Mechanical Ventilation: New Modes, Old Modes

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Mechanical ventilation refers to the application of a mechanical device to either partially or fully provide ventilation for a patient. The principal goal of mechanical ventilation is to maintain an alveolar ventilation appropriate for the metabolic requirements of the patient, thereby maintaining or enhancing carbon dioxide excretion. Mechanical ventilation relieves the work load that precipitates or accompanies ventilatory failure until the balance between ventilatory demand and breathing capability can be reestablished.

The term ventilator mode usually refers to the functioning arrangement of the ventilator, that is, the method by which the ventilator provides ventilation. Inherently, mode often refers to the capabilities of the machine and its circuitry and the interaction of the ventilator with the patient's spontaneous breathing. Discussion of the modes of ventilatory support conventionally deals with volume-cycled positive-pressure ventilation. For the purpose of this article, a broader definition will be assumed and, thus, newer modes of positive-pressure and negative-pressure ventilation will be discussed.

Positive-Pressure Ventilation

Conventional ventilatory modes

Three modes of volume-cycled positive-pressure mechanical ventilation are commonly described: control mode, assist-control mode, and intermittent mandatory ventilation. Intermittent mandatory ventilation is further divided into synchronized and nonsynchronized intermittent mandatory ventilation. These conventional modes of volume-cycled positive-pressure ventilation have been well described in the literature (1,2). Changes in airway pressure for spontaneous breathing and the conventional mode of mechanical ventilation are depicted in the Figure.

Control mode ventilation describes the delivery of a preselected tidal volume at a selected frequency, irrespective of patient effort. In essence, the ventilator and circuitry are totally unresponsive to patient effort or response.

Assist-control mode ventilation provides the delivery of a selected tidal volume in response to the patient's respiratory effort, usually sensed by a sub-baseline pressure in the inspiratory limb of the ventilator circuit. If such efforts are absent or if the patient's respiratory rate falls below a preset "control" rate, the ventilator will deliver the preselected volume.

Intermittent mandatory ventilation provides mechanical tidal volumes at set intervals, but allows the patient to spontaneously breathe gas of similar oxygenation and humidification as that delivered by the ventilator between the ventilator-delivered breaths. Synchronized intermittent mandatory ventilation combines spontaneous and assisted ventilation, providing a mechanically delivered breath at preset intervals synchronous with the patient's inspiratory efforts. As in assist-control mode ventilation, if the patient does not breathe within a certain time interval, the tidal volume will be delivered at the set intermittent mandatory ventilation rate.

Many putative advantages and disadvantages of each of the traditional volume-cycled positive-pressure ventilation modes have been offered. Theoretically, the lowest work of breathing provided by the patient is offered by the control mode. The respiratory muscles are rested effectively when a controlled breath is delivered without patient effort. Unfortunately, the respiratory muscle rest provided by the mode may, if used for long periods, lead to respiratory muscle disuse atrophy (3). Both assist-control mode ventilation and intermittent mandatory ventilation should offer theoretical advantage over control mode ventilation.

Figure—(A) Spontaneous breathing, (B) controlled mechanical ventilation, (C) assist-control ventilation, (D) nonsynchronized intermittent mandatory ventilation (continuous flow circuit), and (E) synchronized intermittent mandatory ventilation (demand circuit).

Submitted for publication: March 26, 1987.
Accepted for publication: April 20, 1987.
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in preventing disuse atrophy. As respiratory muscle function is an important determinant of weaning from mechanical ventilation, a mode of ventilation that prevents respiratory muscle atrophy and discoordination would be favored.

Respiratory muscle function also may be affected during mechanical ventilation by excessive work of breathing required by the patient, if this work of breathing is sufficient to produce or perpetuate muscle fatigue. Machine settings and equipment during both assist-control and intermittent mandatory ventilation may contribute to this excessive work of breathing. Conceptually, assist-control ventilation allows the patient to control the level of ventilation but spares the patient the majority of the energy expenditure. Recent work has demonstrated that even under the most favorable conditions of minute ventilation, trigger sensitivity, and inspiratory flow rate, normal subjects receiving assisted mechanical ventilation expend energy equivalent to 33% to 50% of the work of passive lung inflation (4). Under the least favorable conditions, inspiratory work of breathing may substantially exceed the energy needed by the ventilator to inflate the passive thorax (4). In an evaluation of 20 critically ill patients receiving assisted mechanical ventilation, Marini et al demonstrated that the patient's component of the mechanical work load during assisted ventilation was an average of 62.6% (range 30.3% to 116.3%) of work performed during spontaneous breathing 30 seconds after discontinuation of ventilator support (5).

