Four Truths of Mechanical Ventilation and the Ten-Fold Path to Enlightenment

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Abstract:

The Four Truths
1. The truth of confusion
2. The truth of the origin of confusion
3. The truth of the cessation of confusion
4. The truth of the path leading to the cessation of confusion

The 10-Fold Path
1. A breath is one cycle of positive flow (inspiration) and negative flow (expiration) defined in terms of the flow-time curve.
2. A breath is assisted if the ventilator does work on the patient.
3. A ventilator assists breathing using either pressure control or volume control based on the equation of motion for the respiratory system.
4. Breaths are classified by the criteria that trigger (start) and cycle (stop) inspiration
5. Trigger and cycle events can be initiated by the patient or the machine.
6. Breaths are classified as spontaneous or mandatory based on both the trigger and cycle events.
7. There are 3 breath sequences: Continuous mandatory ventilation (CMV), Intermittent Mandatory Ventilation (IMV), and Continuous Spontaneous Ventilation (CSV).
8. There are 5 basic ventilatory patterns: VC-CMV, VC-IMV, PC-CMV, PC-IMV, and PC-CSV:
9. Within each ventilatory pattern there are several variations that can be distinguished by their targeting scheme(s).
10. A mode of ventilation is classified according to its control variable, breath sequence, and targeting scheme(s).

Keywords: Breath. Trigger, Cycle, Breath sequences, Ventilatory patterns, Mode of ventilation

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The Four Truths

1. The truth of confusion

There are about 500 unique names of modes on ventilators used in the United States alone, representing only about 50 different mode types. [1]

2. The truth of the origin of confusion

There is no consistency among manufacturers in naming or describing modes. [2]

3. The truth of the cessation of confusion

Confusion ends with a standardized vocabulary used to create a mode taxonomy. [3]

4. The truth of the path leading to the cessation of confusion. [4]

Ten basic concepts explain key vocabulary terms in the context of ventilator design principles leading to a full taxonomy of modes

The 10-Fold Path [4]

1. A breath is one cycle of positive flow (inspiration) and negative flow (expiration) defined in terms of the flow-time curve.

A breath is defined in terms of the flow-time curve (Figure 1). By convention, positive flow (i.e., values of flow above zero) is designated as inspiration. Negative flow (values below zero) indicates expiration.

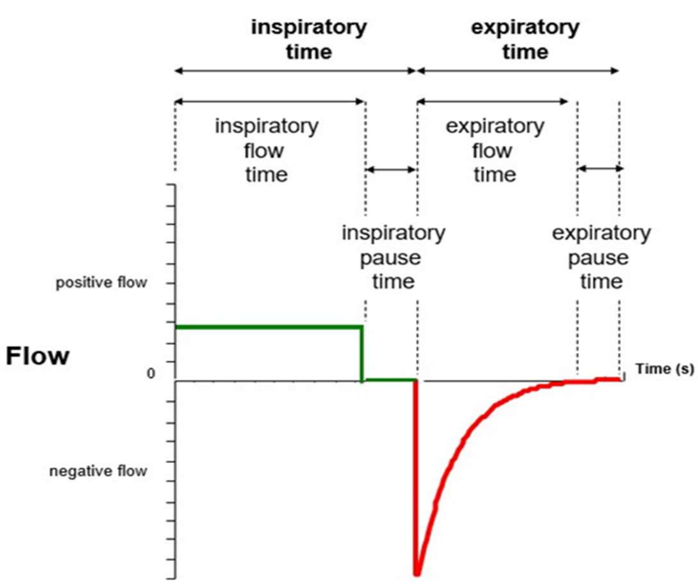

Figure 1: Defining a breath in terms of the flow-time waveform.

2. A breath is assisted if the ventilator does work on the patient.

An assisted breath is one for which the ventilator does some portion of the work of breathing. Work is accomplished when volume is delivered under pressure. For example, in the simplest case, if inflation is achieved with a constant pressure then work is the product of inspiratory pressure times tidal volume. An unassisted breath is one for which the ventilator simply provides flow at the rate required by the patient's inspiratory effort and pressure stays constant throughout the breath.

