2.2 Ventilators

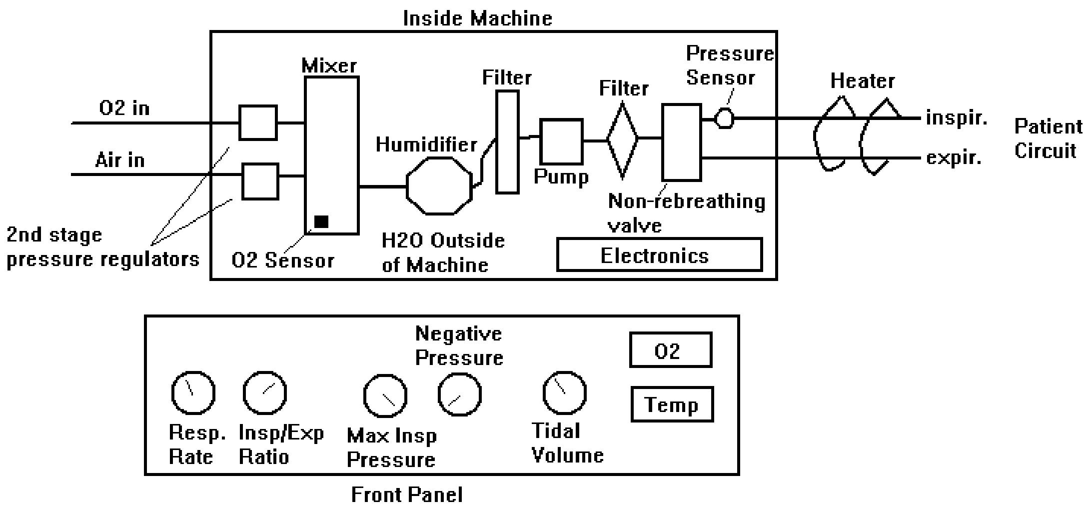
2.2.1 Clinical Use and Principles of Operation

Many patients in an intensive care and the operating room require the mechanical ventilation of their lungs. All thoracic surgery patients, for example, require mechanical ventilation. Some patients simply need assistance breathing, when a patient is recovering from certain illnesses and operations for example. In any case, ventilators can take over the major effort of respiration for the patient.

Some people use the term ventilator and respirator interchangeable. They are not the same. A respirator is a device that supplies or filters air in a harsh environment. The patient is breathing on their own when they use a respirator. In most cases, without the ventilator, the patient could not breathe, or would have great difficulty breathing.

Basic Elements of a Ventilator

A ventilator may include a pump which creates pressured air for delivery to the patient. However, in most cases, compressed gases are connected to the machine. The compressed gas is at a very high pressure, so a pressure regulator is typically connected to the bottle or the ventilator or both (see bottled gases chapter for more details). There are generally moisture traps and particulate filters in line with the incoming gases. The figure below details most of the common components and controls. However, there is considerable variation between manufacturers.



Ventilators are complex devices. In many cases, the only repairs possible in the field are user error, filters and rain out.

Some ventilators can accept air, oxygen or a combination of both. Some will measure the concentration of oxygen delivered to the patient, sounding an alarm if it becomes too high or low.

Very old ventilators will deliver the pressurized gas directly to the patient. However, this is very rare, even in the developing world. More common is for the ventilator to measure the volume (usually derived from measured flow) and pressure of the delivered gases. A computer then controls the timing and pressure for the next cycle.

All ventilators must insure that the patient does not re-breath his own, untreated expired gases, as they will eventually become excessively concentrated in carbon dioxide. So, in most cases, the simple volume limited ventilator contains a "non-rebreathing" valve that opens to allow fresh gas into the cylinder, closes during inflation and opens to allow expiration of the gases from the lungs into the room or a waste collection canister. In most modern ventilators, the non-rebreathing valve is in the tubing set (or circuit), in which case it is disposable.

The non-rebreathing valve may have a separate tube connected to the ventilator to force the valve open and closed. Or, the non-rebreathing valve may operate on the pressure of the inspiratory gas. In either case, it operates as a one-way valve that allows air to flow from the inspiratory tube to the patient, but when the patient is expiring gas, blocks the inspiratory tube, allowing the expired gas to pass through a separate expiratory tube.

Most ventilators will include humidification. Bottled gases delivered from cylinders are too dry for the human body to moisturize comfortably. Sterile water should be used for humidification, but often isn't in the developing world. The water is heated and the vapor drawn into the gas flow to the patient. In some cases, ultrasound is used to nebulize the water.

Most ventilators have an arm that the patient circuit tubing is attached to. This takes the weight off of the tubing where it connects to the patient. Most of the tubing fittings are also specific sizes to make misconnection harder. On adult machines the patient connector at the machine is 22 mm and the patient end of the tubing has a 15 mm connector. These connections are often missing or manipulated in the developing world to allow for the use of mismatched tubing.

