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Artificial ventilation: history, equipment and techniques

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A brief history of artificial ventilators

An artificial ventilator is essentially a device that replaces or augments the function of the inspiratory muscles, providing the necessary energy to ensure a flow of gas into the alveoli during inspiration. When this support is removed gas is expelled as the lung and chest wall recoil to their original volume; exhalation is a passive process. In the earliest reports of artificial ventilation this energy was provided by the respiratory muscles of another person, as expired air resuscitation. Baker[1] has traced references to expired air resuscitation in the newborn as far back as 1472, and in adults there is a report of an asphyxiated miner being revived with mouth to mouth resuscitation in 1744. In the eighteenth century artificial ventilation became the accepted first line treatment for drowning victims, though the use of bellows replaced mouth to mouth resuscitation.[2] Automatic artificial ventilators that did not require a human as a power source took another 150 years to appear, being first suggested by Fell[3] and then made available commercially by Draeger[4] in 1907. These were still devices for resuscitation, for the Draeger company at that time was noted for its mine rescue apparatus.

The introduction of artificial ventilators into anaesthesia proceeded slowly until surgeons ventured into the chest. During thoracic surgery on spontaneously breathing patients the inevitable pneumothoraces and mediastinal shift ("mediastinal flap") that occurred as the pleural cavity was opened caused a high mortality, which was substantially reduced when positive pressure ventilation was used. A further boost to the development of automatic artificial ventilators occurred in 1952, when a catastrophic poliomyelitis epidemic struck Denmark. There was a very high incidence of bulbar lesions and 316 out of 866 patients with paralysis admitted over a period of 19 weeks required postural drainage, tracheostomy, or respiratory support. By using tracheostomy and manual positive pressure ventilation the Danish physicians reduced the mortality from poliomyelitis from 80% at the beginning of the epidemic to 23% at the end. The artificial ventilation was entirely by hand, a total of 1400 university students working in shifts to keep the patients ventilated. The fear that another epidemic might afflict Europe expedited research into powered mechanical ventilators.

Classification of artificial ventilators

The lungs can be artificially ventilated either by reducing the ambient pressure around the thorax (negative pressure ventilation) or by increasing the pressure within the airways (positive pressure ventilation). Negative pressure ventilators use a rigid chamber that encloses either the thorax (cuirass) or the whole body below the neck (tank respirator or "iron lung"). The pressure in the chamber is reduced cyclically by means of a large volume displacement pump, thus causing the lungs to expand and contract. Negative pressure ventilation is fully discussed in article 5 of this series. These ventilators were used extensively for poliomyelitis victims, and are still in use for long term respiratory support or overnight support for patients with respiratory muscle weakness. Tank ventilators occupy much space, access to the patient is poor, and the neck seal can create problems. They are not suitable for use in general intensive care units. There has been a recent revival in interest in negative pressure ventilators in paediatric intensive care units to avoid the need for endotracheal intubation.[5]

The basic classification of positive pressure artificial ventilators was first proposed by Mapleson.[6] Artificial ventilators are devices that control inspiration; expiration is usually passive, and so the classification is based on the mechanism of gas delivery during inspiration. There are two types of machine. A flow generator produces a known pattern of gas flow during inspiration, and the lungs fill at a rate entirely controlled by the ventilator and independent of any effect of lung mechanics. A pressure generator produces a preset pressure in the airway and the rate of lung inflation depends not only on the pressure generated by the ventilator but also on the respiratory resistance and compliance, which determine the time constant of the lungs. With a square wave pattern of pressure the lungs fill in an exponential fashion. The effects of the two types of ventilator on inspiratory flow and lung volume are shown in figure 1.

