The classification and clinical application of mechanical ventilators

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The author provides the practicing nurse anesthetist with a method of classification of the ventilators used today and describes their major modes of function. On a clinical level, function is correlated to changing lung characteristics, with emphasis placed on the inherent hazards to be alert for.

"Indeed, with a slight breath in the case of this living animal the lung will swell to the full extent of the thoracic cavity, and the heart become strong...." Andreas Vesalius, 1543

Since Vesalius' early experiments with a bellows to inflate the lungs of a restrained and nearly lifeless animal, man has sought to develop machines to adequately ventilate those of his fellows whose own lungs have failed in their assigned physiological task. As a result of this effort, an abundance of different styles of ventilators are in use today.

Quite often, it is the anesthetist who is called upon to set up and operate ventilators of any and all configurations. It, thus, has come to the author's attention that a simplified condensation of the scattered literature would serve to place the anesthetist on firmer ground, so to speak, in his or her dealings with such devices.

It is, therefore, the purpose of this article to examine the major considerations involved in artificial ventilation and categorize the many ventilator types according to their major mode of function. Reference will necessarily be made to their effects on ventilation.

No matter what type of ventilator is being discussed, at least three separate functions must be provided for:

1. An inspiratory phase.
2. An expiratory phase.
3. A mechanism for cycling the machine from one phase to the other.

Before delving into each of these functions, I believe it would be wise to state, simply, the theory behind intermittent positive pressure ventilation (IPPV) and list the more important considerations that one should keep in mind when ventilating a patient by artificial means.

IPPV or intermittent step increases in mouth pressure, as Nunn1 aptly describes it, has its effect by creating a pressure gradient between the mouth (or opening to the airway) and the alveoli, thus encouraging gas to flow into the lungs. This is in contradistinction to the action of natural respiration by each lung, in which the patient creates a negative pressure within the thorax.

It has often been said, concerning IPPV, that whatever is of benefit to the lungs is a detriment to the circulation. Certainly, this is the most important aspect of the following considerations:

1. Keep the mean intrathoracic pressure as low as possible to avoid compromising circulation.
2. Provide for the most even pattern of ventilation, that is, strive to ven-
tilate all lung segments evenly and equally.

3. Adequately ventilate the lungs in the face of changing lung characteristics, that is, compliance and resistance.

4. Adjust the ventilator to best provide oxygenation and removal of carbon dioxide, (the latter is frequently overlooked clinically, when one is worrying about the former).

5. Avoid damaging lung tissues, such as through excessive pressures, high inspired oxygen concentrations, or drying of secretions.

6. Achieve all of these five points in the manner which best allows patient control and comfort.

Now that these objectives have been established, the modes of ventilation can be set forth.

Modes of ventilation

Inspiration will be the first phase taken under consideration, and this will be divided into two basic classifications—pressure generators and flow generators, after Mushin. Essentially, the difference between these two is that, in the former, the generated pressure is kept constant throughout inspiration, while in the latter, the flow rate of gas is kept constant. How this occurs will be shown next.

Pressure generation

A pressure ventilator usually features a second-stage reducing valve which can convert the high pressure of the source gas to a more moderate pressure suitable for inflation of the human lung, as is illustrated in Figure 1. Typical of the pressure generator are the Bennett PR-1 and PR-2 ventilators.

The pressure generated by the ventilator is kept constant throughout the period of inspiration. That same pressure is used to overcome the resistance of the air passages of the lungs and to expand the elastic tissue which makes up the alveoli. This resistance and elasticity (properly termed compliance) varies from patient to patient and even from breath to breath in the same patient. These two characteristics of the lungs, in the face of ventilation by a pressure generator, will dictate:

1. How much air gets into the lungs—the tidal volume (VT).
2. How long it takes for the lungs to fill to the desired VT.
3. The instantaneous flow rate (V) from moment to moment.
4. How much of a pressure rise above the atmospheric level occurs in the alveoli and at the mouth (PA, Pmo).