3. A ventilator assists breathing using either pressure control or volume control based on the equation of motion for the respiratory system.

The theoretical framework for understanding control variables is the equation of motion for the passive respiratory system

$$P(t) = EV(t) + R\dot{V}(t) \quad 1$$

This equation relates pressure (P), volume (V) and flow ($\dot{V}$) as continuous functions of time (t) with the parameters of elastance ($E = \Delta P/\Delta V$) and resistance ($R = \Delta P/\Delta \dot{V}$). If any one of the functions (P, V, or $\dot{V}$) are predetermined, the other two may be derived by solving Equation 1 (using calculus because this is a differential equation). The *control variable* refers to the function that is controlled (predetermined) during a breath (inspiration). The pressure, volume, and flow waveforms displayed on a ventilator are simply graphs of the equation of motion (Figure 2).

Volume control (Figure 2) means that *both* volume and flow are preset prior to inspiration. Setting tidal volume is a necessary but not sufficient criterion for declaring volume control because some modes of pressure control allow the operator to set a *target* tidal volume but allow the ventilator to determine the flow (see adaptive targeting schemes below). Similarly, setting flow is also a necessary but not sufficient criterion; some pressure control modes allow the operator to set the inspiratory flow, but the tidal volume depends on the inspiratory pressure target and respiratory system mechanics.

Pressure control (Figure 2) means that inspiratory pressure as a function of time is predetermined. In practice, this currently means that either preset to a achieve a particular waveform, e.g., P(t) = constant, or it is set to be proportional to patient inspiratory effort measured by various means (e.g., P(t) = NAVA level × Edi(t); see targeting schemes below). In a passive patient, after setting the form of the pressure function, volume and flow depend on E and R.[5]

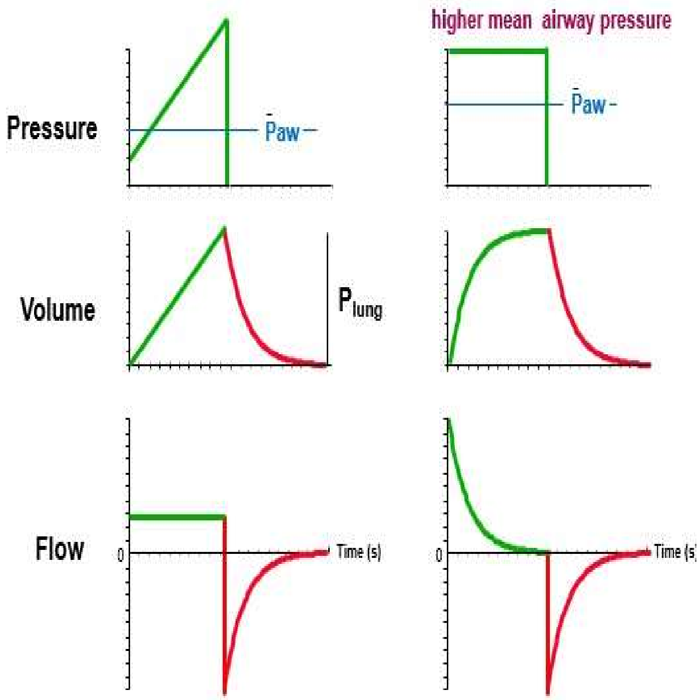

Figure 2
Idealized waveforms for volume control and pressure control with the same tidal volume and inspiratory time

4. Breaths are classified by the criteria that trigger (start) and cycle (stop) inspiration

Inspiration starts, or is *triggered*, when a monitored variable (trigger variable) achieves a preset threshold (the trigger event). The simplest trigger variable is a preset breath frequency. Other trigger variables include a minimum level of minute ventilation, a preset apnea interval, or various indicators of inspiratory effort (e.g., changes in baseline pressure or flow or electrical signals derived from diaphragm movement).

