Part II: Respiratory Failure

Chapter 23: Ventilators

T E Oh

Ventilators are devices used for mechanical ventilation. In Intensive Care, negative pressure ventilators such as the cuirass and iron lungs, are not useful and are not discussed. Instead, intermittent positive pressure ventilation (IPPV) is accomplished with positive pressure machines.

Ideal Requirements

There are numerous ventilators available today, each with different working principles, behaviour, and special functions. For use in an ICU, an ideal ventilator should provide for:

1. Ability to ventilate all sizes of patients, from neonates to adults. However, neonatal ventilators have evolved from T-piece, continuous flow occlusion systgems, because of size constraints imposed by their patients. While these systems are simple and have low resistance and dead space, precise control of respiratory patterns and monitoring of gas volumes are difficult. Modern ventilators catering for older children and adults are more complex but offer greater versatility.

2. Versatility of operation, ie, ability to produce optimal patterns of ventilation for each clinical situation by variation of mode and parameters such as inflating pressure, tidal volume, rate, inspiratory:expiratory (I:E) ratio.

3. Delivery of accurate, pre-determined, stable oxygen concentrations from 21-100%.

4. Complete delivery of all preset volumes despite changes in patient lung characteristics.

5. Minimal circuit resistance and impedance to allow spontaneous breathing modes without incurring excessive work of breathing.

6. Effective and safe humidification of gases and nebulization of bronchodilator drugs.

7. Monitoring of respiratory variables and alarm facilities. These two requirements are complementary in modern ventilators, ie, reliable and sensitive disconnect alarms relate to continuous monitoring of airway pressure and expired volume.

8. Application of positive end expiratory pressure (PEEP) and continuous positive airway pressure (CPAP).

9. Adequate safeguards (cross-)infection, such as simplicity of sterilization (ie, using an autoclavable patient circuit).

10. Electrical and gas safety features including continuing function in the event of an electrical or gas source failure, or high pressure relief valves to prevent barotrauma.

11. Simplicity of use and maintenance, reliability and robustness.

Driving Mechanism

All ventilators require a power source or driving mechanism. The driving mechanism may deliver the gas to the patient directly (single circuit), or by way of another mechanism (double circuit), ie, ventilator compression of a bag or bellows, which in turn delvers the gas to the patient. The types of driving mechanisms used in ventilator may be:

1. *Electrical motors* which may drive either:

(a) an air compressor, with the gas pressure produced being used to ventilate the patient; or

(b) a piston, with the piston drive mechanism being rotary- or linear-drive.

2. *Pneumatic* which may be further subdivided into:

(a) high pressure, utilizing wall source air or oxygen; or

(b) low pressure, with wall source gas passing through a reducing valve or a venturi injector.

3. *Spring tension* driving a bar or bellows which then delivers the gas.

4. *Weight* on bellows, ie, mass utilized as a generating pressure source.

Control Mechanism

Every ventilator demonstrates four phases: inspiratory, inspiratory to expiratory (I to E) cycling, expiratory, and E to I cycling. The control mechanism which initiates each phase of ventilation may operate mechanically, electronically, via fluidic components, by microprocessors, or by any mixture of these. Microcomputers are being increasingly used by new ventilators to control complex electronic valves and regulators, often using servo-controlled (feedback) flow mechanisms.

Paned controls for ventilatory parameters vary from ventilator to ventilator. Gas volumes can be preset by direct control of any two of the three parameters of inspired minute volume, tidal volume and respiratory rate. Duration of inspiration and expiration can be set by any of the following controls:

1. Direct control of rate with a fixed I:E ratio (ie, 1:2).

2. Direct rate control with variation of I:E ratio by altering the inspiratory time. This is accomplished by tidal volume and flow (ie, volume per unit time) changes. High flows with small tidal volumes will decrease inspiratory time and decrease the I:E ratio.

3. Direct control of inspiratory time (which may also include control of pause time) or both inspiratory and expiratory times by timing mechanisms.

Cycling

Some ventilators use the same mechanism to initiate both inspiration and expiration, but others use one mode of cycling to end inspiration and another to end expiration.

1. Inspiratory to Expiratory Cycling

Inspiration can be terminated by the following modes:

(a) *Time cycling.* Cycling is controlled by a timing mechanism.

(b) *Pressure cycling.* Cycling occurs when airway pressure reaches a pre-determined value.

