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# Engineering Principles Applied to Mechanical Ventilation

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*Abstract*-**Mechanical ventilators can be understood in terms of simple physical models that have electrical analogs. These models provide the basis for designing and classifying ventilators as well as understanding ventilator-patient interactions.**
*Keywords*-Mechanical ventilation, respiratory mechanics, modes of ventilation

## INTRODUCTION

Mechanical ventilators are designed and built by engineers. Yet, all textbooks on the subject of mechanical ventilation, almost without exception, are written by and for clinicians. A communication gap exists between producers and end users of this device that causes much frustration on both sides. The purpose of this paper is to help bridge the gap by clarifying terminology and outlining the conceptual models used to design and use mechanical ventilators.

## GOALS OF MECHANICAL VENTILATION

A mechanical ventilator is an automatic machine designed to provide all or part of the work the body must produce to move gas into and out of the lungs. The act of moving air into and out of the lungs is called breathing, or, more formally, ventilation.

The simplest mechanical device we could devise to assist a person's breathing would be a hand-driven, syringe-type pump that is fitted to the person's mouth and nose using a mask. A variation of this is the self-inflating, elastic resuscitation bag. Both of these require one-way valve arrangements to cause air to flow from the device into the lungs when the device is compressed, and out from the lungs to the atmosphere as the device is expanded. These arrangements are not automatic, requiring an operator to supply the energy to push the gas into the lungs through the mouth and nose. Therefore, such devices are not considered mechanical ventilators.

Automating the ventilator so that continual operator intervention is not needed for safe, desired operation requires:

- A stable attachment (interface) of the device to the patient,
- A source of energy to drive the device,
- A control system to regulate the timing and size of breaths, and
- A means of monitoring the performance of the device and the condition of the patient.

The vast majority of ventilators used in the world provide "conventional" ventilation. This employs breathing patterns that approximate those produced by a normal spontaneously breathing person. Tidal volumes are large enough to clear the anatomical dead space during inspiration and the breathing rates are in the range of normal rates. Gas transport in the airways is dominated by convective flow and mixing in the alveoli occurs by molecular diffusion.

There is also a class of "high frequency ventilator" that delivers tidal volumes less than dead space volume at frequencies up to 15 Hz. High frequency ventilators, in theory, minimize the risk of damage to diseased lung tissue that could be caused by volumetric over distention with normal tidal volumes. While this class of ventilator has been studied a great deal over the last two decades, its use is still controversial.

It is interesting to note that modern mechanical ventilators have evolved over the last 40 years through at least five generations. First generation ventilators had relatively primitive electrical or pneumatic control circuits, were capable of only one mode of ventilation, had uncalibrated dials and no alarms. Second generation devices used simple analog electronic or fluidic control circuits, offered several modes of ventilation, and provided some basic alarms. Third generation machines are characterized by the use of digital electronics (microprocessors), for both control and operator interface functions. Fourth generation ventilators made full use of computerized operator interfaces (CRT and LCD displays). Software developments allowed integration of waveform monitoring, calculated lung mechanics and extensive system diagnostics. The current, fifth generation mechanical ventilator makes use of the "virtual instrument" operator interface design along with more advanced control software allowing for a "universal machine" that can ventilate neonatal, pediatric, and adult patients. The hardware platform seems to have stabilized and now upgrades are mainly control software and display enhancements.

## MODELS OF VENTILATOR-PATIENT INTERACTION

A ventilator is simply a machine designed to transmit applied energy in a predetermined manner to perform useful work. Ventilators are powered with energy in the form of either electricity or compressed gas. That energy is transmitted (by the ventilator's drive mechanism) in a predetermined manner (by the control circuit) to assist or replace the patient's muscular effort in performing the work of breathing (the desired output). Thus, to understand ventilators we must first understand their four mechanical characteristics:

1) Input power
2) Power conversion and transmission
3) Control system
4) Output (pressure, volume, and flow waveforms)

We can expand this simple outline to add as much detail about a given ventilator as desired.

Models of breathing mechanics provide a foundation for understanding how ventilators work. These models simplify and illustrate the relations among variables of interest. Specifically, we are interested in the pressure needed to drive gas into the airway and inflate the lungs.