Inspiration stops, or is *cycled* off, when a monitored variable (cycle variable) achieves a preset threshold (cycle event). The simplest cycle variable is a preset inspiratory time. Other cycle variables include pressure (e.g., peak airway pressure), volume (e.g., tidal volume), flow (e.g., percent of peak inspiratory flow) and electrical signals derived from diaphragm movement.

5. Trigger and cycle events can be initiated by the patient or the machine.

Inspiration can be patient triggered or patient cycled by a signal representing inspiratory effort (e.g., the electrical signal derived from diaphragm activity as with Neurally Adjusted Ventilatory Assist [6] or a calculated estimate of P_{mus}[7]). The ventilator may also be triggered or cycled by the volume or flow generated by the patient's ventilatory muscles. Furthermore, the ventilator can be triggered or cycled solely by the patient's passive respiratory system mechanics (E and R).[8] For example, an increase in E or R in some modes will increase airway pressure beyond the alarm threshold and cycle inspiration.

Patient triggering means starting inspiration based on a patient signal independent of a machine trigger signal.

Machine triggering means starting inspiratory flow based on a signal (usually time) from the ventilator, independent of a patient trigger signal.

Patient cycling means ending inspiratory time based on signals representing the patient determined components of the equation of motion, (i.e., elastance, or resistance and including effects due to inspiratory effort.

Machine cycling means ending inspiratory time independent of signals representing the patient determined components of the equation of motion.

As a further refinement, patient triggering can be defined as starting inspiration based on a patient signal occurring in a *trigger window*, independent of a machine trigger signal. A trigger window is the period comprised of the entire expiratory time minus a short "refractory" period required to reduce the risk of triggering a breath before exhalation is complete. If a signal from the patient (indicating an inspiratory effort) occurs within this trigger window, inspiration starts and is defined as a patient triggered event.

A *synchronization window* is a short period, at the end of a preset expiratory time or at the end of a preset inspiratory time, during which a patient signal may be used to synchronize the beginning or ending of inspiration to the patient's actions. If the patient signal occurs during an expiratory time synchronization window, inspiration starts and is defined as a machine triggered event initiating a mandatory breath. This is because the mandatory breath would have been time triggered regardless of whether the patient signal had appeared or not and because the distinction is necessary to avoid logical inconsistencies in defining mandatory and spontaneous breaths (see below) which are the foundation of the mode taxonomy.

Sometimes a synchronization window is used at the end of the inspiratory time of a pressure controlled, time cycled breath. If the patient signal occurs during such an inspiratory time synchronization window, expiration starts and is defined as a machine cycled event, ending a mandatory breath. Some ventilators offer the mode called Airway Pressure Release Ventilation (or something similar with a different name) that may use both expiratory and inspiratory synchronization windows.

6. Breaths are classified as spontaneous or mandatory based on both the trigger and cycle events.

A *spontaneous breath* is a breath for which the patient retains control over timing. This means that the start and end of inspiration are determined by the patient, independent of any machine settings for inspiratory time and expiratory time. That is, the patient both triggers and cycles the breath. A spontaneous breath may occur during a mandatory breath (e.g. Airway Pressure Release Ventilation). A spontaneous breath may be assisted or unassisted. Indeed, the definition of a spontaneous breath applies to normal breathing as well as mechanical ventilation. Some authors use the term spontaneous breath to refer only to unassisted breaths; but that is an unnecessary limitation that prevents the word from being used as a key term in a mode taxonomy.

A *mandatory breath* is a breath for which the patient has lost control over timing (i.e., frequency or inspiratory time). This means a breath for which the start or end of inspiration (or both) is determined by the ventilator, independent of the patient - the machine triggers and/or cycles the breath. A mandatory breath can occur during a spontaneous breath (e.g., High Frequency Jet Ventilation). A mandatory breath is, by definition, assisted.