(c) *Volume cycling.* Expiration is started after a fixed tidal volume has been delivered. Some ventilators which are time or pressure cycled use a double circuit "bellows in bottle" delivery system, with the tidal volume being set by limiting the bellows travel. If the inflating pressure or cycling pressure in these machines is set by very high (relative to airway pressure), then the preset tidal volume will always be delivered. Hence, these machines when used in this manner are strictly speaking, volume limited, time or pressure cycled, but may also be referred to as being volume cycled.

(d) *Flow cycling.* Inspiration is terminated when gas flow to the patient falls to a critical preset value. It is an uncommonly used mechanism.

(e) *Mixed cycling.* More than one mode of cycling is possible because of independent cycling mechanisms, or variable performance of a single mechanism.

2. Expiratory to Inspiratory Cycling

Triggering (Assist)

Expiratory to inspiratory cycling may use any of the methods terminating inspiration. In addition, there is patient cycling, in which the patient starts to inhale and in doing so, initiates inspiration. This is also called triggering, and the cycling mechanism depends on the slight negative pressure or gas flow generated by the patient. The sensitivity of the triggering mechanism can vary, and there is always a slight delay between sensing the inspiratory attempt and initiating inspiration. Patient triggering is thus usually unsatisfactory at high respiratory rates. Patient cycling also decreases the expiratory time, and hence the I:E ratio rises from the set value.

Triggering is known in North America as the "assist" mode, and a patient-cycled machine can be referred to as an assister. (A ventilator which controls inspiration by time cycling is called a controller.) An assist/control mode then allows triggering, but which also initiates mechanical ventilation if spontaneous respiration ceases. Most ventilators allow assist/control, as assist-only machines are hazardous if the patient fails to take spontaneous breaths.

Classification

Classification of ventilators facilitates the understanding of their functional characteristics. The intensivist can then choose the most appropriate ventilator for his needs, use that ventilator optimally, and predict the effect of lung changes on ventilator function. Classification which have been described include:

1. Volume or Pressure Preset (Hunter 1961)

Volume preset machines can be set to deliver a fixed tidal volume, and do so despite changes in lung characteristics. Increase in airway resistance or decrease in compliance will result in an increased airway pressure. Any leaks in the circuit will be uncompensated and will result in a fall in inspired minute volume.

Pressure preset machines generate a preset pressure, and I to E cycling occurs when a predetermined airway pressure is reached. Reduced compliance or increased airway resistance will usually result in a fall in minute volume (measured as expired volume). Small leaks in the circuit will, however, be compensated for, because the pattern of airway pressure remains unchanged. In general, pressure preset ventilators are not useful in the ICU. This classification, although simple and useful is no longer adequate.

2. Force Generators (Norlander 1964)

Ventilators are classified based on a concept of force, assesed as a product of flow and pressure, using a test lung. Two major groups are *constant force generators* (subdivided into those with adjustable or non-adjustable flow) and *increasing force generators* (subdivided into those with direct or indirect action). This classification is not useful. Cycling and some decreasing force generators are ignored.

3. Stable or Flexible Volume and Flow (Grogono 1972)

Minute volume, tidal volume, and inspiratory volume flow are classified as *"stable"* if constant values are maintained, and as *"flexible"* if the values change with changes in the patient's lungs (Table 1). However, "stable" characteristics in normal patients may become "flexible" with grossly abnormal lungs, and modes of cycling are not classified.

4. Flow Pattern, Force and Cycling (Baker 1974)

Ventilators are considered as flow producers (Table 2). *Flow-controlled* (or load-independent) ventilators can maintain a predetermined inspiratory flow pattern against patient impedance. *Flow-uncontrolled* (or load-dependent) machines cannot maintain the flow pattern; ie, flow is affected by patient lung changes. In general, flow control is more likely to be achieved by a high driving force or generating pressure. An arbitrary generating force of 50 mmHg (6.7 kPa) was chosen to divide flow-controlled from flow-uncontrolled.

Other characteristics are grouped into force patterns (*constant, varying* and *adjustable*) which in turn, are subdivided into their methods of *I to E cycling.*

The division into flow-controlled or uncontrolled is dependent upon the generating pressure. Since a high value was selected, this classification is more suited to abnormal lung mechanics. Nonetheless, this classification is useful to predict how a ventilator will perform in a clinical setting, but unfortunately, it is not commonly used.