The physical model of breathing mechanics most commonly used is a rigid flow conducting tube connected to an elastic compartment (Figure 1). The basic electrical model is a resistor in series with a capacitor, which may be expanded to include two lungs, the chest wall, and ventilator circuit properties (Figure 2). This model is a simplification of the actual biological respiratory system from the viewpoint of pressure (voltage), volume (charge), and flow (current), but it has been very practical.

The mathematical model that relates pressure, volume, and flow during ventilation is known as the equation of motion for the respiratory system:

$$P_{vent} + P_{mus} = E \cdot V + R \cdot \dot{V}$$

where $P_{vent}$ is the pressure generated by the ventilator, $P_{mus}$ is the pressure generated by the ventilatory muscles, $E$ is respiratory system elastance, $V$ is lung volume, $R$ is respiratory system resistance, and *Vdot* is flow (the derivative of volume with respect to time).

Pressure, volume and flow are variable functions of time, all measured relative to their end expiratory values. These values are normally: muscle pressure = 0, ventilator pressure = 0, volume = functional residual capacity, flow = 0. During mechanical ventilation, these values are: muscle pressure = 0, ventilator pressure = positive end expiratory pressure (PEEP), volume = end expiratory volume, flow = 0. Elastance and resistance are constants.

When airway pressure rises above baseline (as indicated by the ventilator's airway pressure display), inspiration is assisted. The pressure driving inspiration is called transrespiratory system pressure (Fig. 1). It is defined as the pressure at the airway opening (mouth, endotracheal tube or tracheostomy tube) minus the pressure at the body surface. Transrespiratory system pressure has two components, transairway pressure (defined as airway opening pressure minus lung pressure) and transthoracic pressure (defined as lung pressure minus body surface pressure).

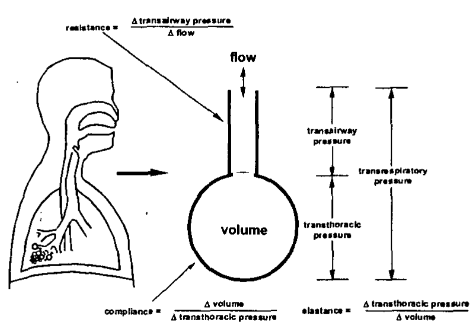


Figure 1. Pneumatic model of respiratory system.

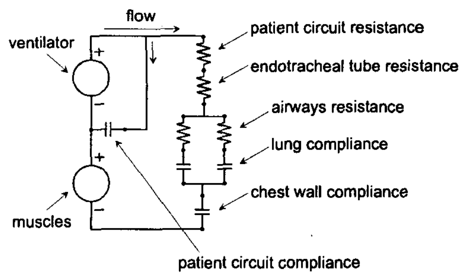


Figure 2. Electrical model of ventilator-patient system.

The equation of motion is a pivotal concept in understanding ventilators. Not only does it serve as a useful model of ventilator-patient interaction, but it also provides the basis for monitoring patient condition (in terms of the mechanical properties of elastance and resistance). All ventilators that display calculated values for elastance (or alternatively, compliance, its reciprocal) and resistance make parameter estimates using the equation of motion. In addition, the equation provides the basis for classifying ventilators in terms of their control variables. The control variable is the independent variable in the equation of motion. For example, a pressure controller maintains a consistent airway pressure waveform despite changes in elastance and resistance, with volume and flow being dependent on the pressure waveform and the mechanical properties of the respiratory system. In contrast, volume and flow controllers maintain consistent volume and flow waveforms despite changing mechanical properties, with airway pressure being the dependent variable. (Flow and volume controllers are distinguished by the feedback control signal; either volume or flow.) A ventilator can control only one variable at a time but may actually switch among them during a breath. Breath control complexity gives rise to the need to identify and describe "modes" of ventilation.

## MODES OF VENTILATION

The objective of mechanical ventilation is to assure that the patient receives the minute ventilation (tidal volume times ventilatory frequency) required to satisfy respiratory needs while not damaging the lungs, impairing circulation, or increasing the patient's discomfort. A mode of ventilation is the manner in which a ventilator achieves this objective. *A mode is any ventilatory pattern that can be uniquely identified by specifying:*

1. The breathing pattern, which includes the primary breath control variable and the breath sequence,
2. The control type, and
3. The specific control strategy.

These characteristics are detailed in Table 1. Note that ventilator manufacturers have dozens of arbitrary names for their modes, and none of them give clear definitions of all the important mode characteristics.

