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Part 2

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Section V: complications of mechanical ventilation

Although mechanical ventilation offers vital life support, its use can result in untoward or life-threatening side effects [70]. Many such hazards can be modified or avoided by appropriate attention to the technique of implementation. Interventions associated with mechanical ventilation include airway intubation, application of positive pressure to the respiratory system, provision of supplemental oxygen, imposition of unnatural breathing patterns, and the administration of sedative or paralytic agents.

A. Complications of airway intubation

Endotracheal intubation is usually performed transnasally or transorally. The nasal route provides a more stable artificial airway and allows mouth closure, improving comfort in some patients. However, a bleeding diathesis is a contraindication to nasal intubation. Moreover, because a nasal tube is generally smaller than its oral counterpart, it presents greater flow resistance and may impede extraction of retained secretions from the central airways [71]. Sinusitis is a potential complication of ostial occlusion and drainage impeded by the nasal tube.

The artificial airway allows potential pathogens to enter the trachea from the external environment, dramatically increasing the risk of nosocomial pneumonia [70, 71]. Moreover, disruption of the coughing mechanism and mucociliary escalator encourages retention of airway secretions. Endotracheal tubes prevent aspiration of gross particulates but permit pharyngeal secretions to enter the trachea via the interstices of the balloon cuff, frequently resulting in tracheal colonization and increasing the risk of nosocomial pneumonia.

Tube misplacement and dislocation occur frequently. Although intubation of the right or (less frequently) left main bronchus most commonly occurs at the time of intubation, head movement may cause the tube orifice to migrate 2 cm in either direction from its neutral position along the tube axis. Overdistention of the ventilated lung and hypoventilation or atelectasis of the non-intubated lung are especially likely to occur in the heavily sedated patient receiving positive pressure ventilation. Hypoxemia, barotrauma, and cardiovascular compromise may result. Inadvertent extubation is among the most dangerous complications associated with mechanically ventilating a physiologically unstable patient; consequently, disoriented and uncooperative patients should be made as comfortable as possible, but securely restrained.

Glottic injury often occurs during unusually difficult or emergency intubation. Glottic edema and minor erosive lesions of the vocal cords occur commonly during prolonged intubation. Post-extubation glottic dysfunction and lasting damage to the vocal cords may occur, especially among women and among those patients in whom large tubes are placed. Risk factors for tracheal erosion, glottic stenosis, tracheal dilatation and tracheomalacia are not precisely defined; however, cuff pressures that exceed capillary perfusion pressure ($= 25\ cmH_2O$) are likely to cause ischemic ulceration and more advanced forms of mucosal damage [71]. In the absence of reliable guidelines to indicate optimal timing, most practitioners reserve tracheostomy for those patients who are not making clear and steady progress after 2–3 weeks of therapy or for those with suspected pathology of the upper airway. Tracheostomy affords reduced deadspace, partially restores glottic function, improves secretion clearance, enhances comfort, and holds the potential to allow both oral feeding and verbal communication. It may be associated, however, with such life-threatening complications such as tracheal erosion, tracheo-innominate artery fistula (hemorrhage), and migration of the tube orifice in the early postoperative period. Stomal granulation or stenosis are frequent problems after decannulation.

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Participants: see Part 1

Abbreviations and definitions: see Part 1

B. Complications of positive pressure ventilation

During positive pressure ventilation, the lungs and chest wall distend, intrathoracic pressure rises, and the lungs are often exposed to high inspired fractions of oxygen. In the setting of ARDS, for example, oxygen exchange is improved by providing high fractional concentrations of inspired O_2 and by raising mean and end-expiratory alveolar pressures. Each of these interventions has an associated risk/benefit ratio. Although considerable experimental data have been accumulated, detailed clinical information is not yet available regarding which oxygen concentrations, pressures, and ventilation patterns are safe to apply for extended periods.

1. Barotrauma. For adult patients, flow limited, volume cycled ventilation using large tidal volumes (10–15 ml/kg), rapid inspiratory flow rates, and positive end-expiratory pressure when needed to adjust lung volume has previously been the standard of practice in managing most problems of ventilatory support [72]. Widely held objectives of ventilation have given priority to "normalizing" arterial blood gases and ensuring adequate oxygen delivery. Until recently, respiratory system pressures have been monitored, but not tightly constrained.

