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Ventilators

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Ventilators

Introduction

Ventilators, which are often also called respirators, are used to artificially ventilate the lungs of patients who are unable to naturally breathe from the atmosphere.

The very early devices used bellows that were manually operated to inflate the lungs as in figure 1. Today's respirators employ an array of sophisticated components such as microprocessors, fast response electrical valves, and precision transducers to perform the task of ventilating the lungs.

A large variety of ventilators are now available for short-term treatment of acute respiratory problems as well as long-term therapy for chronic respiratory conditions.

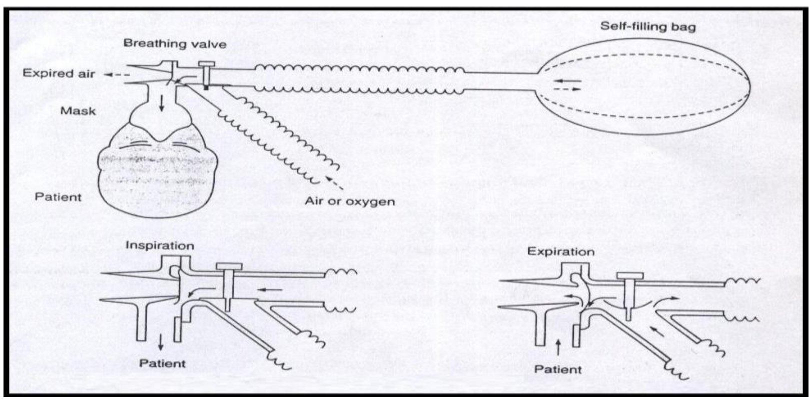

Figure 1, manually operated ventilator

It is reasonable to broadly classify today's ventilators into two groups:

- The first is the intensive care respirators used primarily in hospitals to support patients following certain surgical procedures or assist patients with acute respiratory disorders.
- The second group includes less complicated machines that are primarily used at home to treat patients with chronic respiratory disorders.

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The level of engineering design and sophistication for the intensive care ventilators is higher than the ventilators used for chronic treatment. However, many of the engineering concepts employed in intensive care ventilators can also be applied in the simpler chronic care units. Therefore, we will focus on the design of intensive care ventilators.

At the beginning, the designers of mechanical ventilators realized that the main task of a respirator was to ventilate the lungs in a manner as close to natural respiration as possible. Since natural inspiration is a result of negative pressure in the pleural cavity generated by distention of the diaphragm, designers initially developed ventilators that created the same effect. These ventilators are called *negative-pressure ventilators*.

However, more modern ventilators use pressures greater than atmospheric pressures to ventilate the lungs; they are known as *positive-pressure ventilators*.

Negative-Pressure Ventilators:

Flow of air to the lungs is created by generating a negative pressure around the patient's thoracic cage. The negative pressure moves the thoracic walls outward expanding the intra-thoracic volume and dropping the pressure inside the lungs. The pressure gradient between the atmosphere and the lungs causes the flow of atmospheric air into the lungs. The inspiratory and expiratory phases of the respiration are controlled by cycling the pressure inside the body chamber between a sub-atmospheric level (inspiration) and the atmospheric level (exhalation). Flow of the breath out of the lungs during exhalation is caused by the recoil of thoracic muscles.

Although it may appear that the negative-pressure respirator incorporates the same principles as natural respiration, but major difficulty has been in the design of a chamber for creating negative pressure around the thoracic walls.

One approach has been to make the chamber large enough to house the entire body with the exception of the head and neck. The main drawback was that the negative pressure generated inside the chamber was applied to the chest as well as the abdominal wall, thus creating a venous blood pool in the abdomen and reducing cardiac output.

