Dual	The ventilator selects which operator-adjusted targets are enforced at the moment	Inspiration starts out in pressure control and switches to volume control Inspiration starts out in volume control and switches to pressure control	Volume Assured Pressure Support P_{max}	Bird 8400ST Dräger Evita 4
Servo	The output of the ventilator automatically follows a varying input	The instantaneous value of pressure is proportional to the instantaneous volume and/or flow generated by the patient	Proportional Assist Automatic Tube Compensation	Puritan Bennett 840 Dräger Evita 4
Adaptive	One target of the ventilator is automatically adjusted to achieve another target as the patient's condition changes	Mandatory breaths are pressure controlled and the pressure target is automatically adjusted between breaths to achieve the preset tidal volume Inspiratory time is adjusted to maintain I:E = 1:2 as patient breathing frequency changes	Pressure Regulated Volume Control AutoFlow Adaptive I-Time	Maquet Servo-i Dräger Evita XL VersaMed *i*Vent
Optimal	One target of the ventilator is automatically adjusted to optimize another target according to some model of system behavior whose output can be maximized or minimized dynamically	Each breath is pressure controlled; pressure target is automatically adjusted between breaths (using ventilatory mechanics measurements) in such a way that the work of breathing is minimized	Adaptive Support Ventilation	Hamilton Galileo
Intelligent	Targets are automatically adjusted according to a rule-based expert system	The inspiratory pressure for spontaneous breaths is automatically adjusted to maintain appropriate breathing frequency, tidal volume and end-tidal CO_2 depending on the type of patient	SmartCare	Dräger Evita 4

I:E: Inspiratory time:expiratory time; PC-IMV: Pressure-control intermittent mandatory ventilation.
Adapted with permission from [18].

and volume support on a Maquet Servo-i ventilator. The author would suggest these simple descriptions: pressure support is pressure controlled (PC)-CSV with set-point control of inspiratory pressure. Volume support is PC-CSV with adaptive control of inspiratory pressure. Assuming that you know the definitions of these words and acronyms (and they are explicitly defined in the Appendix), you can immediately understand how different the modes are. Your attention would also be directed to the clinical implications for the patient (e.g., what settings are required). Specifying the targeting scheme also allows the clinician to see that something like Dräger's AutoFlow feature is not just a 'supplement' or 'extra setting' as the operator's manual would have you believe, but indeed creates a whole new mode. For example, operating the Dräger Evita 4 in CMV yields volume controlled (VC)-CMV with set-point control of inspiratory volume and flow. However, activating AutoFlow when CMV is set (i.e., CMV + AutoFlow) yields PC-CMV with adaptive control of inspiratory pressure and vastly different clinical ramifications for the patient. Indeed, these two modes are about as different as any two modes can be.

How to use the system

This three-level mode specification provides the scalability required in practical applications. Knowing the control variable and breath sequence allows us to classify any mode into one of only five categories or breathing patterns:

- Volume-control continuous mandatory ventilation (VC-CMV)
- Volume-control intermittent mandatory ventilation (VC-IMV)
- Pressure-control continuous mandatory ventilation (PC-CMV)
- Pressure-control intermittent mandatory ventilation (PC-IMV)
- Pressure-control continuous spontaneous ventilation (PC-CSV)

Adding the targeting scheme allows for more detailed descriptions as may be needed when attempting to optimize patient care, teaching modes or deciding which ventilator to purchase. For example, at the bedside we may refer to a mode using only the control variable (e.g., we could say the patient was switched from volume control to pressure control to improve synchrony). To distinguish among similar modes and brand names we would

Table 2. Specifications for some of the modes found on the Dräger Evita XL ventilator.

Dräger mode name	Breathing pattern	Mandatory breaths†				Spontaneous breaths			
		Target scheme	*Trigger‡*	*Target§*	*Cycle*	*Target scheme*	*Trigger*	*Target*	*Cycle*
CMV	VC-CMV	Set-point	T	F, V	T	NA	NA	NA	NA
CMV + AutoFlow	PC-CMV	Adaptive	T, F	P	T	NA	NA	NA	NA
CMV + Pressure Limited Ventilation	VC-CMV	Dual	T, F	F, V, P	T	NA	NA	NA	NA
SIMV	VC-IMV	Set-point	T, F	F, V	T	Set-point	P	P	P
PCV+	PC-IMV	Set-point	T, F	P	T	Set-point	F	P	F
SIMV + AutoFlow	PC-IMV	Adaptive	T, F	P	T	Set-point	P	P	P
CPAP	PC-CSV	NA	NA	NA	NA	Set-point	P	P	P
Pressure Support	PC-CSV	NA	NA	NA	NA	Set-point	F	P	F