7. There are 3 breath sequences: Continuous mandatory ventilation (CMV), Intermittent Mandatory Ventilation (IMV), and Continuous Spontaneous Ventilation (CSV).

A breath sequence is a particular pattern of spontaneous and/or mandatory breaths. The 3 possible breath sequences are: continuous mandatory ventilation, (CMV), intermittent mandatory ventilation (IMV), and continuous spontaneous ventilation (CSV). Continuous mandatory ventilation, commonly known as "Assist/Control" is a breath sequence for which spontaneous breaths **are not** possible between mandatory breaths because every patient trigger signal in the trigger window produces a machine cycled inspiration (i.e., a mandatory breath). Machine triggered mandatory breaths may be delivered at a preset frequency. Therefore, in contrast to IMV, the mandatory breath frequency may be higher than the set frequency but never below it (i.e., the set frequency is a minimum value). In some pressure control modes on ventilators with an active exhalation valve, spontaneous breaths may occur during mandatory breaths, but the defining characteristic of CMV is that spontaneous breaths are not permitted between mandatory breaths. Intermittent mandatory ventilation, commonly known as "SIMV" is a breath sequence for which spontaneous breaths **are** possible between mandatory breaths. In contrast to CMV, with IMV, the mandatory breath frequency can never be higher than the set rate (i.e., the set frequency is a maximum value) but it may be lower as is the case for IMV types 2-4 (see below).

There are 4 variations of IMV:

(1) Mandatory breaths are always delivered at the set frequency (e.g., Covidien's SIMV Volume Control). If a synchronization window is used, the actual ventilatory period for a mandatory breath may be shorter than the set period. Some ventilators will add the difference to the next mandatory period to maintain the set mandatory breath frequency (e.g., Dräger Evita XL).

(2) Mandatory breaths are suppressed when the spontaneous breath frequency rises above the set frequency (e.g., Philips Respironics BiPAP S/T mode)

(3) Mandatory breaths suppressed when the measured minute ventilation (i.e., product of breath frequency and tidal volume) is above a preset threshold (examples include Dräger's Mandatory Minute Volume Ventilation mode and Hamilton's Adaptive Support Ventilation mode).

(4) Individual mandatory breaths are suppressed if the patient's inspiratory effort is large enough to switch the control variable form volume to pressure and the cycle variable from time to flow (see dual targeting below).

8. There are 5 basic ventilatory patterns: VC-CMV, VC-IMV, PC-CMV, PC-IMV, and PC-CSV:

A ventilatory pattern is a sequence of breaths (CMV, IMV, or CSV) with a designated control variable (volume or pressure) for the mandatory breaths (or the spontaneous breaths for CSV or IMV). Thus, with 2 control variables and 3 breath sequences there are 5 possible ventilatory patterns: VC-CMV, VC-IMV, PC-CMV, PC-IMV, PC-CSV. The combination VC-CSV is not possible because volume control implies machine cycling and machine cycling makes every breath mandatory, not spontaneous (Maxim 6). Because any mode of ventilation can be associated with one and only one ventilatory pattern, the ventilatory pattern serves as a simple mode classification system.

9. Within each ventilatory pattern there are several variations that can be distinguished by their targeting scheme(s).

A target is a predetermined goal of ventilator output. Targets can be viewed as the goals of the targeting scheme Targets can be set for parameters within a breath, within-breath targets. These are the pressure, volume, or flow waveform. Examples of within-breath targets include inspiratory flow or pressure and rise time (set-point targeting), tidal volume (dual targeting) and constant of proportionality between inspiratory pressure and patient effort (servo targeting).

Targets can be set between breaths to modify the within-breath targets and/or the overall ventilatory pattern, we call this between-breath targets. These are used with more advanced targeting schemes, where targets act over multiple breaths. Examples of between-breath targets and targeting schemes include average tidal volume (for adaptive targeting), percent minute ventilation (for optimal targeting) and combined PCO_2, volume, and frequency values describing a "zone of comfort" (for intelligent targeting, e.g. SmartCare PS or IntelliVent-ASV).