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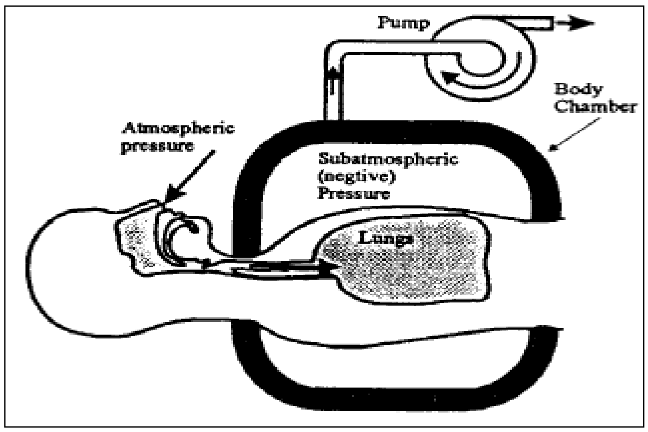
More recent designs have tried to restrict the application of the negative pressure to the chest walls by designing a chamber that goes only around the chest as in figure 2. Negative-pressure ventilators also made the patient less accessible for patient care and monitoring. Further, synchronization of the machine cycle with the patient's effort has been difficult and they are also typically noisy and bulky.



A

B

Figure 2. A. simplified illustration of negative pressure ventilator. B. Iron lung.

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Positive-Pressure Ventilators:

Positive-pressure ventilators generate the inspiratory flow by applying a positive pressure to the airways. Figure 3 shows a simplified block diagram of a positive-pressure ventilator.

During inspiration, the inspiratory flow delivery system creates a positive pressure in the tubes connected to the patient airway, called **patient circuit**, and the exhalation control system closes a valve at the outlet of the tubing to the atmosphere. When the ventilator switches to exhalation, the inspiratory flow delivery system stops the positive pressure and the exhalation system opens the valve to allow the patient's exhaled breath to flow to the atmosphere. The use of a positive pressure gradient in creating the flow allows treatment of patients with high lung resistance and low compliance. As a result, positive-pressure ventilators have been very successful in treating a variety of breathing disorders and have become more popular than negative-pressure ventilators.

Positive-pressure ventilators have been employed to treat patients ranging from neonates to adults.

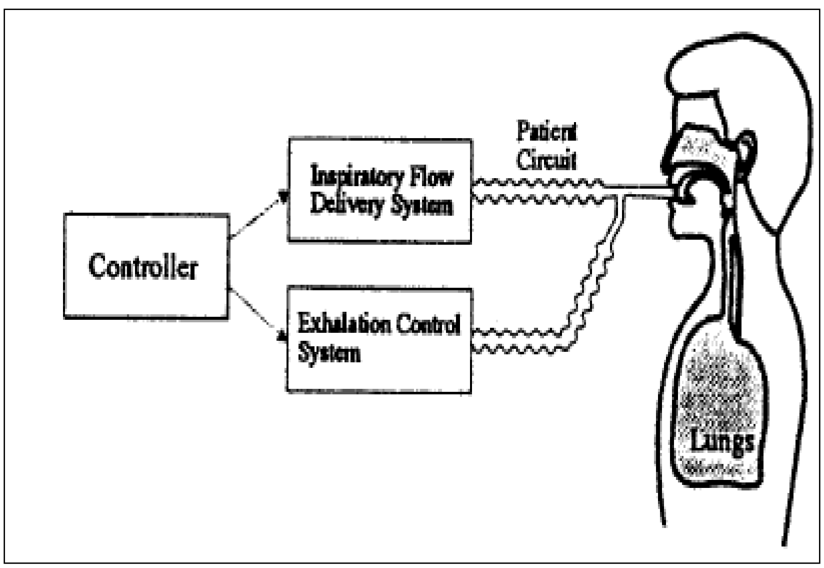

Figure 3, simplified block diagram of positive pressure ventilator

Ventilation Modes:

Ventilator modes are based on patient conditions which are:

Mandatory Ventilation:

In this mode, the respirator completely takes over the task of ventilating the lung of the patients.