In general, the flow generator ventilator is used for adults and the pressure generator ventilator for children, or adults when control of peak airway pressure is important. The

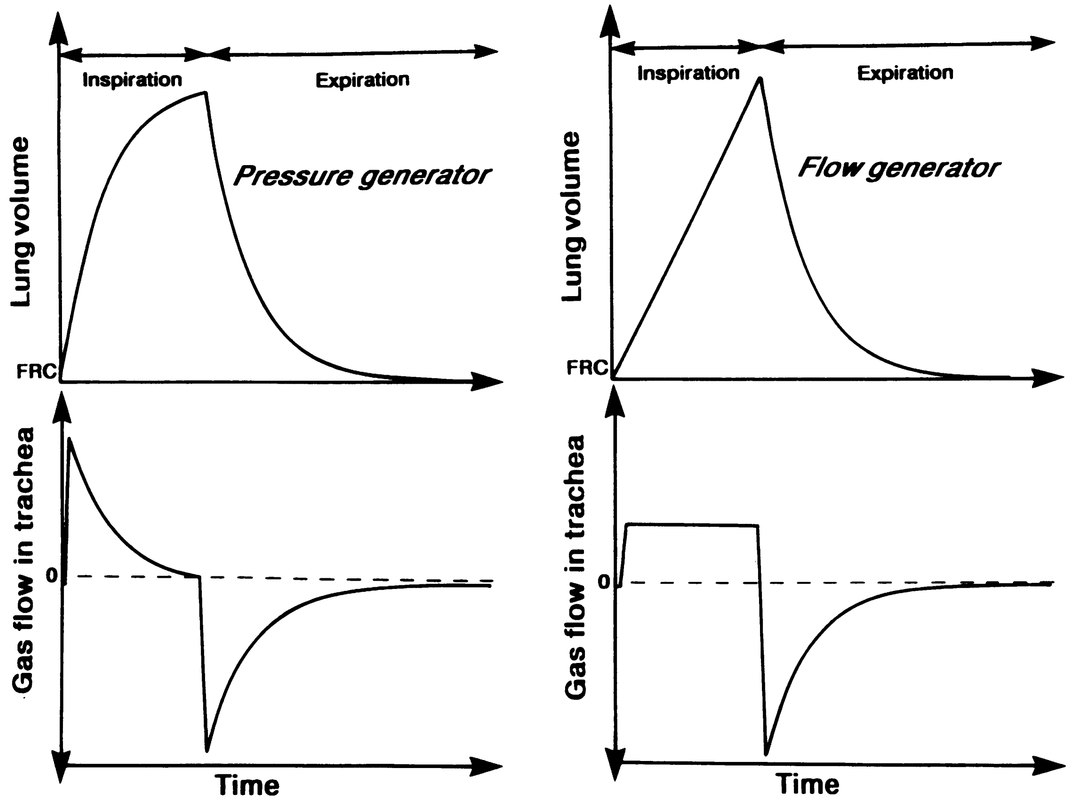

Figure 1 Lung volume and gas flow during one respiratory cycle with pressure and flow generator ventilators.

pressure generator is particularly useful in children where uncuffed endotracheal tubes are used and there is a leak of gas around the endotracheal tube during inspiration. A pressure generator tends to compensate for this leak by increasing the flow into the airway, whereas with a flow generator a proportion of the tidal volume is lost.

A ventilator must also have a mechanism to cause it to cycle between inspiration and expiration. Ventilators are usually subclassified as time cycled, pressure cycled, or volume cycled machines. Time cycled ventilators switch between inspiration and expiration after a preset time interval, pressure cycled ventilators switch when a preset airway pressure threshold has been reached, and volume cycled ventilators cycle when a preset tidal volume has been delivered. Cycling from expiration to inspiration is usually effected by a timing mechanism or by a patient triggering device that senses the subatmospheric pressure or the flow generated in the inspiratory tube by the patient's inspiratory effort.

This traditional classification was devised during a period when ventilators were totally mechanical, and driven either by compressed gas or by an electrically powered piston or bellows. By 1954, however, Donald had used an electronic trigger that initiated inspiration and in 1958 an electronic timing device was incorporated in the Barnet ventilator.[7] In 1971 the Siemens-Elema company introduced the Servo 900 ventilator, which combined a simple pneumatic system with a sophisticated electronic measuring and control unit.[8] Gas flow to and from the patient's lungs was controlled by a pair of scissor valves and monitored with pressure and flow sensors. The control unit adjusted the scissor valves to ensure that the flow patterns measured by the sensors corresponded to those selected by the operator. This method of control is termed a servo or feedback system and is very flexible. Potentially one machine could mimic all the previously described categories of ventilator.