There is little doubt that high ventilating pressures and excessive *regional* lung volumes are damaging. All forms of barotrauma that have previously been described in the pediatric literature, including interstitial and subcutaneous emphysema, pneumomediastinum, pneumoperitoneum, pneumopericardium, pneumothorax, tension cysts, systemic gas embolism, and damage similar to bronchopulmonary dysplasia, have now been recognized in adult patients. Susceptibility to barotrauma may vary with the stage of the disease process; pressures well tolerated during the earliest stage of illness may prove excessive later on [73]. Many forms of barotrauma occur with increased frequency after ventilation for extended periods, especially in patients with the adult (or acute) respiratory distress syndrome (ARDS).

It has been shown in a variety of animal models that ventilation with high tidal volumes or high peak airway pressure can induce or extend acute lung injury [74–80]. In previously normal lungs, such damage is characterized by granulocyte infiltration, hyaline membranes and increased vascular permeability. Fibroblast proliferation follows over a period of days [79]. Such lung injury occurs with peak inspiratory pressure (PIP) as low as 30 cmH_2O in normal sheep [81], and with PIP as low as 20 cmH_2O in rabbits whose lungs have been lavaged with saline [79]. There are also suggestions from the experimental literature that ventilatory pattern influences the incidence and severity of injury, but further evidence is needed, and an optimal pattern has not been defined [79].

Although ARDS has previously been considered a problem of *diffuse* lung injury and a generalized increase of tissue recoil, it now appears that the radiographic, densitometric, and mechanical consequences of ARDS are heterogeneous [38, 82]. In severe cases, the inflation capacity of the lungs may be less than one-third of normal [38]. The compliance and fragility of tissues comprising the aerated compartment in ARDS may be closer to normal than previously envisioned, especially in the earliest phase of this disease. It is currently believed that ventilatory patterns that apply high transalveolar stretching forces cause or perpetuate tissue edema and damage [74–76, 79]. Some experimental data suggest that large tidal volumes, themselves, may also extend tissue edema, independent of the maximal pressure to which the alveolus is exposed [75, 80]. It is not clear, however, that large tidal volumes are injurious when peak alveolar pressures are kept below 35 cmH_2O and sufficient PEEP is used to prevent widespread alveolar collapse and thereby maximize respiratory system compliance. Use of small tidal volumes that avoid tissue over-distention and the acceptance of any consequent elevation of $PaCO_2$ (permissive hypercapnia) have been suggested to minimize the risk of barotrauma in asthma and ARDS [37, 83, 84]. Although it remains unproven, some data suggest that periodic inflations with a relatively large volume may be needed, to avert collapse of unstable lung units when very small tidal volumes and low levels of PEEP are used [77, 79, 85]. In animal models, recruitment of lung volume by adequate amounts of PEEP can substantially reduce the ventilator-associated lung injury resulting from high peak inspiratory pressures [77, 80]. Such application has not as yet been shown to have a similar benefit in patients.

Strategies that prevent the exposure of the lung to high pressures (limiting overdistension) and those that lower the minute ventilation requirement may be associated with less ventilator-induced tissue injury and improved outcome. Such approaches include permissive hypercapnia [37, 84], pressure controlled ventilation [86] and pressure limited, volume cycled ventilation [87]. Based on the experimental literature, maximal transalveolar pressure should not exceed 30–35 cmH_2O during each tidal cycle [74, 75, 79]. [This usually corresponds to 35–45 cmH_2O end-inspiratory static (plateau) pressure, depending on chest wall compliance.] In certain experimental settings, even pressures lower tha this have been associated with tissue injury, especially when applied for extended periods. It may be desirable to allow spontaneous ventilatory efforts whenever it is possible to do so without incurring an excessive breathing workload or unbalancing the VO_2/DO_2 relationship. These modes, which include intermittent mandatory ventilation (IMV), pressure support, airway pressure release ventilation (APRV) [88], Bi-level airway pressure, intermittent mandatory pressure release ventilation (IMPRV) [89], continuous positive airway pressure (CPAP) [90], a various modes applied without airway intubation (non-invasive ventilation), tend to reduce maximal transalveolar pressure but do not guarantee a reduced incidence of barotrauma.