Designers of adult ventilators have employed two rather distinct approaches for delivering mandatory breaths: **volume controlled ventilation** and **pressure controlled ventilation**. Volume controlled ventilation, which presently is more popular, refers to delivering a specified tidal volume to the patient during the inspiratory phase. Pressure controlled ventilation, however, refers to raising the airway pressure to a level, set by the therapist, during the inspiratory phase of each breath. Regardless of the type, a ventilator operating in mandatory mode must control all aspects of breathing such as tidal volume, respiration rate, inspiratory flow pattern, and oxygen concentration of the breath. This is often labeled as **controlled mandatory ventilation (CMV).**

Figure 4 shows the flow and pressure waveforms for a volume controlled ventilation (CMV). In this illustration, the inspiratory flow waveform is chosen to be a half sinewave. In Figure 4a, t_i is the inspiration duration, t_e is the exhalation period, and Q_i is the amplitude of inspiratory flow. The ventilator delivers a tidal volume equal to the area under the flow waveform in Figure 4a at regular intervals ($t_i + t_e$) set by the therapist. The resulting pressure waveform is shown in Figure 4b. It is noted that during volume controlled ventilation, the ventilator delivers the same volume irrespective of the patient's respiratory mechanics. However, the resulting pressure waveform such as the one shown in Figure 4b, will be different among patients. Of course, for safety purposes, the ventilator limits the maximum applied airway pressure according to the therapist's setting.

As can be seen in Figure 4b, the airway pressure at the end of exhalation may not end at atmospheric pressure.

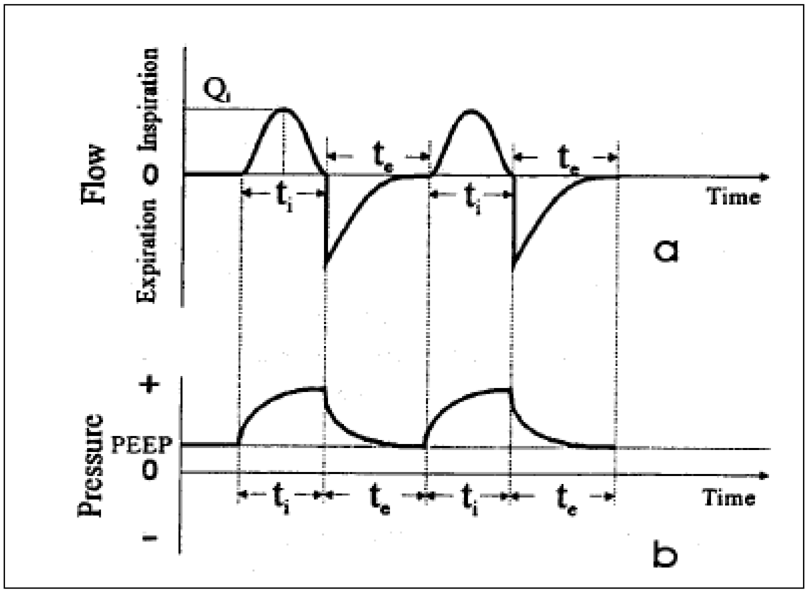

Figure 4, (a) Inspiratory flow for a controlled mandatory volume controlled ventilation breath, (b) airway pressure resulting from the breath delivery with a non-zero PEEP.

The **positive end expiratory pressure (PEEP)** is sometimes used to keep the alveoli from collapsing during expiration. In other cases, the expiration pressure is allowed to return to the atmospheric level.

Figure 5 shows a plot of the pressure and flow during mandatory pressure controlled ventilation.

In this case, the respirator raises and maintains the airway pressure at the desired level independent of patient airway compliance and resistance. The level of pressure during inspiration, *P*i, is set by the therapist. While the ventilator maintains the same pressure trajectory for patients with different respiratory resistance and compliance, the resulting flow trajectory, shown in Figure 5b, will depend on the respiratory mechanics of each patient.

We will focus on volume ventilators, as they are more common. Further, in a microprocessor-based ventilator, the mechanisms for delivering mandatory volume and pressure controlled ventilation have many similar main components. The primary difference lies in the control algorithms governing the delivery of breaths to the patient.