Modern intensive care unit ventilators

Most modern intensive care unit ventilators use similar technology. A simplified diagram of such a ventilator is shown in figure 2. The respiratory gas is held in a pressurised reservoir and delivered to the patient via an inspiratory valve. The inspiratory valve and hence the inspiratory flow is controlled by the electronic control unit. The airway pressure and flow of gas into the patient are monitored by the pressure and inspiratory flow sensors. The expiratory flow can also be monitored to check for leaks and disconnection of the patient from the ventilator. This design enables the ventilator to be used as either a flow or a pressure generator. For example, if the operator selects a constant flow during inspiration the ventilator will open the inspiratory valve until the flow sensor measures the required flow. If the inspiratory flow decreases the inspiratory valve will be opened further to compensate, and vice versa. If the operator wishes the ventilator to act as a constant pressure generator, the ventilator will open the inspiratory valve until the pressure sensor indicates that the desired pressure has been reached. The ventilator will then maintain the airway pressure at the desired

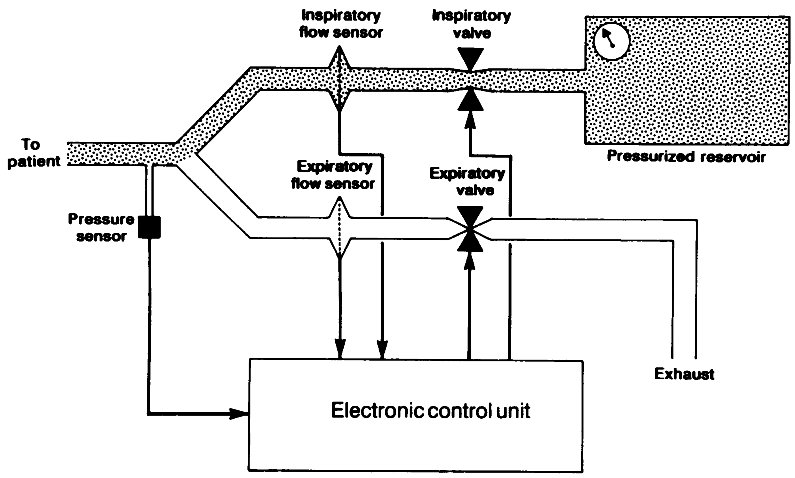

Figure 2 A block diagram of a modern ventilator. The shaded area indicates the gas path during inspiration.

level by opening or closing the inspiratory valve. The bulk of a modern ventilator is now the electronic unit and the pneumatic units are often very compact. Figure 3 is a photograph of a Servo 900D ventilator. The pneumatic systems are housed in the top section and the bottom section contains only electronics.

The use of electronic feedback systems in ventilators has many advantages. The moving parts within the ventilator are kept to a minimum, sophisticated alarm systems are possible, the ventilators can be made physically small, and maintenance and repair are simple. If a new mode of ventilation appears to be useful clinically it can often be added to an existing machine by altering the software in the electronic unit—indeed, our ability to produce new modes of artificial ventilation far exceeds our ability to test them clinically.

Interactions between patients and ventilators

As early as 1929 it was observed that a patient who "fought" the ventilator was difficult to manage and suffered complications.[9] To minimise these problems many ventilated patients are sedated, and in some cases paralysed with neuromuscular blocking agents (for example, pancuronium). In the early 1980s paralysis of ventilated patients was very common in British intensive care units,[10 11] and sedation was used to dissociate the patients from their surroundings. Over the last decade the amount of sedative and paralysing drugs given to intensive care patients has been reduced considerably.

Paralysis of ventilated patients is not without risks.[12] The paralysed patient is unable to make any spontaneous respiratory effort, so a disconnection from the ventilator is rapidly fatal. The patient may be aware of his or her surroundings but is unable to communicate, and the risk of pulmonary embolus is probably increased. Even sedative drugs are not without risk,[13] as shown by the substantial increase in mortality in trauma patients given etomidate infusions. This was subsequently shown to be caused by suppression of adrenal activity by the drug.