A targeting scheme is the software that relates the operator set inputs and ventilator outputs to achieve a specific ventilatory pattern, usually in the form of a feedback control system. Targeting schemes are designed to make modes more robust in serving the basic goals of ventilation, i.e., safety (adequate gas exchange and lung protection), comfort (synchrony and adequate assistance with work of breathing) and liberation (i.e., minimizing the duration of ventilation). Furthermore, only one of these goals is most important for any particular patient at any specific time, simplifying the rational choice of a mode of ventilation.[9] The targeting scheme (or combination of targeting schemes) is what distinguishes one ventilatory pattern from another.

There are currently 7 basic targeting schemes that comprise the wide variety seen in different modes of ventilation. The names of the targeting schemes are associated with abbreviations (shown in parentheses):

Set-point (s): A targeting scheme for which the operator sets all the parameters of the pressure waveform (pressure control modes) or volume and flow waveforms (volume control modes).

Dual (d): A targeting scheme that allows the ventilator to switch between volume control and pressure control *during a single inspiration*.

Bio-variable (b): A targeting scheme that allows the ventilator to automatically set the inspiratory pressure or tidal volume randomly to mimic the variability observed during normal breathing.

Servo (r): A targeting scheme for which inspiratory pressure is proportional to inspiratory effort. proportional to the patient's inspiratory effort.

Adaptive (a): A targeting scheme that allows the ventilator to automatically set one target (e.g., pressure within a breath) to achieve another target (e.g., average tidal volume over several breaths).

Optimal (o): A targeting scheme that automatically adjusts the targets of the ventilatory pattern to either minimize or maximize some overall performance characteristic.

Intelligent (i): A targeting scheme that uses artificial intelligence programs such as fuzzy logic, rule based expert systems, and artificial neural networks.

10. A mode of ventilation is classified according to its control variable, breath sequence, and targeting scheme(s).

A "mode" of ventilation is simply a predetermined pattern of patient-ventilator interaction. Modes are given arbitrary names by manufacturers just like drugs are given arbitrary brand names for marketing purposes. Just as generic names are essential for learning about and using drugs, generic classifications of modes accomplish the same thing. The preceding 9 maxims create a theoretical foundation for a taxonomy of mechanical ventilation. Taxonomy is the science of classification. In short, the first step is to create a standardized set of definitions. We have refined such a vocabulary over the last 20 years (Appendix 1). Selected terms in the vocabulary are used to create a hierarchical classification system (essentially an outline) that forms the structure of the taxonomy.

The taxonomy is based on the previous 9 theoretical constructs and has 4 hierarchical levels:

Control Variable (Pressure or Volume, for the primary breath)

Breath Sequence (CMV, IMV, or CSV)

Primary Breath Targeting Scheme (for CMV or CSV)

Secondary Breath Targeting Scheme (for IMV)

The "primary breath" is either the only breath there is (mandatory for CMV and spontaneous for CSV) or it is the mandatory breath in IMV. The targeting schemes can be represented by single, lower-case letters: set-point = s, dual = d, servo = r, bio-variable = b, adaptive = a, optimal = o, intelligent = i. For example, on the Covidien PB 840 ventilator there is a mode called “A/C Volume Control”. This mode is classified as volume control, continuous mandatory ventilation with set-point targeting, represented by VC-CMVs.

Conclusions

Over the last four decades, the computerization of mechanical ventilators has resulted in an exponential increase in the number and complexity of modes of ventilation. This complexity necessitates a taxonomy for understanding and selecting appropriate modes just as a drug taxonomy is essential in pharmacology. The taxonomy itself is based on a set of definitions called a standardized vocabulary. Mastery of mechanical ventilation requires the learner to memorize the definitions, use the taxonomy to compare and contrast modes and ultimately select the mode most capable of serving the immediate goal of mechanical ventilation for a specific patient at a specific point in time.

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