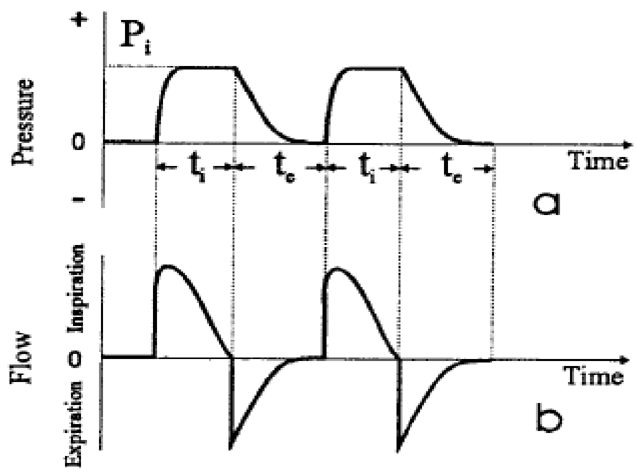

Figure 5, (a) Inspiratory pressure pattern for a controlled mandatory pressure controlled ventilation breath. (b) Airway flow pattern resulting from the breath delivery. Note that PEEP is zero.

Spontaneous Ventilation

An important phase in providing respiratory therapy to a recovering pulmonary patient is weaning the patient from the respirator. As the patient recovers and gains the ability to breathe independently, the ventilator must allow the patient to initiate a breath and control the breath rate, flow rate, and the tidal volume. Ideally, when a respirator is functioning in the spontaneous mode, it should let the patient take breaths with the same ease as breathing from the atmosphere. This, however, is difficult to achieve because the respirator does not have an infinite gas supply or an instantaneous response. In practice, the patient generally has to exert more effort to breathe spontaneously on a respirator than from the atmosphere. However, patient effort is reduced as the ventilator response speed increases. Spontaneous ventilation is often used in conjunction with mandatory ventilation since the patient may still need breaths that are delivered entirely by the ventilator. Alternatively, when a patient can breathe completely on his own, but needs oxygen-enriched breath or elevated airway pressure, spontaneous ventilation alone may be used.

Several modes of spontaneous ventilation have been devised by therapists. Two of the most important and popular spontaneous breath delivery modes are described below.

Continuous Positive Airway Pressure (CPAP) in Spontaneous Mode

In this mode, the ventilator maintains a positive pressure at the airway as the patient attempts to inspire.

Figure 6 illustrates a typical airway pressure waveform during CPAP breath delivery. The therapist sets the sensitivity level lower than PEEP. When the patient attempts to breathe, the pressure drops below the sensitivity level and the ventilator responds by supplying breathable gases to raise the pressure back to the PEEP level. Typically, the PEEP and sensitivity levels are selected such that the patient will be impelled to exert effort to breathe independently. As in the case of the mandatory mode, when the patient exhales the ventilator shuts off the flow of gas and opens the exhalation valve to allow the exhaled gases to flow into the atmosphere.

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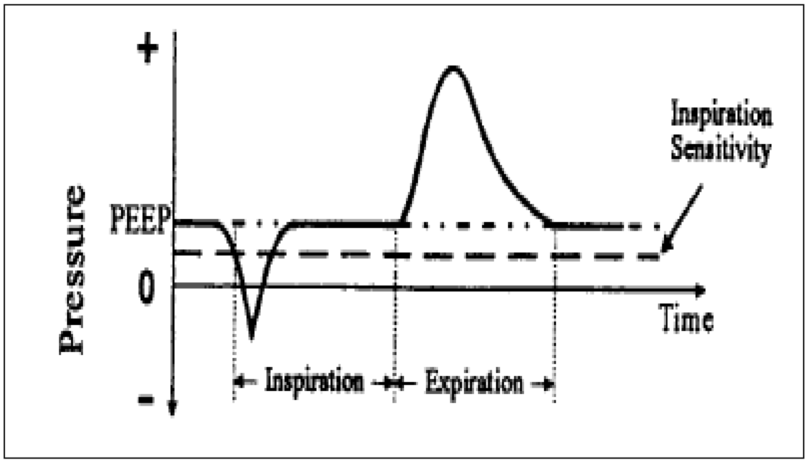

Figure 6, Airway pressure during a CPAP spontaneous breath delivery

Pressure Support in Spontaneous Mode

This mode is similar to the CPAP mode with the exception that during the inspiration the ventilator attempts to maintain the patient airway pressure at a level above PEEP.