From the foregoing, we can see that of the parameters listed, (that is, VT, V, PA, Pmo, and PG—generated pressure), this type of ventilator allows direct control by the operator of only one variable—that of the generated pres-

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**Figure 1**

Pressure generated ventilator

Key: (1) represents the source gas, usually from a tank or wall supply @ 60-70 psi; (2) the ventilator proper which serves, through its internal mechanisms, to step-down the source pressure to physiological limits and release it to the delivery system when cycled; (3) control pressure gauge—indicates peak pressure at which the ventilator will operate, as dictated by the operator. Positioned at the outlet to the delivery system, it reads a constant pressure. (4) “airway” or “system” pressure gauge—reads the pressure at the mouth or ET tube which results from interaction of flow from ventilator and resistance: compliance factors of the lungs and tube system. (5) is a one-way valve which opens and closes depending upon the cycling mechanism employed. (6) the patient.
sure (PG); the rest are determined by the lung characteristics of the patient. The following example (with reference to Figure 2) may show this more clearly.

Figure 2
Flow rate of the pressure generated ventilator

Key: PG—generated pressure from ventilator; V—flow rate; VT—volume of gas passing to patient; P_A—pressure within the alveoli; P_mo—pressure at the opening to the patient’s airway, e.g.: mouth, endotracheal tube or tracheostomy. All graphs cover the indicated inspiratory time of one second.

Assume a patient’s compliance (C) and resistance (R) to be:

\[
\begin{align*}
C &= 0.05 \text{ L/cm H}_2\text{O} \\
R &= 6 \text{ cm H}_2\text{O/L/sec in the patient} \\
&= 4 \text{ cm H}_2\text{O/L/sec in the ventilator} \\
&= 10 \text{ cm H}_2\text{O/L/sec total} \\
PG &= 14 \text{ cm H}_2\text{O}
\end{align*}
\]

The total resistance indicated is that which must be overcome by the pressure generator before gas can flow into the lungs. The generated pressure, at its source in the ventilator, is brought immediately to its preset value, thus, instantly overcoming total system resistance and initiating flow of gas into the lungs. Flow is initially high and then begins to taper off as the alveoli fill and their pressure climbs—this occurs in an exponential manner.

Flow is given in L/sec, and may be calculated from the formula:

\[
\frac{PG - PA}{R} \text{ or in this example,}
\]

\[
\frac{14 \text{ cm H}_2\text{O}}{10 \text{ cm H}_2\text{O/L/sec}} = 1.4 \text{ L/sec.}
\]

This describes the initial flow rate. If this flow rate were maintained at the indicated level, VT would be reached very quickly. However, as the alveolar pressure rises, the value given by PG-PA falls; and thus, the flow rate decreases until ultimately it ceases altogether. It is at this point of no flow that the compliance of the patient dictates what the VT is; that is, if the alveolar pressure has risen to the same value as the PG* (as it must have if flow has ceased), then the product of the equation \( C \times P = VT \) and in this case it would be:

\[
0.05 \times 14 = 0.7 \text{ L.}
\]

If we now go back and substitute a higher value for the total resistance (as is often found in diseased lungs\(^4\)), we will see that this decreases the flow rate (assuming PG remained the same) and, thereby, prolongs inspiration. This lengthening of inspiration, if the inspiratory/expiratory ratio is to be main-

*In clinical application, this rarely occurs since \( P_{mo} \) reaches PG before PA does; therefore, PA is always somewhat less than PG.
tained, would necessitate slowing of the respiratory rate with a resultant decrease in minute ventilation. Also, if lower values for compliance are used (in cases of asthma or pulmonary congestion, for example), $V_T$ will fall accordingly. It is these changes in lung characteristics which most severely limit the efficiency of the pressure generator.

In order to compensate for increases in resistance or decreases in compliance, the operator of the pressure generator can only increase the $P_G$. This may lead to a detrimental effect on the circulation. It should also be noted that should a leak exist within the delivery system of this type of ventilator, unless the inspiratory period is time-cycled, the machine will continue to generate pressure until alveolar pressure rises to the preset level. Thus, delivery of the desired tidal volume will be assured. If the leak is large enough, however, the machine may become stuck in the inspiratory phase.

A note also should be made here of the danger of interpreting readings from “airway” pressure gauges on any type of ventilator as being alveolar pressure readings. These gauges measure the pressure at the opening to the airway and should not be taken to indicate the alveolar pressure. At all times during a given inspiration, the mouth pressure will exceed the alveolar pressure by some amount; and in cases of high resistance, this may be a high value indeed. False security regarding tidal ventilation is thus obtained and may lead to severe underventilation.

**Flow generation**

Where the ventilatory effects of the pressure generator were influenced by lung characteristics, the flow generator does its job irrespective of those characteristics. The key to understanding why this is so lies in realizing that: the work force generated by the ventilator far exceeds any counterforce that could possibly be offered by the compliance and resistance of the human lung. Imagine Goliath employing Vesalius’ bellows to inflate the lungs of David; barring complete airway obstruction, the young man would certainly be made to inspire!