†The patient can take spontaneous breaths during mandatory breaths with PCV+ and AutoFlow but not with Pressure Limited Ventilation.
‡Flow trigger may be turned off. When off, mandatory breaths cannot be triggered but spontaneous breaths are automatically pressure triggered with factory set sensitivity.
§Volume targeting occurs if inspiratory time set longer than tidal volume/flow. Volume target may occur for any volume-controlled breath.
CMV: Continuous mandatory ventilation (all breaths are mandatory); CPAP: Continuous positive airway pressure; CSV: Continuous spontaneous ventilation (all breaths are spontaneous); F: Flow; IMV: Intermittent mandatory ventilation (spontaneous breaths between mandatory breaths); NA: Not available; P: Pressure; PC: Pressure controlled; PCV: Pressure-controlled ventilation; SIMV: Synchronized intermittent mandatory ventilation; T: Time; V: Volume; VC: Volume controlled.

use the other components (e.g., we could say that pressure regulated volume control is the same as CMV-AutoFlow because they are both forms of PC-CMV with adaptive pressure targeting schemes). Table 2 gives an example of how this system would be used to describe some of the modes available on the Dräger Evita XL ventilator.

Expert commentary & five-year view

Ventilator manufacturers and the respiratory care academic community have not yet adopted a standardized system for classifying and describing modes of ventilation. The International Standards Organization and Integrating the Healthcare Enterprise groups are working on such standards and their efforts may be informed by this article and previous work. In the next 5 years, we can expect modes of ventilation to continue evolving more complex targeting schemes. These schemes will rely on more complex monitoring than simply pressure, volume and flow signals to include volumetric CO_2 and pulse oximetry. These extra signals will allow automation of many procedures that clinicians currently perform, such as selecting minute ventilation based on patient size, automatic adjustment of inspired oxygen concentration and optimizing positive end expiratory pressure levels. We can also expect ventilators to automate protocols not only for weaning (e.g., SmartCare/PS™) but also for initiation and maintenance of ventilatory support. Modes will allow adaptive interaction between mandatory and spontaneous breaths and the spontaneous breaths will be assisted in ways that optimize patient–ventilator synchrony (e.g., proportional assist ventilation or neurally adjusted ventilatory support). Along with these advances in automation, the need to understand ventilator operation will also escalate. A control scheme is only as good as its input signals and its effectiveness is limited to how well its model fits the reality of the patient's current condition. Thus, clinicians must understand both how ventilators get their information and how they react to it in order to make sure they do not automatically take us down the wrong road.

Financial & competing interests disclosure

Robert L Chatburn has received compensation for consulting work from the American Association for Respiratory Care, Dräger, Hamilton, CareFusion, Covidien, Newport, IngMar and Radiometer America. He has received grants from Breathe Technologies and Alpha-1 Antitrypsin Foundation. The author has no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed.

No writing assistance was utilized in the production of this manuscript.

Key issues

- A standardized vocabulary and taxonomy are needed to fully understand the scope of the capabilities of mechanical ventilators.
- Modes of ventilation can be classified according to three criteria: the control variable, the sequence of mandatory and spontaneous breaths, and the targeting scheme.
- The control variable (pressure or volume) is what the ventilator uses as a feedback signal to manipulate inspiration.
- A spontaneous breath is one in which inspiration is triggered and cycled by the patient.
- A mandatory breath is one in which inspiration is triggered and/or cycled by the ventilator.
- A targeting scheme is a feedback control system used by a mechanical ventilator to deliver a specific ventilatory pattern. The six basic targeting schemes currently available are set-point, dual, servo, adaptive, optimal and intelligent.