**Table 1.** Mode classification scheme

**I. Breathing pattern**
- A. Primary breath control variable
  - 1. Volume
  - 2. Pressure
  - 3. Dual
- B. Breath sequence
  - 1. Continuous mandatory ventilation (CMV)
  - 2. Intermittent mandatory ventilation (IMV)
  - 3. Continuous spontaneous ventilation (CSV)

**II. Control type**
- A. Set point
- B. Servo
- C. Adaptive
- D. Optimal

**III. Control strategy**
- A. Phase variables (trigger, limit, cycle)
- B. Operational logic (conditional variables, output variables, performance function)

## Breathing Pattern

### *Primary Breath Control Variable*

Specifying only the breath control variable for a mode, we can only distinguish among pressure control, volume control, and dual control modes. Often this is all we need to communicate. For example, at the bedside we might simply have to indicate that the patient's lung mechanics have become unstable and therefore the mode has been changed from volume control to dual control.

*Volume Control (VC)*

A ventilator can be classified as either a pressure, volume, or flow controller. When classifying modes of ventilation, we do not need to be so specific. Because control of volume implies control of flow and vice versa, we can refer to two basic modes of ventilation: volume control and pressure control (Fig. 3).

*Pressure Control (PC)*

Pressure control means that the airway pressure waveform is preset (for example by setting peak inspiratory pressure and end expiratory pressure). Tidal volume and inspiratory flow are then dependent on these settings and the elastance and resistance of the respiratory system.

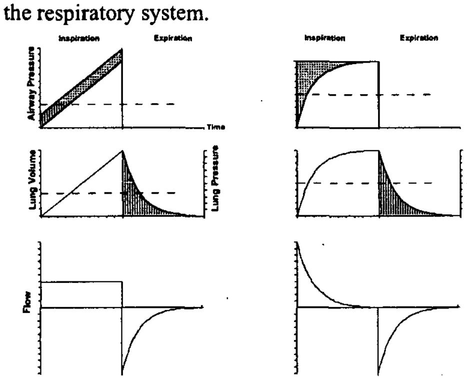


Figure 3. Waveforms for volume vs. pressure control.

*Dual Control (DC)*

There are clinical advantages and disadvantages to volume and pressure control. Simply put, volume control results in a more stable minute ventilation (and hence more stable gas exchange) than pressure control if lung mechanics are unstable. On the other hand, pressure control allows better synchronization with the patient because inspiratory volume and flow are not limited to arbitrary preset values.

While it is possible to control only one variable at a time, a ventilator can *automatically* switch between pressure control and volume control in an attempt to guarantee minute ventilation while maximizing patient synchrony. When a ventilator uses both pressure and volume signals to control the breath size, it is called dual control. There are two types of dual control. Dual control between breaths means that the ventilator controls pressure during each breath but adjusts the pressure limit to achieve a tidal volume target over several breaths. Alternatively, the ventilator can switch between volume and pressure control during a single breath (dual control within breaths, as shown in Fig. 4).

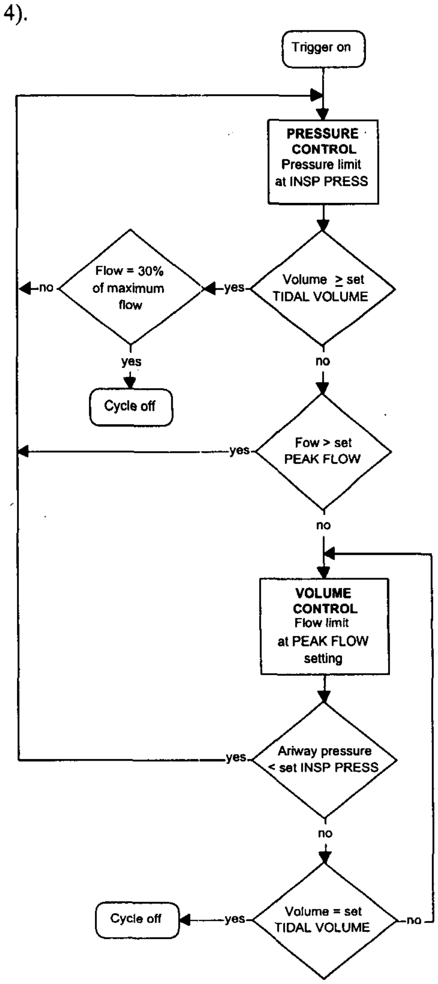


Figure 4. One example of dual control (within breaths).