Figure 7 shows a typical airway pressure waveform during the delivery of a pressure support breath. In this mode, when the patient's airway pressure drops below the therapist-set sensitivity line, the ventilator inspiratory breath delivery system raises the airway pressure to the **pressure support level** (>PEEP), selected by the therapist. The ventilator stops the flow of breathable gases when the patient starts to exhale and controls the exhalation valve to achieve the set PEEP level.

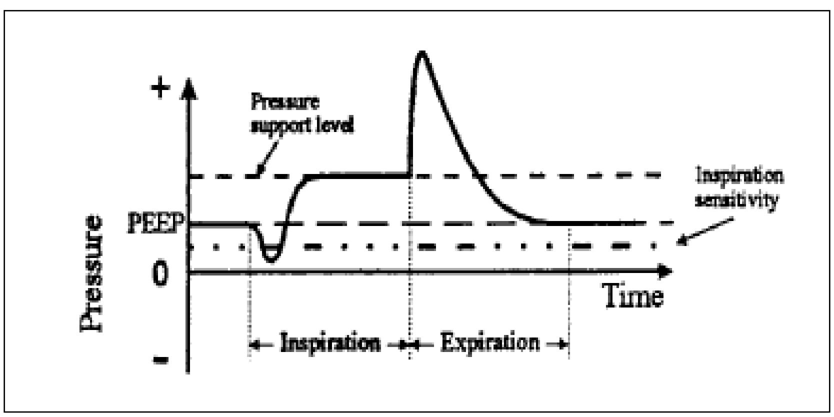

Figure 6, Airway pressure during a pressure support spontaneous breath delivery.

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Breathe Delivery Control

Figure 8 shows a simplified block diagram for delivering mandatory or spontaneous ventilation.

Compressed air and oxygen are normally stored in high pressure tanks (~=1400 kPa) that are attached to the inlets of the ventilator. In some ventilators, an air compressor is used in place of a compressed air tank. Manufacturers of respirators have designed a variety of blending and metering devices. The primary mission of the device is to enrich the inspiratory air flow with the proper level of oxygen and to deliver a tidal volume according to the therapist's specifications. With the introduction of microprocessors for control of metering devices, electromechanical valves have gained popularity. In Figure 8, the air and oxygen valves are placed in closed feedback loops with the air and oxygen flow sensors. The microprocessor controls each valves to deliver the desired inspiratory air and oxygen flows for mandatory and spontaneous ventilation. During inhalation, the exhalation valve is closed to direct all the delivered flows to the lungs. When exhalation starts, the microprocessor actuates the exhalation valve to achieve the desired PEEP level. The airway pressure sensor, shown on the right side of Figure 8, generates the feedback signal necessary for maintaining the desired PEEP (in both mandatory and spontaneous modes) and airway pressure support level during spontaneous breath delivery.