This type of ventilator is exemplified by the Bennett MA-1 and the Emerson Postoperative (electric) ventilators, among others. Here, the flow is delivered from, respectively, the compression of a reservoir bag and the action of a piston within a cylinder which serves as a mixing chamber. (See Figure 3.) These are two very common mechanisms of flow generation.

![Figure 3](https://example.com/figure3.png)

**Figure 3**

**Flow generated ventilator**

Key: (A) The lever, moving in the direction of the arrow, exerts a “squeezing” action on the bag below it. (B) The piston, on its upstroke, forces out gas to the patient from within the cylinder.

A third common type of flow generator employs the use of a high pressure source flowing past a restriction within the ventilator itself. The restriction decreases the pressure to within limits safe for inflating human lungs, while at the same time, it keeps the flow constant throughout the period of inspiration. Thus, since flow is maintained regardless of opposing compliance and resis-
It is the alveolar pressure which varies significantly with this type of operation. That is, in the patient with low compliance, the PA will reach high values in the face of a VT identical to that used in the patient with normal compliance. Importantly, the VT will be delivered within the desired period of time, despite the low compliance. Likewise, the same is certainly true in the patient with increased resistance.

It is for these reasons that the flow generator has for many years been considered more reliable in delivering accurate tidal volumes. However, in the case of a leak, no compensation will occur as was found in the pressure generator, instead the volume will pass to the environment.

A note should be made here that in American medical phraseology, "pressure-limited" and "volume-limited" are frequently used instead of "pressure" and "flow" generator.

**Expiratory phase**

Usually the ventilator, be it a pressure or flow generator, merely allows the expired gases to escape into the atmosphere (though it may pass first through a ventilation meter of some sort). However, much recent interest has been shown in the employment of positive pressures either at the end of inspiration or expiration.

Keeping in mind that it is the functional residual capacity of the lungs (FRC) that serves as a source of oxygen to the pulmonary circulation during expiration, it is theorized that application of these positive pressures would serve to increase the FRC. Thus, there would be an allowance for increased equilibration surface and time in the alveoli. Reports are now in the literature regarding the beneficial effect of these maneuvers on the arterial oxygen tensions and the lack of detrimental effect on the circulation.\(^7\), \(^8\), \(^9\), \(^10\)

Another aspect of expiration is the application of a negative pressure. This was originally done in the hopes of:

1. Decreasing the mean intrathoracic pressure.
2. Shortening expiration time in the patient with obstructive disease.
3. Decreasing mean jugular vein pressures to aid venous drainage in the patient with intracranial pathology.
4. Augmenting venous return in the hypovolemic patient.

The attendant hazards of such therapy, however, (that is, airway collapse with air trapping in the emphysemic and pulmonary edema of patients with congestive failure), would seem to outweigh the questionable benefits to circulation.\(^11\)

**Cycling mechanisms**

If time is the parameter used to determine cycling in a flow generator, then, the flow rate will be dependent on the amount of time allowed for inspiration. This may be best illustrated by considering the reverse situation; that is, if the flow rate is controlled, then the time allowed for inspiration is dependent on the flow rate. Consider, for example, if the flow rate chosen is 30 liters per minute (a common setting on many ventilators), then this translates to 500 cc/sec. If the desired tidal volume is 500 cc, inspiration will obviously take only one second.

Now, the converse. If the time of inspiration is the controlled parameter and a 500 cc tidal volume is required, the one second inspiration will require a flow rate of 500 cc/sec or 30 liters/min. In this way, the cycling mechanism may be said to control the flow. It is also important to note that, where the flow rate is a controllable feature, inspiration may be either shortened or prolonged by increasing or decreasing the flow, respectively.

It was at one time thought that the shorter the inspiration, the better to keep the intrathoracic pressure down. It is now felt by many that a slightly longer inspiration is better, from the standpoint of evenness of gas distribution within the lung segments, and that effects on the circulation are minimal. Recent ev-
idence indicates that it may, indeed, be disadvantageous to the patient with pre-existing instability of the cardiovascular system, and that higher frequencies with shortened inspiratory times may be preferable.