***Breath Sequence***

The second component of the breathing pattern specification is the breath sequence. A breath is defined as a positive change in airway flow (inspiration) paired with a negative change in airway flow (expiration), both relative to baseline flow and associated with ventilation of the lungs. This definition excludes flow changes caused by hiccups or cardiogenic oscillations. But the definition allows the superimposition of, say, a spontaneous breath on a mandatory breath or vice versa. On the other hand, mandatory breaths are superimposed on spontaneous breaths during high frequency oscillatory ventilation.

As noted earlier, not all ventilators will accommodate a spontaneous breath while a mandatory breath is being delivered, which results in greater patient work and discomfort. The longer the mandatory inspiratory time and the more active the patient, the more important this issue becomes.

The classification of modes requires the definition of two basic types of breaths: spontaneous and mandatory. A spontaneous breath is a breath for which the patient controls the start time and the tidal volume. That is, the patient both triggers (starts) and cycles (ends) the breath. A spontaneous breath may either be assisted or unassisted.

A mandatory breath is a breath for which the machine sets the start time and/or the tidal volume. That is, the machine triggers and/or cycles the breath. Mandatory breaths, by definition, are all assisted.

Having defined spontaneous and mandatory breaths, there are three possible sequences of breaths, designated as follows:

- *Continuous Mandatory Ventilation (CMV):* all breaths are mandatory
- *Continuous Spontaneous Ventilation (CSV):* all breaths are spontaneous
- *Intermittent Mandatory Ventilation (IMV):* breaths can be either mandatory or spontaneous. Breaths can occur separately or breaths can be superimposed on each other. When the mandatory breath is patient triggered, it is commonly referred to as synchronized IMV (SIMV). However, because the trigger variable can be specified in the description of phase variables, we will use IMV instead of SIMV to designate general breath sequences.

When we add the breath sequence to the control variable in classifying a mode, we get a greater ability to discriminate modes. We can distinguish between, say, pressure controlled IMV and pressure controlled CSV. If we confine ourselves to classifying modes based solely on the breathing pattern, we see that there are only eight possibilities: VC-CMV, VC-IMV, PC-CMV, PC-IMV, PC-CSV, DC-CMV, DC-IMV, and DC-CSV. Note that VC-CSV is impossible by definition.

**Control Type**

We have discussed "control variables" and the differences between pressure, volume, and dual control but, we have not really explained what is meant by "control" in the first place. There are two general ways to control a variable; open loop control and closed loop control.

Open loop control is essentially no control. For example, early high frequency ventilators simply generated pulses of gas flow without measurement or control of pressure, volume, or flow. Flow into the patient was a function of the relative impedances of the respiratory system and the exhalation manifold. Thus, both pressure and volume were affected by any disturbances in the system, such as changing lung mechanics, the patient's ventilatory efforts, and leaks.

Closed loop control is an improvement in that the delivered pressure, volume, and flow can be measured and used as feedback information to control the driving mechanism. The actual output is measured (as a feedback signal) and compared to the desired value (intended by the set input). If there is a difference, an error signal is sent to the controller to adjust the output towards the desired output. Thus, inspiratory volumes, flows, and pressures can be made to match or follow specified input values despite disturbances such as changes in patient load and minor leaks in the system. Note that closed loop control does not require an electronic system. A simple pressure regulator is an example of mechanical feedback control.

For single variable, closed loop control, setpoint and servo types have been employed. Setpoint control means that the output of the ventilator automatically matches a constant, unvarying, operator preset input value (such as the production of a constant inspiratory pressure or flow from breath to breath). Servo control means the output automatically follows a dynamic, varying, operator specified input. For example, the Automatic Tube Compensation feature on the Dräger Evita 4 ventilator measures instantaneous flow and forces instantaneous pressure to be equal to flow multiplied by a constant (representing endotracheal tube resistance).

Dual variable, closed loop control (dual control) has used setpoint and adaptive setpoint control. Setpoint dual control means that the operator selects both the pressure and volume setpoints (pressure limit and tidal volume) and the ventilator switches between pressure control and volume control as needed. Examples of this are Pressure Limited Ventilation (Dräger Evita 4), Pressure Augment (Bear 1000) and Volume Assured Pressure Support (Bird 8400ST).