Intermittent mandatory ventilation circuits may also contribute to high patient work loads. Intermittent mandatory ventilation systems using "demand" flow during the spontaneous breathing phase, which is required for synchronized intermittent mandatory ventilation, may require the generation of a significant negative pressure to initiate flow (6,7). Such systems may also have high maximal expiratory resistance (6). Both of these factors may significantly worsen respiratory muscle performance by "loading" weakened or fatigued respiratory muscles of patients with minimal reserve. Several ventilators impose differing work loads on inspiratory and expiratory muscles (6). This disadvantage imposed by the demand valve systems required by synchronized intermittent mandatory ventilators is not offset by any major advantage over nonsynchronized intermittent mandatory ventilators (8).

Rest of fatigued respiratory muscles is vital for functional recovery (9,10). As respiratory muscle function is a critical determinant of weaning from mechanical ventilation, modes of mechanical ventilation that properly provide adequate rest for reversal of fatigue without producing disuse functional losses would be favored. Both assist-control and intermittent mandatory ventilation have putative advantages, but neither appears to have a clear-cut advantage from a muscle function standpoint (11). Of greatest importance is the recognition of the way in which equipment and technical factors influence respiratory muscle function regardless of mode.

**New ventilatory modes**

Two newer modes of positive-pressure ventilation have been described recently: 1) mandatory minute volume ventilation; and 2) inspiratory pressure support, or pressure support, ventilation. Mandatory minute volume ventilation is a mode of ventilation that allows the patient to breathe from a metered, preselected minute volume of fresh gas, with the ventilator delivering the volume difference between the preselected minute volume and the patient's spontaneous minute ventilation (12,13). The system assures the patient a constant, predetermined minute ventilation. A potential disadvantage of this mode is that patients may breathe at rapid rates and low tidal volumes approaching or equal to physiological dead space, thereby resulting in ineffective ventilation yet maintaining the predetermined minute ventilation. To prevent this disadvantage, mandatory minute volume ventilators must monitor spontaneous and machine tidal volumes and rates, triggering alarms if these values fall from preselected ranges. Additional technology is required to provide this monitoring, thereby adding expense and the potential of machine failure. The effects of this type of ventilation on patient inspiratory work load should be considered similar to synchronized intermittent mandatory ventilation, due to the demand valve flow system during spontaneous breathing. This mode has been reported as offering more rapid weaning from mechanical ventilation, but this has never been proven.

Inspiratory pressure support, or pressure support, ventilation provides a predetermined pressure to the patient's circuit during the inspiratory phase (14). Pressure support is the simultaneous pressurization of the ventilator circuit as the demand valve opens during spontaneous breathing efforts. Pressure support augments spontaneous breaths with a variable, clinician-selected pressure, which is provided as long as the patient effort continues. The patient thus has control of the ventilatory rate and the inspiratory assist time and can interact with the machine-delivered pressure to determine the inspiratory flow and the delivered tidal volume. Pressure support is designed to assist each spontaneous breath, but can be given in conjunction with intermittent mandatory ventilation. Reported advantages in the patient's comfort, reduction in the patient's ventilatory work, and provision of a more balanced pressure and volume change form of muscle work to the patient (14). Pressure support has also been reported to allow more rapid weaning from mechanical ventilation after coronary artery bypass surgery (15). A major potential advantage of this method of support may be to provide additional energy to overcome system-imposed work, especially the increased work of breathing associated with the activation of demand valves on synchronized intermittent mandatory ventilators and to assist breathing efforts in difficult-to-wean patients. Experience and research is limited with this mode. Further work is needed to determine the role, if any, of pressure support ventilation in the armamentarium of the respiratory intensive care unit team.

High-frequency ventilation is a method of ventilation delivering small tidal volumes, approximating or even less than anatomical dead space, at rates greater than 60 breaths per minute (16). The advantage of this ventilatory mode is predominately related to the low mean airway pressure required to achieve adequate ventilation. Lower airway pressures provided by this technique are thought to reduce the risk of barotrauma and adverse cardiac effects. The three distinct modes of high-frequency ventilation, each having unique physiologic characteristics, include: high-frequency positive-pressure ventilation, high-frequency jet ventilation, and high-frequency oscillation.
Although high-frequency ventilation offers an exciting and innovative physiologic technique, clinical experience remains limited, and the clinical indications for the modes of high-frequency ventilation remain to be established. To date, high-frequency ventilation appears most promising in patients with bronchopleural fistula and major air leaks (17). The mode has also shown promise in neonatal ventilation for infant respiratory distress syndrome and persistent fetal circulation (18). Clinical use of high-frequency ventilation on patients with respiratory failure should be reserved for controlled, prospective clinical trials that allow an assessment of the risk/benefit considerations in these patients and also in selected patients in whom conventional ventilation has failed or is significantly likely to fail.