Some ventilators have the ability to heat the tubing or the delivered air or both. This can prevent "rain-out" of the vapor in the gases being delivered to the patient. On some older systems you still may find water traps where the "rain-out" collects in the tubing.

Modes of Ventilation

There are many different types or modes of ventilation. Most ventilators can switch between several modes, but not all. The selection of the ventilator is ideally dependent on the patient's condition, but is often dictated by availability in the developing world. In fact, ventilation is so critical that availability of the appropriate ventilator or ventilator mode often dictates what procedures can and cannot be conducted in a given hospital.

There are three basic modes of ventilation, volume limited, pressure limited and timed cycle. Timed cycle is a combination of the other two basic modes. Jet ventilation is a fundamentally different mode of ventilation, but it is rarely seen in the developing world.

In the volume limited mode a preset volume of gas is delivered to the patient regardless of the pressure reached in the lungs or the time required to complete the inflation. This is a simple system where a gas is drawn into a cylinder and then forced out of the cylinder and into the lungs. It is rarely used by itself in humans because of the lack of pressure sensitivity.

In a simple volume limited ventilator, the cylinder is adjusted for the volume of gas desired. The motor is rate adjustable, generally between 5 and 50 breaths per minute (respiration rate). The drive mechanism is a cam that creates a rapid inflation of the lungs and allows for a longer period of time for the deflation of the lungs.

In the pressure limited mode a pressure limit is set where gas will flow into the lungs until that pressure is reached, regardless of the volume of gas delivered. This is a simple system where pressurized gas is passed through a pressure regulator to the desired pressure, then a valve that allows the gas to enter the patient. It is rarely used by itself in humans because of the lack of volume sensitivity.

The simplest device typically used on humans is the timed cycle ventilator. This is the most common mode because it combines both the volume and pressure limited methods of operation.

In the timed cycle mode the physician sets the respiration rate, the tidal volume (the volume of gas to be delivered), the upper pressure limit, and the inspiratory/expiratory ratio. If the pressure limit is not exceeded, then the device will deliver the desired volume of air, more or less evenly during the entire inspiratory time. The inspiratory time is the total respiration time (one over the respiration rate) times the inspiratory/expiratory ratio. For example, at a tidal volume of 1 liter, a respiration rate of 20 breaths per minute (3 seconds per breath), and an inspiratory/expiratory ratio of 0.5 (inspiratory half as long as expiratory), the total inspiratory time would be 1.0 seconds. One liter of gas would be delivered in one second.

If the pressure limit was exceeded, then an alarm will flash. Gas is still delivered to the patient when the pressure limit alarm is indicated. However, the pressure is not allowed to exceed the specified limit. Therefore the tidal volume desired has probably not been reached.

The Jet-Frequency mode is a newer ventilation mode. It is rarely seen in the developing world. This mode is mostly used on neonates. There is no inspiratory/expiratory ratio and no pressure limits to be set. The basic principle is a constant series of small volume pulses of gas is supplied to the patient.

Ventilation Control

There are several modes for controlling the ventilator. The basic modes are controlled and assisted. However, again, the combination of the two is the most common in practice.

The simplest mode is the controlled ventilation mode. In this mode the patient makes no effort to initiate respiratory effort. The ventilator delivers a set volume of gas at a set rate for as long as needed. Some units have a "sigh" level where every so many breaths or minutes the machine automatically provides the patient with a greater volume of gas.

In the assisted mode of ventilation, the patient will trigger the flow of gas by starting to inhale. When the patient reaches a preset withdrawn volume or a preset negative pressure, the ventilator will start the flow of gas into the lungs. The assisted mode is typically used while the patient is being weaned from the ventilator.

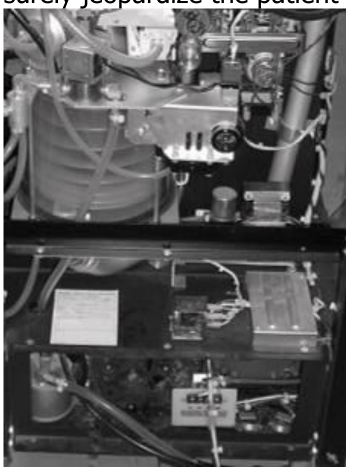
The most common mode is a combination of the controlled and assisted modes. At first, the patient is on a completely controlled ventilation mode. As the patient starts to recover they will make efforts to breathe on their own. This is called "fighting the ventilator" and is an important clinical milestone in the recovery of a patient. Once that milestone is reached, the staff will switch the ventilator to the assist mode, and begin to wean the patient from the ventilator.

Weaning is accomplished by slowly increasing the amount of negative pressure or withdrawn volume required to trigger the flow of gas. This weaning process can take from hours to months depending upon the patient's condition. If the patient fails to initiate a respiratory effort in a certain number of seconds the machine will automatically switch back to controlled ventilation mode, breathing for the patient until another respiratory effort is made by the patient.