Only a few clinicians now favour deep sedation and paralysis,[14] the preferred approach being a comfortable patient who can be easily aroused and can communicate with the staff. To achieve this goal ventilators have to be more flexible and adapted to the needs of the patient. In its simplest form this is achieved by inserting a valve into the ventilator tubing, which allows the patient to breathe spontaneously from another gas source between the breaths delivered by the ventilator. This mode of ventilation is termed intermittent mandatory ventilation (IMV) and was initially used as a technique to wean patients from mechanical ventilation to spontaneous respiration. By 1987, however, over 70% of American intensive care units were using intermittent mandatory ventilation as their primary mode of ventilatory support.[15] It is not a truly interactive mode of ventilation—the ventilator continues to deliver the preset pattern of ventilation regardless of the patient's respiratory effort. The advent of microprocessor controlled ventilators has produced several "smart" modes of ventilation, where the ventilator adjusts the ventilatory support it supplies according to the patient's respiratory efforts. The commonest modes used are synchronised intermittent mandatory ventilation, mandatory minute ventilation, and inspiratory pressure support.

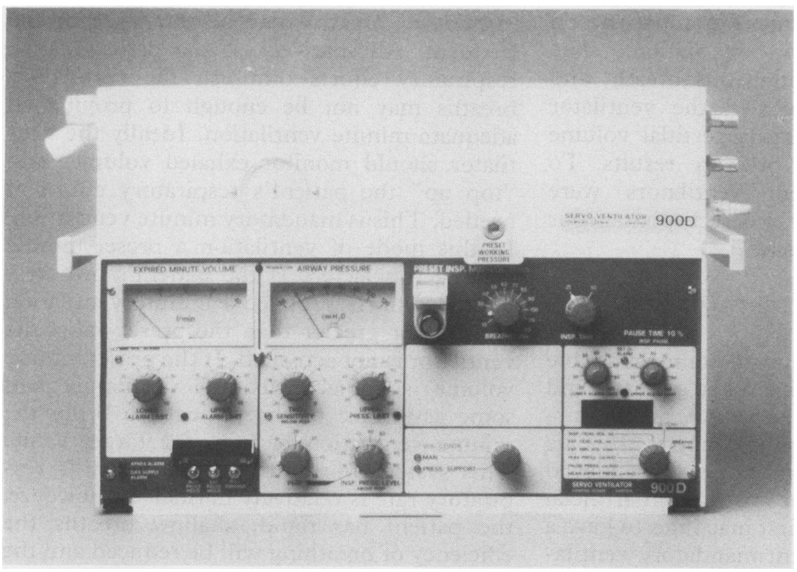

Figure 3 A Siemens Servo 900D ventilator.

Ventilatory strategies in common use

INTERMITTENT POSITIVE PRESSURE VENTILATION

Each year millions of patients are ventilated during anaesthesia for surgical procedures that require muscular relaxation. Nearly all of these patients are ventilated with basic intermittent positive pressure ventilation by means of a simple mechanical ventilator. For these short periods of respiratory support these ventilators are perfectly adequate, for as the patient is both paralysed and anaesthetised there is no need for interactive ventilators. Weaning is accompli-

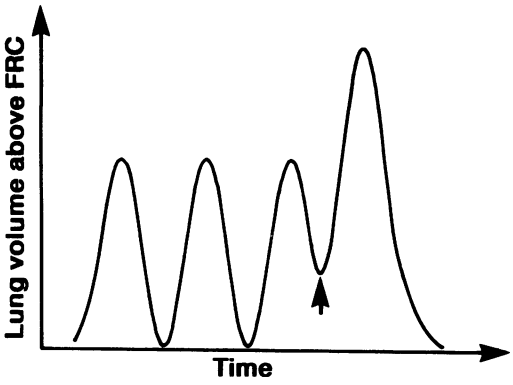

Figure 4 "Stacking" of breaths during intermittent mandatory ventilation. The arrow indicates where a mandatory breath starts before the patient has fully expired.

shed by reversing the muscle relaxation and lightening the anaesthetic. In intensive care units this mode of ventilation is used when the patient has to be heavily sedated and paralysed to treat the primary condition (for example, tetanus) or when the patient is unable to make any respiratory movement (for example, severe Guillain-Barré syndrome). Intermittent positive pressure ventilation can be achieved with almost any artificial ventilator as no special refinements are needed.