Time limiting in the pressure generator has a very severe pitfall as well. If the compliance is low, inspiration may be a lengthy period, as was illustrated previously. The same effect may be found in the face of increased resistance. Should this occur in a time-limited ventilator, inspiration may be cut short before the desired tidal volume is transferred to the patient. This is not a worry in the flow generator.

In the flow generator, volume limiting usually takes the form of a preset value, rather than the passage of a certain quantity of gas. Since the flow generator is known to deliver the desired tidal volume within a physiological period of time (no matter what the lung characteristics), it may be felt by the operator that measurement of the passage of that volume of gas is not required. Such is not the case, however, for the reasons listed:

1. Compression of the gases within the ventilator reservoir, delivery tubes, and patient airway (that is, endotracheal tube), relative to Boyle's law. This tends to decrease the volume reaching the patient and is dependent on the volumes of these areas and the pressures used.

2. Compliance of the tube delivery system. This also decreases the amount of gas reaching the lungs, and varies with the type of tubes used and the pressures applied.

Mushin\(^1\) suggests computation of the volume lost as a result these two factors by figuring 5 cc/cm \(H_2O\). A third factor to be considered is:

3. If the ventilator is in line with an anesthesia machine which is providing a steady in-flow of fresh gases, this may be considered as a small flow generator contributing to the action of the ventilator. Therefore, such a factor may add to the tidal volume.

In any case, there is no substitute for monitoring of the exhaled volume to guide the operator in adjusting the ventilator to the proper setting. Several small, portable meters are available and should be used when possible.\(^1\)

The volume limiting pressure generators require very close observation. If the resistance is high, volume limiting may cause inspiration to be prolonged to a point where respiratory frequency is severely depressed. Thus, minute ventilation falls, though tidal volume is adequate. On the other hand, if compliance is low, the volume may not be reached at the set pressure, and so the machine would not cycle, remaining stuck at inspiration.

Pressure limiting of some sort is employed as a safety feature in almost all ventilators. This is to prevent excessive pressures being built up in the lungs with resultant tissue damage. In the case of either type of ventilator, such a condition may result in the termination of inspiration before tidal volume is delivered. In the flow generator featuring flow rate control, excessive mouth pressures in the face of high resistance may be decreased by decreasing the flow rate. It should be kept in mind that this maneuver will also lengthen inspiration.

Patient effort as a cycling device is usually employed in the transition from expiration to inspiration. This is a valuable asset for maintaining the patient's ability to ventilate himself properly once off the ventilator, that is, weaning. The patient can achieve self-ventilation by creating a negative pressure, thereby opening a valve in the machine that allows gas to flow within the system.

The best example of such a system is the Bennett valve. Its sensitiveness to negative pressures can be adjusted to minuscule values, and it affords instantaneous flow to the patient on demand. Patient control is desirable in all but the unconscious and should be employed where possible. Such sensitive devices are known, however, to result in self-cycling by the ventilator at very rapid
rates, to the detriment of the patient—this occurs if an inaccurate setting has been made by the operator.

No conclusive studies to date have shown which pattern of ventilation is best in a given disease state, and certainly both patterns ventilate the healthy lung equally well.\(^1\),\(^2\) This lack of evidence may be due to the fact that, until recently, technology in this field has been far ahead of clinical application. We may expect to see authoritative information come forth in the near future.

Without a doubt, artificial ventilation has achieved wide prominence with the advent of intensive care specialties. The reader is encouraged to employ the principles presented within this article in his or her own clinical experience and seek further clarification where needed. Nunn\(^1\) and Safar\(^1\) offer excellent criteria to follow in choosing a ventilator, and Mushin’s\(^1\) classic text is indispensable to a thorough understanding of all ventilator types.

REFERENCES

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Mark S. Manyczuk, RN, began his professional education in the military where he trained as a Special Forces Medic with the U.S. Army. His military experience stimulated him to pursue a career in health care in civilian life. He received his RN at Barnes Hospital School of Nursing in St. Louis, Missouri. He is currently enrolled in the Barnes Hospital School of Nurse Anesthesia as a senior student. His work experience includes that of an inhalation therapy technician, staff nurse in coronary care and respiratory intensive care, and a cardiopulmonary researcher.

This paper was prepared by Mr. Manyczuk at the Barnes Hospital School of Nurse Anesthesia, with the recommendation of Louise S. Grove, CRNA, the school’s education director. It is an expanded version of a lecture Mr. Manyczuk presented to a local chapter of the American Association of Critical Care Nurses.