Artificial organs – internal & external (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.

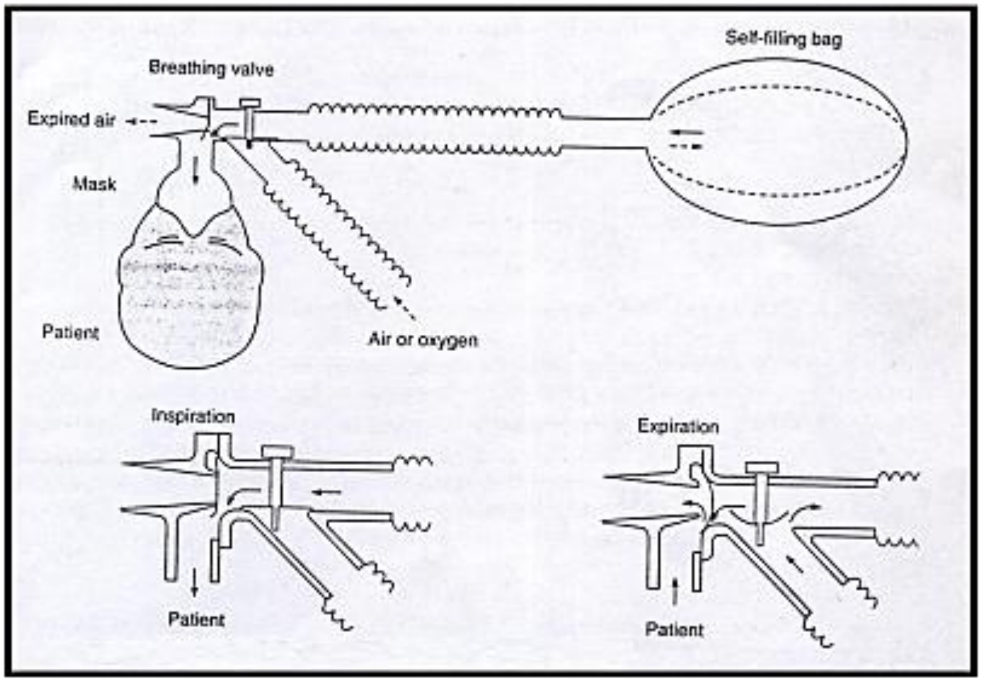

Figure 1, manually operated ventilator

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.

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 <u>generating a negative pressure around the patient's thoracic cage</u>. 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.
- 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.

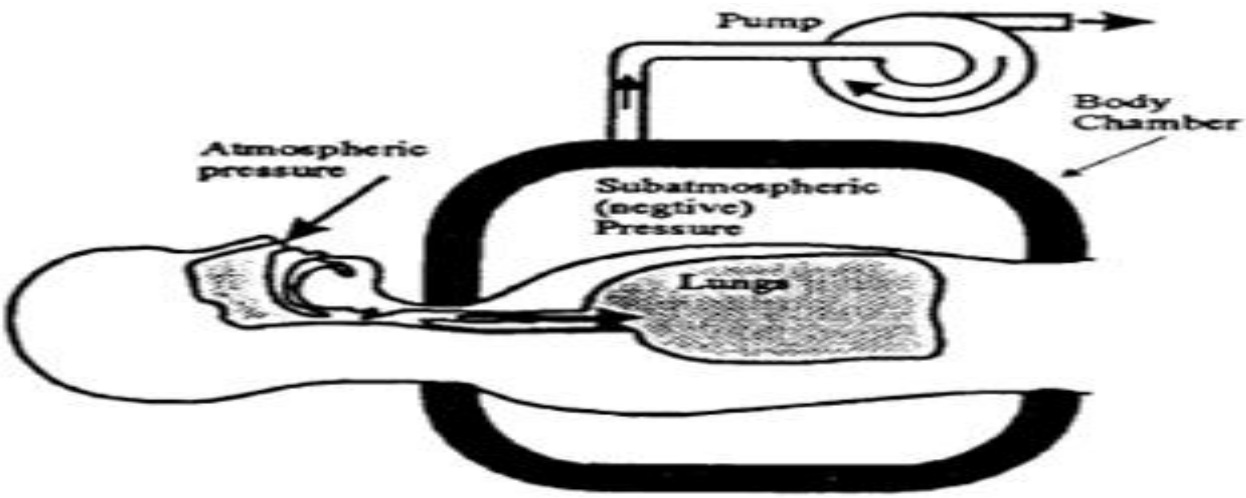

Figure 2. Iron lung.