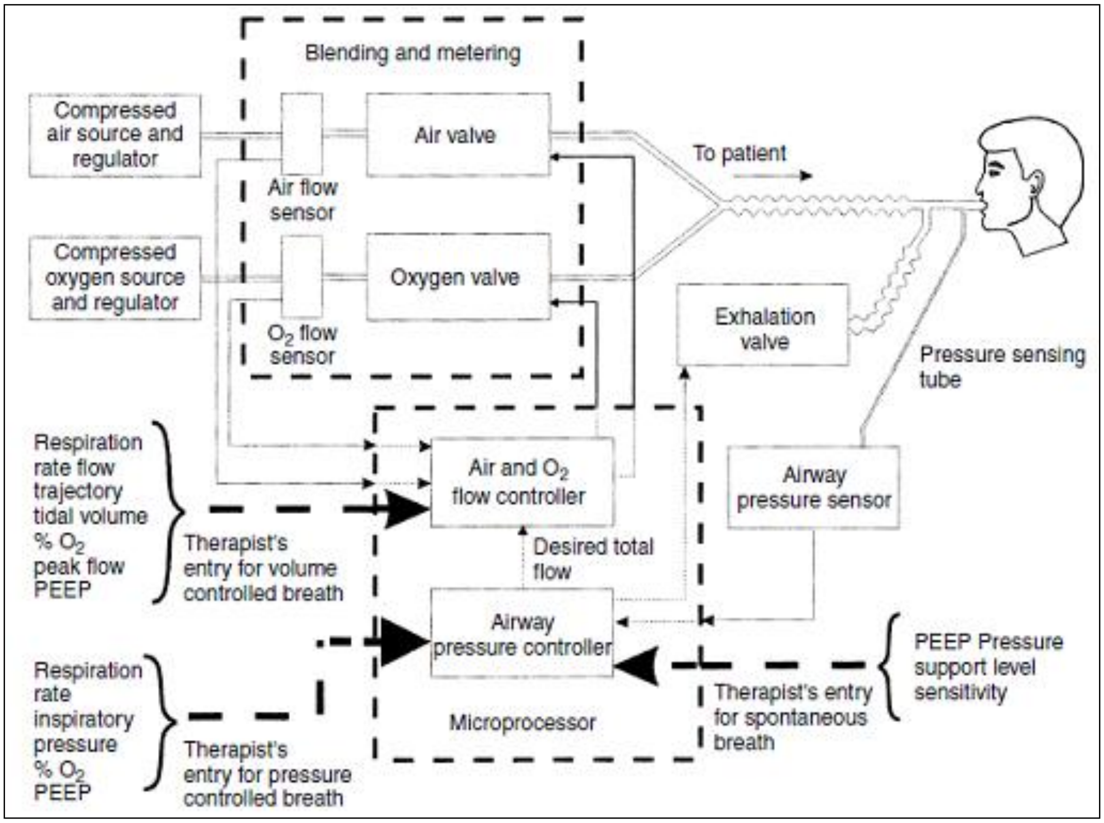

Figure 8, a simplified block diagram of a control structure for mandatory and spontaneous breath delivery

Mandatory Volume Controlled Inspiratory Flow Delivery:

The electronically actuated valves open from a closed position to allow the flow of blended gases to the patient. The control of flow through each valve depends on the therapist's specification for the mandatory breath. That is, the clinician must specify the following parameters for delivery of CMV breaths (1) respiration rate; (2) flow waveform; (3) tidal volume; (4) oxygen concentration (of the delivered breath); (5) peak flow; and (6) PEEP, as shown in Figure 8. It is noted that the PEEP selected by the therapist in the mandatory mode is only used for control of exhalation flow. The microprocessor utilizes the first five of the above parameters to compute the total desired inspiratory flow trajectory.

Pressure Controlled Inspiratory Flow Delivery

The therapist entry for pressure-controlled ventilation is shown in Figure 8. The total desired flow is generated by a closed loop controller labeled as Airway Pressure Controller. This controller uses the therapist-selected inspiratory pressure, respiration rate, and the inspiratory- expiratory ratio to compute the desired inspiratory pressure trajectory. The trajectory serves as the controller reference input. The controller then computes the flow necessary to make the actual airway pressure track the reference input.

Expiratory Pressure Control in Mandatory Mode

It is often desirable to keep the patient's lungs inflated at the end of expiration at a pressure greater than atmospheric level. That is, rather than allowing the lungs to deflate during the exhalation, the controller closes the exhalation valve when the airway pressure reaches the PEEP level.

When expiration starts, the ventilator terminates flow to the lungs; hence, the regulation of the airway pressure is achieved by controlling the flow of patient exhaled gases through the exhalation valve.

In a microprocessor-based ventilator, an electronically actuated valve can be employed that has adequate response (~= 20 msec rise time) to regulate PEEP. For this purpose, the pressure in the patient breath delivery circuit is measured using a pressure transducer. The microprocessor will initially open the exhalation valve completely to minimize resistance to expiratory flow. At the same time, it will sample the pressure transducer's output and start to close the exhalation valve as the pressure begins to approach the desired PEEP level. Since the patient's exhaled flow is the only source of pressure, if the airway pressure drops below PEEP, it cannot be brought back up until the next inspiratory period.