INTERMITTENT MANDATORY VENTILATION

As outlined above, intermittent mandatory ventilation describes a mode of mechanical ventilation that allows the patient to breathe spontaneously through the ventilator circuit. At predetermined intervals a positive pressure breath is provided by the ventilator totally independently of the patient's spontaneous ventilatory pattern. The system is a simple mechanical device that can be fitted to almost any ventilator, though care has to be taken to ensure that the oxygen concentration is the same in the spontaneous breaths as during the breaths delivered by the ventilator and that the inspired gas is appropriately humidified.[16] Though simple it is not without disadvantages. There is no synchronisation between the patient's respiratory efforts and the ventilator, and this can lead to "stacking" of breaths and high airway pressures. Figure 4 shows a plot of lung volume against time for a patient on intermittent mandatory ventilation. The patient can take a spontaneous breath, and before he has fully exhaled the ventilator delivers a breath. A very large tidal volume with high peak airway pressure results. To overcome this problem ventilators were developed that were able to detect spontaneous breaths taken by the patient.

SYNCHRONISED INTERMITTENT MANDATORY VENTILATION

To avoid "stacking" the ventilator must be able to sense that the patient has taken a breath, and then avoid delivering a mandatory breath during the period of the spontaneous breath. This level of sophistication was not easily achieved before electronic control was used in artificial ventilators. One of the first machines to have a synchronised intermittent mandatory ventilation facility was the Servo 900B, a refinement of the original Servo 900. This machine dispensed with external intermittent mandatory ventilation valves and used its internal valves and sensors to provide synchronised intermittent mandatory ventilation. Any spontaneous inspiratory activity by the patient was sensed by the pressure sensor and then the expiratory valve was closed and the inspiratory valve opened. The flow of gas through the inspiratory valve was matched to the patient's inspiratory flow rate by opening and closing the inspiratory valve. This allowed the patient to breathe spontaneously through the ventilator. When a mandatory breath was due the ventilator would wait until the patient began to inspire and then deliver the mandatory breath, synchronising the mandatory breath with the patient's own inspiratory effort.

All ventilators with synchronised intermittent mandatory ventilation systems use some form of synchronisation between patient and machine, the exact details varying between machines. All synchronised intermittent mandatory ventilation machines are not equally effective, for the time taken for the inspiratory valve to open after the pressure sensor has been triggered varies between machines. During the period between the beginning of the patient's inspiration and the opening of the inspiratory valve the patient inspires against a closed valve, increasing the work of breathing.[17] Machines with a short lag between the beginning of an inspiratory effort and the opening of the inspiratory valve are preferred. Although subjectively patients usually appear more comfortable with synchronised intermittent mandatory ventilation than intermittent positive pressure ventilation or intermittent mandatory ventilation, there is no evidence that it reduces morbidity or mortality in intensive care units.

MANDATORY MINUTE VENTILATION

The synchronised intermittent mandatory ventilation systems described add a preset number of breaths of a preset volume to the patient's own respiratory efforts. If the patient's spontaneous breaths are providing most of the required minute ventilation, the mandatory breaths may be too large or too frequent. Alternatively, if the patient's own respiratory efforts diminish the mandatory breaths may not be enough to provide an adequate minute ventilation. Ideally the ventilator should monitor exhaled volumes and "top up" the patient's respiratory efforts if needed. This is mandatory minute ventilation. In this mode of ventilation a preset minute volume is selected. If the patient's own respiratory efforts produce a minute ventilation equal to or greater than the preset value the ventilator is not activated. If the preset minute volume is not achieved the ventilator gives some assistance to the patient, to bring the minute ventilation back to the target value. This system works well if the patient's respiratory rate is relatively normal. If, however, the patient has rapid, shallow breaths the efficiency of breathing will be reduced and the mandatory volume may become inadequate.

The method used to provide ventilatory

assistance depends on the design of the ventilator. The Ohmeda CPU1 and Engstrom Erica will provide synchronised mandatory breaths of a preset tidal volume at an increasing frequency as the patient's own respiratory efforts diminish. The Hamilton Veolar uses a different approach and provides increasing inspiratory pressure support (see below) as the patient's own efforts decrease. Whichever method is used, the machines ensure that the patient always receives a predetermined minute volume.