Notes:

An iron lung, also known as a negative pressure ventilator, is a device used for assisted ventilation of patients with respiratory muscle paralysis, typically caused by conditions like polio. Here's how it works:

- Enclosed Chamber: The patient is placed inside a sealed cylindrical chamber made of metal, hence the name "iron lung." The patient's head and neck protrude from the chamber, and their body is enclosed inside.
- Negative Pressure: The chamber creates a partial vacuum, reducing the air pressure around the patient's chest. This causes the patient's chest to expand, allowing air to be drawn into the lungs.
- Intermittent Pressure Changes: To simulate natural breathing, the pressure within the chamber is alternated between negative and atmospheric pressure. When the pressure drops, the patient's chest expands, drawing air into the lungs, and when the pressure returns to normal, the patient exhales.
- Cyclic Ventilation: The cycle of pressure changes continues, providing cyclic ventilation to the patient. It essentially assists the patient's breathing by changing the pressure around the chest cavity.
- The iron lung maintains this cyclic process to ensure that the patient receives sufficient oxygen and can expel carbon dioxide. While iron lungs were once a crucial tool for polio patients, they have primarily been replaced by modern mechanical ventilators and other advanced respiratory support systems.

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.

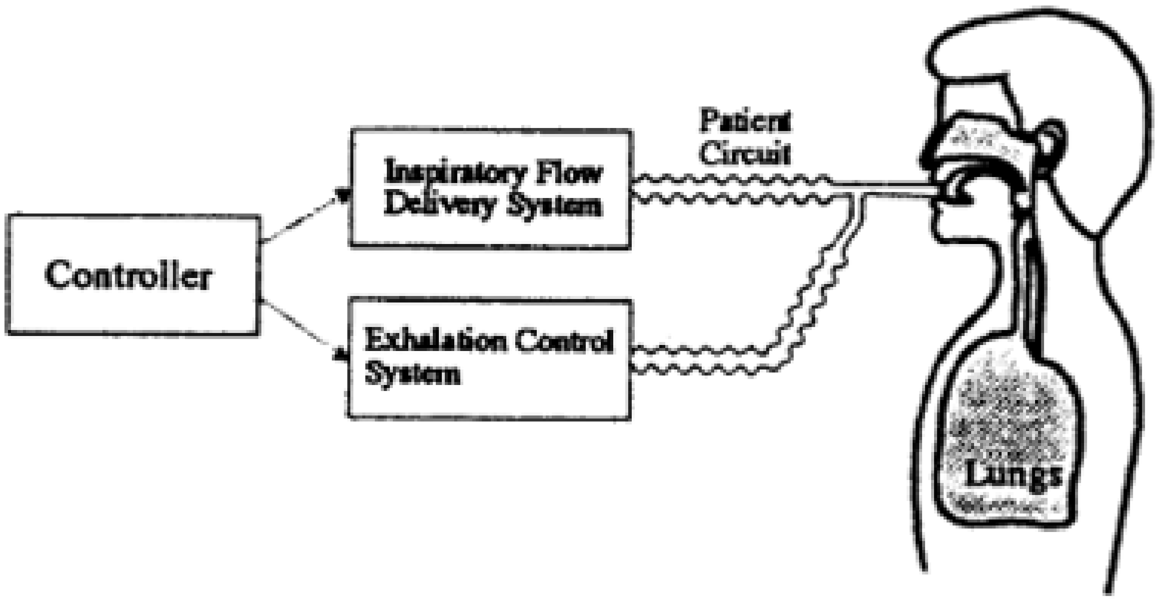

Figure 3 simplified block diagram of posaitive pressure ventilator

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.

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- 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.