Spontaneous Breath Delivery Control

The small diameter (~= 5 mm) pressure sensing tube, shown on the right side of Figure 8, pneumatically transmits the pneumatic pressure signal from the patient airway to a pressure transducer placed in the ventilator. The output of the pressure transducer is amplified, filtered, and then sampled by the microprocessor. The controller receives the therapist's inputs regarding the spontaneous breath characteristics such as the PEEP, sensitivity, and oxygen concentration. The desired airway pressure is computed from the therapist entries of PEEP, pressure support level, and sensitivity. The multiple-loop control structure shown in Figure 8 is used to deliver a CPAP or a pressure support breath. The sensed proximal airway pressure is compared with the desired airway pressure. The airway pressure controller computes the total inspiratory flow level required to raise the airway pressure to the desired level. This flow level serves as the reference input or total desired flow for the flow control loop. Hence, in general, the desired total flow trajectory for the spontaneous breath delivery may be different for each inspiratory cycle. If the operator has specified oxygen concentration greater than 21.6% (the atmospheric air oxygen concentration of the ventilator air supply), the controller will partition the total required flow into the air and oxygen flow rates. The flow controller then uses the feedback signals from air and oxygen flow sensors and actuates the air and oxygen valves to deliver the desired flows.

If a non-zero PEEP level is specified, the same control strategy as the one described for mandatory breath delivery can be used to achieve the desired PEEP.

Summary

Today's mechanical can be broadly classified into negative-pressure and positive-pressure ventilators. Negative-pressure ventilators do not offer the flexibility and convenience that positive-pressure ventilators provide; hence, they have not been very popular in clinical use. Positive-pressure ventilators have been quite successful in treating patients with pulmonary disorders. These ventilators operate in either mandatory or spontaneous mode. When delivering mandatory breaths, the ventilator controls all parameters of the breath such as tidal volume, inspiratory flow waveform, respiration rate, and oxygen content of the breath. Mandatory breaths are normally delivered to the patients that are incapable of breathing on their own. In contrast, spontaneous breath delivery refers to the case where the ventilator responds to the patient's effort to breathe independently. Therefore, the patient can control the volume and the rate of the respiration. The therapist selects the oxygen content and the pressure at which the breath is delivered. Spontaneous breath delivery is typically used for patients who are on their way to full recovery, but are not completely ready to breathe from the atmosphere without mechanical assistance.

Ventilators

Defining Terms

Continuous positive airway pressure (CPAP): A spontaneous ventilation mode in which the ventilator maintains a constant positive pressure, near or below PEEP level, in the patient's airway while the patient breathes at will.

Mandatory mode: A mode of mechanically ventilating the lungs where the ventilator controls all breath delivery parameters such as tidal volume, respiration rate, flow waveform, etc.

Patient circuit: A set of tubes connecting the patient airway to the outlet of a respirator.

Positive end expiratory pressure (PEEP): A therapist-selected pressure level for the patient airway at the end of expiration in either mandatory or spontaneous breathing.

Pressure controlled ventilation: A mandatory mode of ventilation where during the inspiration phase of each breath, a constant pressure is applied to the patient's airway independent of the patient's airway resistance and/or compliance respiratory mechanics.

Pressure support: A spontaneous breath delivery mode during which the ventilator applies a positive pressure greater than PEEP to the patient's airway during inspiration.

Pressure support level: Refers to the pressure level, above PEEP, that the ventilator maintains during the spontaneous inspiration.

Spontaneous mode: A ventilation mode in which the patient initiates and breathes from the ventilator supplied gas at will.

Volume controlled ventilation: A mandatory mode of ventilation where the volume of each breath is set by the therapist and the ventilator delivers that volume to the patient independent of the patient's airway resistance and/or compliance respiratory mechanics.

Lung Compliance: is the ability of the alveoli and lung tissue to expand on inspiration. It is represented by the ration of volume delivered to the pressure rise during the inspiratory phase in the lung, and it is expressed as liters/cm H_2O.

Airway Resistance: relates to the ease with which air flows through the tubular respiratory structures. Higher resistances occur in smaller tubes such as bronchioles and alveoli that have not emptied properly.