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Appendix: glossary

- **Active exhalation valve:** a feature on some ventilators that allows the patient to breathe spontaneously during a mandatory (i.e., time-triggered and time-cycled) pressure-controlled breath. This definition could be extended to dual-targeting schemes for which inspiration starts out as volume control but switches to pressure control with flow cycling if the patient makes a sufficient inspiratory effort.
- **Adaptive targeting scheme:** feedback control system that allows the ventilator to set some (or conceivably all) of the targets in response to varying patient conditions. The most common example is adaptive pressure targeting (e.g., Pressure-Regulated Volume Control mode on the Maquet Servo-i ventilator) where a static inspiratory pressure is targeted within a breath (i.e., pressure-controlled inspiration), but this target is automatically adjusted by the ventilator between breaths to achieve an operator set tidal volume target.
- **Airway pressure release ventilation:** a form of pressure-control intermittent mandatory ventilation with an active exhalation valve (i.e., unrestricted spontaneous breathing), using I:E ratios much greater than 1:1 and usually relying on short expiratory times/gas trapping to maintain end expiratory lung volume rather than a preset positive end expiratory pressure (PEEP). This is in contrast to bilevel positive airway pressure which is also pressure-control intermittent mandatory ventilation but with I:E ratios closer to 1:1, expiratory times that do not create significant gas tapping and preset PEEP levels above zero.
- **Assisted breath:** a breath during which all or part of the inspiratory (or expiratory) flow is generated by the ventilator doing work on the patient. In simple terms, if the airway pressure rises above end expiratory pressure during inspiration, the breath is assisted (as in the pressure support mode). It is also possible to assist expiration by dropping airway pressure below end expiratory pressure (such as Automatic Tube Compensation on the Dräger Evita 4 ventilator). By contrast, spontaneous breaths during continuous positive airway pressure are unassisted because the ventilator attempts to maintain a constant airway pressure during inspiration.
- **Asynchrony (dyssynchrony):** regarding the timing of a breath, asynchrony means triggering or cycling of an assisted breath that either leads or lags the patient's inspiratory effort. Regarding the size of a breath, asynchrony means the inspiratory flow or tidal volume does not match the patient's demand. Asynchrony may lead to increased work of breathing and discomfort.
- **Automatic Tube Compensation:** a feature that allows the operator to enter the size of the patient's endotracheal tube and have the ventilator calculate the tube's resistance and then generate just enough pressure (in proportion to inspiratory or expiratory flow) to compensate for the added resistive load (see servo targeting scheme).
- **Autotrigger (sometimes mistakenly called 'autocycling'):** a condition in which the ventilator repeatedly triggers itself because the sensitivity is set too high. For pressure triggering, the ventilator may autotrigger due to a leak in the system dropping airway pressure below a pressure trigger threshold. When sensitivity is set too high, even the heartbeat can cause inadvertent triggering.
- **Breath:** a positive change in airway flow (inspiration) paired with a negative change in airway flow (expiration), associated with ventilation of the lungs. This definition excludes flow changes caused by hiccups or cardiogenic oscillations. However, it allows the superimposition of, for example, a spontaneous breath on a mandatory breath or vice versa. The flows are paired by size, not necessarily by timing. For example, in airway pressure release ventilation there is a large inspiration (transition from low pressure to high pressure), possibly followed by a few small inspirations and expirations, followed finally by a large expiration (transition from high pressure to low pressure). These comprise several small spontaneous breaths superimposed on one large mandatory breath.
- **Breathing pattern:** a sequence of breaths (continuous mandatory ventilation [CMV], intermittent mandatory ventilation [IMV] or continuous spontaneous ventilation [CSV]) with a designated control variable (volume, pressure or dual control) for the mandatory breaths (or the spontaneous breaths for CSV).
- **Continuous mandatory ventilation (CMV):** commonly known as 'assist/control'; all breaths are mandatory unless there is provision for spontaneous breaths during mandatory breaths (i.e., using a so-called active exhalation valve); the defining characteristic is that spontaneous breaths are not permitted between mandatory breaths because an inspiratory effort after a mandatory breath triggers another mandatory breath.
- **Control variable:** the variable (i.e., pressure or volume) that the ventilator uses as a feedback signal to manipulate inspiration. For simple set-point control, the control variable can be identified as follows: if the peak inspiratory pressure remains constant as the load experienced by the ventilator changes, then the control variable is pressure. If the peak pressure changes as the load changes but tidal volume remains constant, then the control variable is volume. Volume control implies flow control and vice versa, but it is possible to distinguish the two on the basis of which signal is used for feedback control. Some primitive ventilators cannot maintain either constant peak pressure or tidal volume and thus control only inspiratory and expiratory times (i.e., they may be called time controllers).