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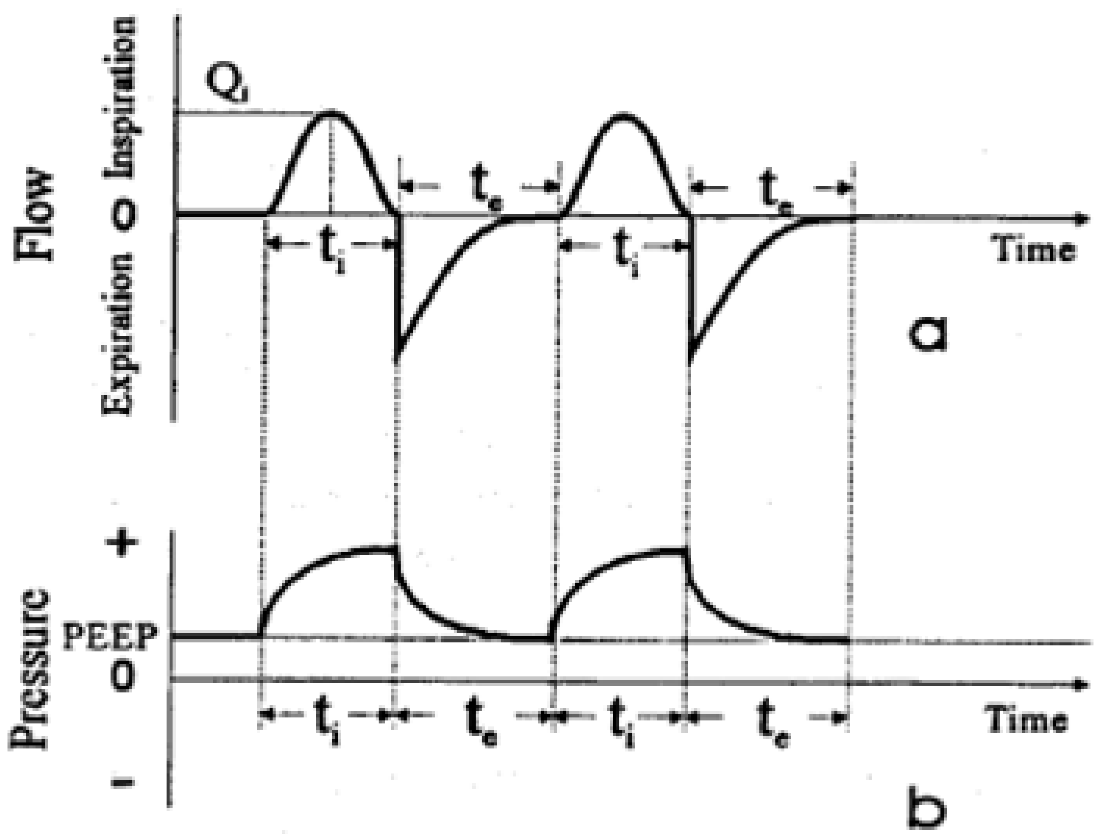

Figure 4. (a) Inspiratory flow for a controlled mandatory volume-controlled ventilation breath, (b) airway pressure resulting from the breath delivery with a non-zero PEEP.

- 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.

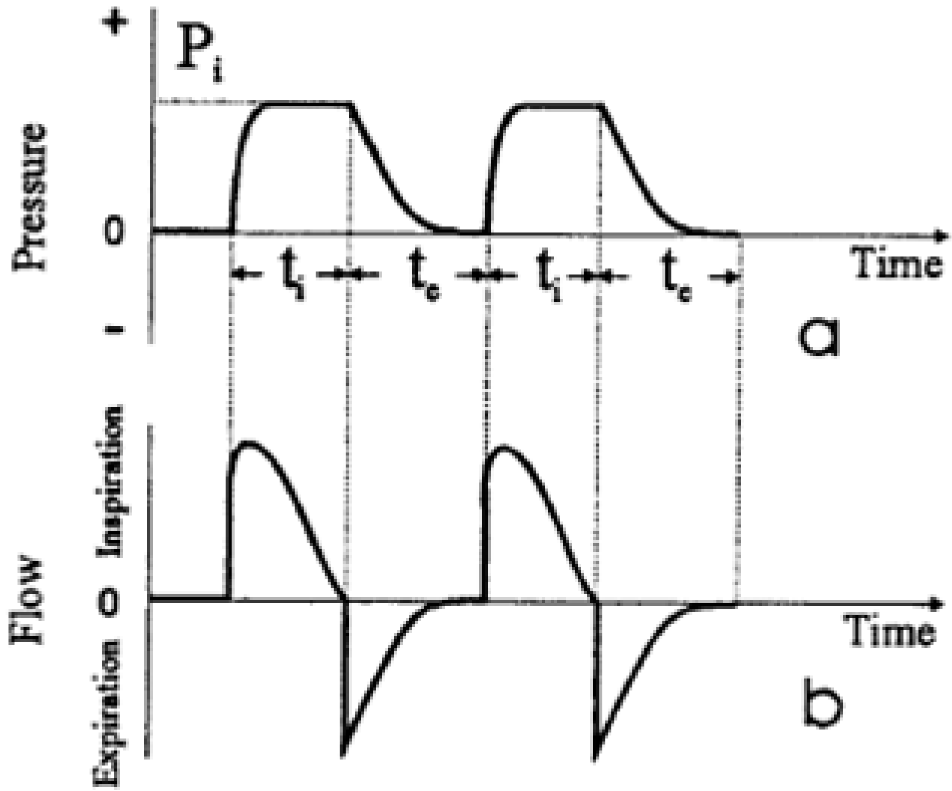

Figure 5, (a) Inspiratory pressure pattern for a controlled mandatory pressure-controlled ventilation breath. (b) Airway flow pattern resulting from the breath delivery. Note that positive end-expiratory pressure (PEEP) is zero.