2.2.2 Common Problems

Ventilators are one of a small group of life support devices that if it fails death will occur unless there is intervention by staff and a replacement device available. In addition, the lungs are a very delicate tissue which can be easily destroyed by a poorly calibrated ventilator. With that knowledge it is paramount that the ventilators are kept in top working condition.

However, the dangers posed by a lack of ventilation combined with the dangers posed by a poorly calibrated ventilator places the developing world engineer in a very difficult position. On the one hand, without specific training on the ventilator at hand, you may endanger the patient by working on the device. On the other hand, with no substitute ventilator available, you will surely jeopardize the patient if you do not work on the device.



The inside of the Bennet ventilator illustrates the complexity of the device. Fortunately, the required repairs are typically simple. If they are not, repair in the field may not be possible.

Fortunately, ventilators are very reliable devices. The most common problems are user error, the power supply, filtration and the tubing. The most common problem with user error is that the controls are not standardized between manufacturers and the manuals were either not supplied with the donation or were supplied in a language that the hospital staff does not speak.

If the problem is related to the power supply to the ventilator or a simple mechanical problem (such as the wheels, lid or tubing arm) repair is straightforward.

The most common problem with the tubing is that disposable tubing is being reused. The non-rebreathing valve may break or the tubing may leak. Leaks can be fixed with epoxy or a silicon sealant in most cases. The non-rebreathing valve cannot be repaired in general. However, it may be possible to adapt the non-rebreathing valve from one leaking circuit to be used on another circuit that doesn't leak, but has a non-rebreathing problem.

If the problem is not one of the problems described above, it is probably better not to attempt to fix the ventilator without specialized training. However, your decision should be made in careful consultation with the physicians. Discuss what the risks are to the patient if you do not work on the machine and what the risks are to the patient if you work on the machine, and it accidentally over pressurizes or under-ventilates the patient. Ultimately the decision is the physician's and you must follow his instructions.

2.2.3 Suggested Minimal Testing

If your repair has been a simple mechanical fix or the power supply. Then you can release the machine to the floor for use with only simple testing. The simple testing should consist of measuring the breathing rate (it should be within a few breaths per minute of the setting over the entire range) and measuring the inspiratory/expiratory ratio (it should be within approximately 20% of the set ratio). Test the pressure limit by partially occluding the connection to the patient with your hand. The pressure limit light should flash.

If the ventilator is likely to be used in an intensive care unit, then it will likely be used to wean patients. In this case, check that the assisted mode is working. After conducting the simple tests, you can connect the ventilator to yourself. Do this by gently placing the patient tube in your mouth (being sure that you can easily remove it if there is a problem). In the assisted mode, as long as you are breathing, the device will deliver gas only when you inhale. Then, remove the tube from your mouth. The device should take over in a controlled breathing fashion. Place the tube back in your mouth and breathe normally and the device should automatically return to assisted mode.

If your repair has been on the breathing circuit, then you only need to test the tubing and the non-rebreathing valve. The tubing should be leak free (occlude one end and blow hard into the other end with the tube submerged in water. There should be no bubbles. The non-rebreathing valve is a one-way valve. If it does not have a connection to the ventilator, then you can check it by simply blowing into the patient connection end and making sure that the air goes down the expiratory tube. Then suck from the patient end and make sure the air is coming in from the inspiratory tubing. If the non-rebreathing valve has a connection to the ventilator, then you will have to operate the ventilator. Check that the gas is flowing down the correct tubing by occluding the other tubing by squeezing the appropriate tubing and making sure that there is no change in the ability to deliver or collect air.

If your repair has been anything more than power supply, tubing or mechanical, then you must complete more tests. Be sure to discuss your limited ability to test the machine with the physician and the potential dangers to his patients before conducting any repairs beyond the power supply, tubing or simple mechanical repairs. However, if you and the physician determine that you must attempt a repair; complete at least two more tests before releasing the ventilator: the pressure limit and the delivered volume. Both the volume and pressure are typically tested with dedicate equipment you will likely not have. However, they can be approximated.

The pressure limit is adequately tested by connecting the patient tubing to a u-shaped bend of tubing filled with water. The ventilator should push the far end of the column of water the height of the pressure setting, and then indicate a pressure limit alarm. For example, if the pressure limit is set to 25 cm of water, then the top of the column of water away from the ventilator should be 25 cm of water higher than the top of the column of water near to the ventilator. Test several settings of the pressure limit. Discuss the accuracy of the limit test with the physician.

The volume can be approximated by connecting a balloon to the patient tubing. You must calibrate the balloon to volume before you begin. The easiest way to do this is to fill the balloon with a known volume of water. Make two marks on the balloon a fixed distance apart, indicating the volume next to the mark. Repeat this procedure for several volumes. Now, when the balloon expands to the indicated volume, the marks should be your set distance apart. To use your calibrated balloon, clamp off the balloon at the end of the inspiratory cycle. Test several settings of the volume and discuss the accuracy of the test with the physician.