- **Continuous spontaneous ventilation (CSV):** all breaths are spontaneous.
- **Cycle:** to end the inspiratory time (and begin expiratory flow).
- **Cycle variable:** the variable (usually pressure, volume, flow or time) that is used to end inspiration (and begin expiratory flow).
- **Dual targeting scheme:** feedback control system that allows the ventilator to switch between volume control and pressure control during a single inspiration. Control can switch from volume to pressure (e.g., P_{max} on the Dräger Evita 4) or from pressure to volume (e.g., Volume-Assured Pressure Support on Bird 8400).
- **Dynamic compliance:** the slope of the pressure–volume curve drawn between two points of zero flow (e.g., at the start and end of inspiration).
- **Dynamic hyperinflation:** the increase in lung volume that occurs whenever insufficient exhalation time prevents the respiratory system from returning to its normal resting end expiratory equilibrium volume between breath cycles.
- **Elastic load:** the pressure difference applied across a system (e.g., a container) that sustains the system's volume relative to some reference volume, and/or the amount of its compressible contents relative to some reference amount (for a linear system: elastance × volume, or volume/compliance; for a container, the overall effective elastance [compliance] includes the elastances [compliances] of its structural components and the compressibility of the fluid [gas or liquid] within it).
- **Equation of motion for the respiratory system:** a relation among pressure difference, volume and flow that describes the mechanics of the respiratory system. The simplest and most useful form is a differential equation with constant coefficients describing the respiratory system as a single deformable compartment including the lungs and chest wall:

$$\Delta P_{TR} + \Delta P_{mus} = EV + R\dot{V}$$

where:

ΔP_{TR} = the change in transrespiratory pressure difference (i.e., airway opening pressure minus body surface pressure), measured relative to end expiratory pressure. This is the pressure generated by a ventilator (ΔP_{vent}) during an assisted breath.

ΔP_{mus} = ventilatory muscle pressure difference: the theoretical chest wall transmural pressure difference that would produce movements identical to those produced by the ventilatory muscles during breathing maneuvers (positive during inspiratory effort, negative during expiratory effort).

V = volume change relative to functional residual capacity

$\dot{V}$ = flow, the first derivative of volume with respect to time

E = elastance (inverse of compliance; E = 1/C)

For the purposes of classifying modes of mechanical ventilation the equation is often expressed as:

$$\Delta P_{vent} + \Delta P_{mus} = EV + R\dot{V}$$

where:

ΔP_{vent} = the transrespiratory pressure difference generated by the ventilator during an assisted breath.

- **Expiratory flow time:** the period from the start of expiratory flow to the instant when expiratory flow stops.
- **Expiratory pause time:** the period from cessation of expiratory flow stops to the start of inspiratory flow.
- **Expiratory time:** the period from the start of expiratory flow to the start of inspiratory flow; expiratory time equals expiratory flow time plus expiratory pause time.
- **Feedback control:** closed-loop control accomplished by using the output as a signal that is fed back (compared) to the operator-set input. The difference between the two is used to drive the system towards the desired output (i.e., negative feedback control). For example, pressure-controlled modes use airway pressure as the feedback signal to manipulate gas flow from the ventilator to maintain an inspiratory pressure set-point.
- **Flow control:** maintenance of an invariant inspiratory flow waveform despite changing respiratory system mechanics.
- **Flow cycle:** inspiration ends and expiratory flow starts when inspiratory flow reaches a preset threshold.
- **Flow target:** inspiratory flow reaches a preset value that may be maintained before inspiration cycles off.
- **Flow trigger:** assisted inspiration starts when inspiratory flow due to patient inspiratory effort reaches a preset threshold.