INSPIRATORY PRESSURE SUPPORT

The most recent mode of ventilation to be widely used is inspiratory pressure support. As the patient initiates a breath the ventilator raises the airway pressure to a preset value. The positive airway pressure provides some of the energy needed to expand the lung and the efforts of the patient provide the rest. At the end of inspiration the positive airway pressure is removed to allow unimpeded expiration. By selection of an appropriate level of airway pressure patients can be given only the respiratory assistance they actually require. The patient also determines his or her own respiratory rate. This is a relatively new mode of ventilation and has not yet been fully assessed. This form of ventilation differs from the assist mode commonly used in the 1960s. In the assist mode the magnitude of the breath was preset by the adjustment of controls on the ventilator and the breath was initiated whenever the patient trigger was activated. In inspiratory pressure support a constant pressure is applied after the patient triggers the ventilator so that the patient can determine the flow pattern and size of breath. Inspiration is terminated when the inspiratory flow ceases.

POSITIVE END EXPIRATORY PRESSURE

Patients who are anaesthetised or comatose or who have recently undergone abdominal surgery have a reduced functional residual capacity. The reduction may be sufficient to cause airway closure in dependent areas of the lung before the end of expiration, leading to underventilation of these areas and ventilation–perfusion mismatch.[18] This in turn leads to hypoxaemia. The functional residual capacity can be maintained by leaving a constant standing pressure on the lungs, keeping them slightly inflated even at the end of expiration. This is positive end expiratory pressure or PEEP. The use of PEEP, and how best to determine its optimum level, has been the subject of debate for many years. On the positive side, it causes an increase in arterial oxygen tension for the same inspired oxygen tension. On the negative side, the constantly raised intrathoracic pressure causes a diminution in venous return to the heart, a decrease in cardiac output, and an increased risk of pneumothorax. The controversy may now be resolved, for a recent study showed that mortality increased with the aggressive application of PEEP and that the minimum level which kept arterial oxygenation within acceptable limits was "best PEEP."[19]

UNUSUAL MODES OF VENTILATION

There are several modes of ventilation that are still being evaluated clinically. In high frequency jet ventilation brief, frequently repeated pulses of gas (up to 300 a minute) are directed from a high pressure nozzle down the airway. The tidal volumes delivered are small, airway pressures are low, and the patient can breathe spontaneously while being ventilated.[20] High frequency oscillation techniques oscillate gas in the airways using a piston pump or diaphragm pump. The tidal volumes used are very small, much less than the anatomical dead space, so gas movement occurs by mechanisms other than tidal exchange. Because of the large size of oscillators needed for adults this technique has been confined to use in infants. There are also two extracorporeal systems in clinical use. In adults with acute respiratory failure extracorporeal membrane oxygenation was abandoned after a large trial showed that it did not reduce mortality.[21] In infants with neonatal respiratory distress, however, the method seems to be very effective. A remarkable reduction in mortality from this condition has been reported in America when extracorporeal membrane oxygenation has been instigated.[22] In adults a new approach has been pioneered by Gattinoni in Italy. He started with the hypothesis that artificial ventilation itself may exacerbate acute respiratory failure. Tidal ventilation is required only to remove carbon dioxide, and oxygenation can be maintained in apnoeic patients if the carbon dioxide is removed by an extracorporeal circuit. By removing carbon dioxide with an extracorporeal artificial lung and reducing ventilation to the minimum he has claimed to reduce mortality from acute respiratory failure.[23]

Conclusion

The distinction between a ventilated patient and a spontaneously breathing patient is becoming increasingly blurred as more sophisticated means of respiratory support are devised. In many cases "respiratory assistance" may be a more appropriate term than "artificial ventilation." The efficacy of many of these ventilatory strategies has not been properly assessed, in terms either of acceptability to the patient or of the effect on morbidity and mortality. It is still true, however, that "the type of ventilator used, provided that its design is satisfactory, is of less importance than the experience of the person using it."[18]

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