**Negative-Pressure Ventilation**

Negative-pressure ventilators are machines that create negative intrathoracic pressure in cycles to ventilate the patient. The prototype of this method of ventilation is the caisson, or “iron-lung,” ventilator, but discussions of negative-pressure ventilators should include all devices that ventilate by producing a negative intrathoracic pressure. This includes cuirass, chest wrap, and pneumobelt devices, as well as oscillating (rocking) beds and chairs and diaphragmatic pacemakers. Although modes of ventilation ordinarily do not refer to negative-pressure ventilators, several methods of this form of ventilation should be reviewed as “new” modes or at least as rediscovered “old” modes.

Negative-pressure ventilators have been used successfully to provide mechanical ventilation to patients with respiratory failure due to chest wall restriction and to neuromuscular disease (19,20). Theoretically, these devices may rest the diaphragm by limiting diaphragmatic energy expenditure. Therefore, individuals with chronic diaphragmatic fatigue, such as certain patients with respiratory muscle fatigue and chronic obstructive pulmonary disease, might be improved by such support (10). Future studies are necessary for evaluation of this concept.

Negative-pressure ventilators are not ideal ventilatory devices. They are generally inefficient in producing the desired minute ventilation, although iron lung ventilation achieves reasonable efficiency. They are somewhat burdensome in application and contribute to a sense of “claustrophobia” and “restriction” according to many patients. Due to the asynchrony of these ventilators with upper airway muscles, eg, the genioglossus, which need to contract during inspiration to maintain upper airway patency, upper airway obstruction may be precipitated in patients with such a predilection (infants or obese patients) (21).

**Cuirass (chest shell) ventilators**

The chest shell ventilator is a dome-shaped apparatus which is fitted over the anterior chest and upper abdomen. Negative-pressure is generated by a pump and transmitted to the chest under the shell, resulting in negative intrathoracic pressure. Ventilation is achieved by controlling the ventilator (pump) rate and the negative pressure developed within the chest shell. The chest shell must be large enough to fit over the chest and upper abdomen. Abnormal chest walls, such as in kyphoscoliosis, may require the molding of special domes to provide sealing of the shell-patient interface.

New designs in cuirass-like ventilators, such as chest wrap devices, eliminate the constricting plastic chest shell and replace it with a half-cylinder mesh large enough to cover the thorax and part of the abdomen. The patient is placed in a plastic wrap, which can be sealed at the neck, arms, and legs and encompasses the wire cage. Tubing access on the wrap allows attachment of a cycling negative-pressure generator. This in effect creates a nonconstricting, easily applied negative-pressure device that can support ventilation in patients without high minute ventilation or ventilatory pressure.

**Oscillating beds**

Oscillating (rocking) beds are devices that angle the patient from a semi-upright to recumbent position approximately 12 to 24 times per minute. The movement from the recumbent to the semi-upright position assists the diaphragm to descend and produces negative intrathoracic pressure, thus providing inspiration. Movement from the semi-upright to the recumbent position causes abdominal contents to move cephalad, producing a corresponding movement of the diaphragm and thus expiration.

Although relatively inefficient, oscillating beds may be useful for patients with predominately diaphragmatic weakness and chronic respiratory failure, a condition in which the oscillating bed was first used during the poliomyelitis epidemics of the early 1950s. Despite creating considerable movement, this mode is generally well tolerated by patients, especially during sleep when the physiologic effects of diaphragmatic weakness are at their greatest.

**Diaphragmatic pacemakers**

Diaphragmatic, or electrophrenic, pacing is a technique developed by Dr. William Glenn at Yale University (22). This technique is the implantation of electrodes onto the phrenic nerve, which are connected to subcutaneously imbedded radio-frequency receivers. A radio frequency transmitter, which in this case is the ventilator, gives electrical stimuli via small antennae placed overlying the receivers on the chest of the individual. This creates an electrical stimulus to the phrenic nerve, which subsequently rhythmically contracts the diaphragm and provides ventilation. The volume of the breath is dependent on the magnitude and characteristic of the electrical stimulus and the response of the muscle. For full ventilatory support, the technique generally needs to be applied to both phrenic nerves to prevent muscle fiber fatigue and injury. A considerable amount of time and effort is needed to establish adequate ventilation by this technique. The technique has had its most common application in individuals with respiratory failure due to quadriplegia, although it has been applied in individuals with central hypventilation (21,22). An added benefit of this mode of negative-pressure ventilation is a possible training effect on the diaphragm (22). Use of this technique is limited to specialized centers with personnel of required surgical and medical expertise and experience in this form of ventilation.
Summary

Although new modes of mechanical ventilation are appearing, the newer approaches often do not offer clearly significant advantages over older modes of mechanical ventilation. The roles of such new modes of ventilation await clinical studies showing the benefits and risks of such techniques. New applications of old modes of ventilation and refinements in current apparatus frequently offer more immediate promise to the clinical sphere of practice.

References