- **Inspiratory flow time:** the period from the start of inspiratory flow to the cessation of inspiratory flow.
- **Inspiratory pause time:** the period from the cessation of inspiratory flow to the start of expiratory flow.
- **Inspiratory time:** the period from the start of inspiratory flow to the start of expiratory flow. Inspiratory time equals inspiratory flow time plus inspiratory pause time.
- **Intelligent control:** a ventilator targeting scheme that uses artificial intelligence programs.
- **Intermittent mandatory ventilation (IMV):** spontaneous breaths are permitted between mandatory breaths. When the mandatory breath is patient triggered, it is commonly referred to as synchronized IMV (or SIMV). Three common variations of IMV are: mandatory breaths are always delivered at the set frequency; mandatory breaths are delivered only when the spontaneous breath frequency falls below the set frequency; and mandatory breaths are delivered only when the spontaneous minute ventilation (i.e., product of spontaneous breath frequency and spontaneous breath tidal volume) drops below a preset or computed threshold (also known as mandatory minute ventilation).
- **Load:** the pressure required to generate inspiration (see 'elastic load' and 'resistive load').
- **Mandatory breath:** a breath for which either the timing and/or size is controlled by the ventilator, that is, the machine triggers and/or cycles inspiration.
- **Mandatory minute ventilation:** a mode in which the ventilator monitors the exhaled minute ventilation as a conditional variable. As long as the patient either triggers mandatory breaths or generates his own spontaneous breaths often enough to maintain a preset minute ventilation, the ventilator does not interfere by delivering mandatory breaths. However, if the exhaled minute ventilation falls below the operator set value, the ventilator will trigger mandatory breaths or increase the pressure limit until the target is reached.
- **Mechanical ventilator:** an automatic machine designed to provide all or part of the work required to move gas into and out of the lungs to satisfy the body's respiratory needs.
- **Mode of ventilation:** a specific combination of control variable, breath sequence and targeting scheme.
- **Neurally adjusted ventilatory assist:** a form of pressure control using a servo targeting scheme in which the controller sets airway pressure to be proportional to patient effort based on the voltage recorded from diaphragmatic activity from sensors embedded in an orogastric tube:

  $P(t)+KEdi(t)$

  where:
  P(t) = inspiratory pressure relative to end expiratory pressure as a function of time, t
  K = the NAVA support level (an amplification factor)
  Edi(t) = the electrical signal from the diaphragm as a function of time

The operator inputs the constant of proportionality between voltage and pressure (gain). The controller then sets airway pressure to equal the product of gain and the Edi.

- **Optimum targeting scheme:** feedback control system that automatically adjusts the targets of the ventilatory pattern to either minimize or maximize some overall performance characteristic.
- **Partial ventilatory support:** the ventilator and the respiratory muscles each provide some of the work of breathing; muscle pressure adds to ventilator pressure in the equation of motion.
- **PC-CMV:** pressure-controlled continuous mandatory ventilation.
- **PC-CSV:** pressure-controlled continuous spontaneous ventilation.
- **PC-IMV:** pressure-controlled intermittent mandatory ventilation.
- **Pressure control:** a general category of ventilator modes for which inspired pressure as a function of time is predetermined before the breath begins. For simple pressure control modes (e.g., pressure support), pressure is the independent variable and volume and flow are the dependent variables in the equation of motion for the respiratory system.
- **Pressure cycle:** inspiration ends (i.e., expiratory flow starts) when airway pressure reaches a preset threshold.
- **Pressure support:** pressure support is a mode using a set-point targeting scheme in which all breaths are pressure or flow triggered, pressure targeted and flow cycled.

- **Pressure target:** inspiratory pressure reaches a preset value and is maintained before inspiration cycles off.
- **Pressure trigger:** inspiration starts when airway pressure reaches a preset threshold.
- **Proportional assist ventilation (PAV):** a form of pressure control using a servo targeting scheme based on the equation of motion for the respiratory system in the form:

$$P(t) = K_1 V(t) + K_2 \dot{V}(t)$$

where inspiratory pressure relative to end expiratory pressure as a function of time *P(t)* is the sum of two components. The first is the 'volume assist' or the amount of elastic load supported, that is, K_1 × volume as a function of time *V(t)*. The second component is the 'flow assist' or the amount of resistive load supported, thus, K_2 × flow as a function of time, $\dot{V}(t)$. The values of K_1 and K_2 are preset by the operator and represent the supported elastance and resistance, respectively, whereas volume and flow are generated by the patient. Because volume and flow are initiated by the patient's inspiratory effort created by muscle pressure, P_{mus}, the pressure generated by PAV can be thought of as an amplifier of P_{mus}.