5. Flow or Pressure Generator (Mapleson 1969)

This widely used classification considers inspiratory and expiratory flow with their methods of cycling, although clinical usefulness involves mainly inspiratory flow and I to E cycling (Table 3). A *flow generator* is a ventilator with a high generating pressure, producing an inspiratory flow which is unaffected by patient lung changes. The flow pattern of a flow generator may be constant or non-constant (ie, sine wave flow pattern produced by a rotary-drive piston).

A *pressure generator* has a lower generating pressure to produce an inspiratory flow which can be influenced by changes in lung characteristics. Although the flow pattern may vary, the pressure wave form remains the same, and may be either constant or non-constant (ie, increasing or decreasing pressure generators). Both flow and pressure generators are subdivided into methods of cycling.

Although this classification divides ventilators according to the generating pressure produced to drive gas into the lungs, it is actually a spectrum, with transition from one group to the other at some intermediate point. A ventilator behaves like a flow generator when the generating pressure is high enough to disregard patient impedance. A pressure generator may become a flow generator if its generating pressure is increased to exceed alveolar pressure by 10 times. Some ventilators allow control of generating pressure, and these machines may then be used either as flow generators or pressure generators.

6. Ventilator Evaluation Data Forms (Desautels 1985)

Forms are completed on ventilators, giving details such as power and drive mechanisms, modes, waveforms, specifications, options, controls, and ease of use. These forms compare ventilators objectively, and when used with bench-test evaluation and Mapleson's classification, give comprehensive information for clinical use.

7. High Frequency Ventilation

The above classification systems are not applicable to high frequency ventilators. Types or techniques of high frequency ventilation are discussed in Chapter 22, Mechanical Ventilatory Support, but are, as yet, to be classified in a clinically useful system.

Minute Volume Dividers

A few ventilators, in addition to being classified into any of the above classifications, can be grouped as *minute volume dividers* or *"flow choppers"*. The minute volume of gas is preset from the flow meters of the gas source. The tidal volume and inflation pressure are determined, thus deriving the rate. No increase in minute volume can be achieved by the patient, even by triggering the ventilator.

Ventilatory Modes or Special Features (See Chapter 22)

1. Controlled Mechanical Ventilation (CMV)

Modern ventilators are able to perform as volume-limited, time cycled flow generators, delivering preset tidal volumes and rates.

2. Patient Triggering (Assist/Control) (See above)

3. Intermittent Mandatory Ventilation (IMV)

IMV aids weaning by obliging the patient to breathe spontaneously via a one-way valve, in between the mandatory ventilatory cycles. A modified IMV circuit may result in hyperinflation when a mandatory breath is "stacked" on top of a spontaneous one. This is overcome in some new ventilators by provision of a synchronized facility, ie, SIMV.

4. Pressure Support or Assist

This is not to be confused with triggering. Pressure support/assist is a mode whereby the patient initiates inspiration and the ventilator delivers a breath up to a constant preset positive airway pressure. As weaning progresses, the pressure support level is decreased stepwise.

5. Mandatory Minute Volume (MMV)

MMV ventilation aids weaning. It incorporates a modified circuit so as to deliver a mandatory preset minute volume which is the sum of spontaneous respiration and mechanical ventilation. The patient breathes spontaneously and the ventilator makes up for the deficit in the minute volume, ie, mechanical ventilation varies minute by minute, inversely to spontaneous respiration.

6. Positive End Expiratory Pressure (PEEP)

PEEP is provided by incorporating an expiratory resistance in the breathing circuit. This can be achieved with a constriction, a spring-loaded valve, a weighted valve, an under-water column, a venturi valve, an electronically controlled scissor valve, or a pressure-actuated solenoid valve placed in the expiratory part of the circuit. All devices produce some retardation of expiratory flow before the final pressure is reached, with a resultant increase in mean airway pressure. Devices which offer gas flow resistance at an orifice are "flow resistors" and those which are "cap" valves opening at a preset pressure are "threshold resistors". A threshold resistor valve presents minimal resistance to gas flow above its threshold (opening) pressures, and unlike flow resistors, pressure gradient across the valve is independent of the gas flow. The lower resistance of threshold resistors are advantageous in reducing work of breathing and avoiding excessively high airway pressures from coughing and straining. PEEP is discussed further in Chapter 22.

7. Continuous Positive Airway Pressure (CPAP)

CPAP or constant positive-pressure breathing allows spontaneous respiration at an elevated baseline pressure when the ventilator is used in the assist mode. The objectives are similar to PEEP.