Adaptive dual control means that the ventilator automatically adjusts the pressure setpoint (the pressure limit) over several breaths to maintain an operator selected volume setpoint (the target tidal volume) as the mechanics of the respiratory system change. Thus, the ventilator adapts to the need for a changing setpoint. The ventilator typically monitors both exhaled volume and respiratory system compliance on a breath-by-breath basis. Then, if the tidal volume falls below the desired value, the ventilator adjusts the set pressure limit to bring the tidal volume closer to the target (required pressure change = exhaled volume ÷ calculated compliance). We say "target" tidal volume because the ventilator aims to achieve it, but for various reasons, may miss (which should trigger an alarm). Examples of adaptive dual control can be seen in modes like Pressure Regulated Volume Control (Servo 300 ventilator) and Auto Flow (Dräger Evita 4 ventilator).

To date, the most advanced control strategy may be called optimum dual control. Here, the ventilator automatically adjusts *both* the pressure and volume setpoints to optimize other performance variables as respiratory mechanics change. The term optimum implies that some measure of system performance is maximized or minimized. The only example of this at present is the Adaptive Support mode on the Hamilton Galileo (perhaps not the best choice of names in light of this classification scheme). In this mode, each breath is pressure controlled and the pressure limit is automatically adjusted between breaths to meet an optimum tidal volume. The optimum tidal volume is based on the estimated minute alveolar ventilation and the optimal frequency. The minute ventilation is estimated from the patient's body weight. The optimal frequency is based on the measured expiratory time constant using an equation that minimizes the work of breathing. The control software also implements "lung protective strategies" by not allowing tidal volume or frequency to get too large or too small. For example, the maximum frequency is based on a minimum inspiratory time equal to one time constant and minimum expiratory time of two time constants.

**Control Strategy**

***Phase Variables***

The phase variable is a signal that is measured and used by the ventilator to initiate some part, or phase, of the breath cycle.

The variable causing a breath to begin is the trigger variable. A variable whose magnitude is constrained to some maximum value during inspiration is called a limit variable. The variable causing a breath to end is the cycle variable. During expiration, the ventilator usually maintains some level of pressure at or above atmospheric pressure, which is referred to as the baseline variable.

Modes of ventilation can be described at various levels of detail, depending on how and with whom we need to communicate. At the highest level of detail, we can fully characterize a mode by adding the specific control strategy it employs. This begins with naming the phase variables (pressure, volume, flow, and time), followed by detailing the operational logic, and, if necessary, giving the parameter values used in the conditional statements.

A mode is a pattern of mandatory and spontaneous breaths. Because these breaths may vary drastically in the way they are controlled, we must specify the phase variables for both types of breaths. For example, a ventilator may provide volume controlled mandatory breaths that are time triggered, flow limited, and volume cycled, interspersed with pressure controlled spontaneous breaths that are pressure triggered, pressure limited, and flow cycled. Each type of breath has a completely different set of phase variables.

***Operational Logic***

Ventilators can also use pressure, volume, flow, or time (and their derivatives such as minute ventilation) as conditional variables. A conditional variable is used by a ventilator's operational logic system to make decisions. The operational logic of a ventilator is a simple description of how the computer uses the conditional variables. Operational logic often takes the form of "if-then" statements. That is, *if* the value of a conditional variable reaches some preset level, *then* some action occurs to change the ventilatory pattern.

For example, *if* a preset time interval has elapsed (the sigh interval), *then* the ventilator switches to the sigh pattern. Another example is the switch between patient-triggered breaths and machine-triggered breaths that occur during intermittent mandatory ventilation. An even more sophisticated example is the operational logic for dual control within breaths.

## CONCLUSION

Mechanical ventilator design has experienced rapid evolution in the last 40 years. In many cases, ventilator capabilities outstrip both scientific evidence of efficacy and operator understanding. The knowledge gap that exists between manufacturers and end users is due in large part to the absence of a standardized lexicon. A shared vocabulary, in turn, depends on the knowledge of rather simple analytical models of ventilator-patient interaction and control schemes.

Most education on the subject of mechanical ventilation is conducted not in the schools but by manufacturers representatives. For this reason, design engineers are in a unique position to drive change in the area of communication. Great good would accrue simply by adopting informal standards and terminology for operator's manuals across manufacturers.

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