- **Ramp:** a mathematical function whose value rises at a constant rate.
- **Resistive load:** the pressure difference applied across a system (e.g., a container) that is related to a rate of change of the system's volume and/or the flow of fluid within or through the system (for a linear system: resistance × flow, or, resistance × rate of change of volume; for a container, the effective resistance includes the mechanical [usually viscous] resistances of its structural components and the flow resistance of the fluid [gas or liquid] within it).
- **Sensitivity:** the sensitivity setting of the ventilator is a threshold value for the trigger variable which, when met, starts inspiration. In other words, the sensitivity is the amount the trigger variable must change to start inspiratory flow.
- **Servo targeting:** feedback control system for which the output of the ventilator automatically follows a varying input. For example, the Automatic Tube Compensation feature on the Dräger Evita 4 ventilator tracks flow and forces pressure to be equal to flow multiplied by a constant (representing endotracheal tube resistance).
- **Set-point targeting:** feedback control system for which the operator sets specific target values and the ventilator attempts to deliver them.
- **Sinusoid:** a mathematical function with a magnitude that varies as the sine of an independent variable (e.g., time).
- **Spontaneous breath:** a breath for which both the timing and size are controlled by the patient. That is, the patient both triggers and cycles inspiration.
- **Synchronized IMV:** IMV in which mandatory breath delivery is coordinated with patient effort. A synchronized mandatory breath is either patient triggered and machine cycled or machine triggered and patient cycled.
- **Target:** a predetermined goal during inspiration or expiration (e.g., inspiratory flow or average tidal volume).
- **Targeting scheme:** feedback control system used by a mechanical ventilator to deliver a specific ventilatory pattern. The targeting scheme is a key component of a mode of ventilation.
- **Tidal pressure:** the change in transalveolar pressure (i.e., pressure in the alveolar region minus pressure in the pleural space) associated with the inhalation or exhalation of a tidal volume.
- **Tidal volume:** the volume of gas, either inhaled or exhaled, during a breath.
- **Time constant:** the time at which an exponential function attains 63% of its steady state value in response to a step input; the time necessary for inflated lungs to passively empty by 63%; the time necessary for the lungs to passively fill 63% during pressure controlled ventilation with a rectangular pressure waveform. The time constant for a passive mechanical system is calculated as the product of resistance and compliance and has units of time (usually expressed in seconds).
- **Total cycle time:** same as ventilatory period, the sum of inspiratory time and expiratory time.
- **Total PEEP:** the sum of autoPEEP and intentionally applied PEEP or continuous positive airway pressure.
- **Total ventilatory support:** the ventilator provides all the work of breathing; muscle pressure in the equation of motion is zero.
- **Transairway pressure difference:** pressure at the airway opening minus pressure in the lungs (i.e., alveolar pressure).
- **Transalveolar pressure difference:** pressure in the lungs minus pressure in the pleural space. Equal to transpulmonary pressure difference only under static conditions.

- **Transchest wall pressure difference:** pressure in the pleural space minus pressure on the body surface.
- **Transpulmonary pressure difference:** pressure at the airway opening minus pressure in the pleural space.
- **Transrespiratory pressure difference:** pressure at the airway opening minus pressure on the body surface; equal to the sum of transairway pressure difference plus transalveolar pressure difference plus transchest wall pressure difference.
- **Transthoracic pressure:** pressure in the lungs minus pressure on the body surface; equal to the sum of transalveolar pressure difference plus transchest wall pressure difference.
- **Trigger:** to start inspiration.
- **VC-CMV:** volume-controlled continuous mandatory ventilation.
- **VC-IMV:** volume-controlled intermittent mandatory ventilation.
- **Ventilatory period:** (also called total cycle time or total breath cycle) the time from the start of inspiratory flow of one breath to the start of inspiratory flow of the next breath; inspiratory time plus expiratory time; the reciprocal of ventilatory frequency.
- **Volume control:** a general category of ventilator modes for which inspired volume (or flow), as a function of time, is predetermined before the breath begins. For simple volume control modes (e.g., assist/control) volume is the independent variable and pressure is the dependent variable in the equation of motion for the respiratory system.
- **Volume cycle:** inspiration ends (i.e., expiratory flow starts) when inspiratory volume reaches a preset threshold (i.e., tidal volume).
- **Volume target:** a preset value (i.e., tidal volume) that the ventilator is set to attain before inspiration cycles off.
- **Volume trigger:** assisted inspiration starts when inspiratory volume (i.e., small initial volume due to patient inspiratory effort) reaches a preset threshold.
- **Work of breathing:** the general definition of work is the integral of pressure with respect to volume during an assisted inspiration. There are two general components of work related to mechanical ventilation. One kind is the work performed by the ventilator on the patient, which is reflected by a positive change in airway pressure above baseline during inspiration. The second component is the work the patient does on the ventilator to trigger inspiration, which is reflected by a negative change in airway pressure below baseline during inspiration.