8. Expiratory Flow Retard

Expiratory retard is accomplished by a restriction on the expiratory outflow tract. The airway pressure gradient across the restriction is proportional to the gas flow through it, and decreases as flow decreases in expiration. Hence airway pressure drops slowly to atmospheric when expiratory gas flow ceases, whereas in PEEP, pressure is held at a value above atmospheric when flow ceases. However, if the expiratory time is insufficient to allow full expiration in between ventilator breaths, expiratory retard will result in PEEP. In either case, the objective of expiratory retard is to maintain a positive airway pressure to prevent airway closure in chronic obstructive airways disorders, and to favour lung emptying in such patients. However, expiratory retard involves the risks of hyperinflation and circulatory depression.

9. End Inspiratory Plateau (EIP)

End inspiratory plateau (or pause, or hold) includes pressure hold and volume hold. With pressure hold, a preset pressure is reached and held for a period of time. EIP may be regarded as a prolongation of the inspiratory phase. EIP may improve ventilation-perfusion mismatch by decreasing the physiological dead space: tidal volume ratio (V_D:V_T). However, the effect is small and EIP may worsen circulatory depression. The benefits of EIP remain largely theoretical.

10. I:E Ratios

Many ventilators do not offer control over the I:E ratio, but this is a desirable feature. Inverse ratio ventilation is an alterantive method to increase FRC.

11. Negative End Expiratory Pressure (NEEP)

The principle of NEEP is to counteract the increased intrathoracic pressure caused by IPPV. However, most ventilated patients compensate adequately, and volume deficit correction and/or inotropic agents are more important. Moreover NEEP may worsen ventilation:perfusion mismatch when airway closure occurs at lung volumes near to the functionals residual capacity. NEEP is usually achieved with a venturi to entrain circuit gas.

12. Sighs

Sighs are programmed periodic hyperinflations. The objective is to prevent progressive atelectasis, but sighs are poorly tolerated by patients, and are probably not necessary with the use of large tidal volumes.

Clinical Considerations

When using a ventilator, the important considerations are:

1. The length of the inspiratory phase.
2. The mode of I to E cycling.
3. Whether cycling is affected by changes in patient lung characteristics thus altering the tidal volume.
4. The length of the expiratory phase, which should be adequate to allow expiration of the inspired tidal volume.
5. Whether E to I cycling is affected by lung changes.
6. The modes of ventilation available.
7. The resistance of components for spontaneous breathing such as demand valves.

Although accelerating and decelerating flow patterns have been advocated, there is no evidence to suggest that any particular wave form is superior in efficient ventilation. Constant flow generators produce a square flow wave form whereas constant pressure generators produce a downward tapering flow wave form.

In general, ventilators which can deliver gas volumes unaffected by any change in the patient's lungs are preferred in the ICU. Classification shows these ventilators to be:

1. Flow generators, which are either time or volume cycled, using Mapleson's classification.

2. Flow-controlled (Load-independent), constant or nonconstant force, which are either time or volume cycled, using Baker's classification.

3. Volume preset, using Hunter's classification.

The working principles of a ventilator being used should be understood to enable it to be classified. The panel controls should be familiarized in order to correctly set tidal volume, rate, inspiratory time, and the alarm mechanisms, Oxygen concentration can be set directly or via an attached oxygen blender. Humidifiers are discussed in Chapter 24, Humidification. Bacterial contamination of ventilator and patient can be minimized by circuit design, protocols for circuit changes, and the use of bacterial filters.

Correct performance of the ventilator is assessed by observation of patient chest movements, chest auscultation, and monitoring respiratory variables. The inspired tidal volume may be less than the preset value because of gas compression within the circuit. The volume of gas compressed is directly related to the end inspiratory pressure. This internal compliance is approximately 3 mL/cm water (0.03 L/kPa). Hence expired volumes should always be measured (ie, with a Wright's respirometer).

Detailed descriptions of individual ventilators are provided elsewhere.

Portable Ventilators

Portable ventilators facilitate transport of ventilated critically ill patients. Resuscitators may be used for short-term patient transport. These are manual self-inflating bags, manual oxygen-inflating bags, or oxygen powered resuscitators. Portable ventilators are specifically designed ventilators for patient transport. The Drager Oxylog and Ohmeda Logic 07 are such compact portable ventilators.

They are oxygen powered with a fluid logic controlled circuit. Air entrainment is possible, thus allowing either 50-60% oxygen or 100% oxygen to be used. The I:E ratio is fixed. IMV and PEEP (using an AMBU or Boehringer valve) modifications are also possible.