Adjunctive measures to conventional ventilation aimed at enhancing tissue oxygen delivery or increasing CO_2 removal [extracorporeal ($ECCO_2R$) or intracaval (IVOX) gas exchange [91], tracheal gas insufflation [86], high frequency ventilation] decrease the exposure of the lung to high pressures (and volumes) and may, at times, enable better gas exchange than is otherwise possible. The

success of these hazardous methods depends heavily on the skill with which they are applied. At the present time their utility for general medical practice must be considered unproven.

2. Oxygen toxicity. High fractions of inspired O_2 are potentially injurious when applied over extended periods [92]. In the laboratory setting, tissue injury depends on the FiO_2 and the duration of exposure. Because alveolar injury is an exponential function of inspired oxygen concentration (FiO_2), even modest reductions in FiO_2 over the range of 0.6–1.0 may attenuate tissue damage. There is no convincing evidence that sustained exposure to $FiO_2 \leq 0.5$ causes tissue injury, and for practical purposes, most clinicians do not attempt aggressive measures to reduce FiO_2 (e.g., vigorous diuresis, inotropic pharmacotherapy, high levels of PEEP, experimental modes of ventilation, or adjunctive support) until the inspired O_2 concentration exceeds ≈ 0.60. The combinations of O_2 concentration and duration of exposure which produce significant damage have not been firmly established in the setting of critical illness, and may well vary with disease type, severity, and individual susceptibility.

3. Cardiovascular complications. Ventilatory support can help restore the balance between O_2 delivery and O_2 consumption when it alleviates an intolerable breathing workload. Conversely, positive pressure ventilation often impairs cardiac output by disturbing the loading conditions of the heart as described earlier in Section IV, A-3 [93].

Mean lung volume or mean alveolar pressure correlates best with the tendency of a given ventilatory pattern to cause hemodynamic compromise. *Under conditions of passive inflation,* mean airway pressure (as a clinically measurable reflection of mean alveolar pressure), relates fundamentally to oxygen exchange, cardiovascular performance, and fluid retention [44, 94]. The importance of each effect varies greatly in different patients. Mean airway pressure can be raised by adding PEEP, by extending the inspiratory time fraction (increasing I:E), or by increasing minute ventilation (V_E). The tendency for an elevation of mean airway pressure to compromise hemodynamic performance is heightened by impaired cardiovascular reflexes and depletion of intravascular volume. The proportion of the alveolar pressure transmitted to the pleural space is determined by the relative compliances of the lung and chest wall:

$$\Delta Ppl = \Delta Palv \times [CI/(CI+Cw)] \ .$$

Therefore, the hemodynamic effect of a given increment in mean alveolar pressure will be accentuated when the lungs are relatively compliant and/or the chest wall is stiff. Hemodynamic consequences are predictably less when the patient makes spontaneous breathing efforts. For these reasons, dynamic hyperinflation occurring in a passively ventilated patient with severe airflow obstruction produces auto-PEEP that is particularly likely to cause hemodynamic compromise [22, 95]. Auto-PEEP can be attenuated by reducing minute ventilation or by reducing I:E, thus increasing expiratory time.

Limiting tissue demand for oxygen and maintaining effective cardiovascular function are essential to an effective ventilation strategy. Recent studies suggest that survival in overt sepsis and sepsis syndrome correlates with oxygen delivery [96, 97]. At the time of this writing, however, it is not clear whether therapeutic interventions which attempt to maximize O_2 delivery (when it is already in the normal range) or avoid depression of cardiac output improve outcome. Maximizing O_2 delivery may require expansion of intravascular volume, an intervention which has been associated with adverse outcomes in patients with acute lung injury.

4. Breathing effort and patient-ventilator asynchrony. The use of mechanical ventilation superimposes a clinician-selected pattern of ventilation on the patient's natural breathing rhythm. Circuits that impose substantial resistance and machines that respond poorly to the flow demands or cycling cadence of the patient may result in dyspnea and an unnecessary breathing workload. Factors that have been shown to increase the breathing workload during partial ventilatory support include endotracheal tube resistance, excessive triggering threshold or response delay, insufficient flow capacity of the ventilator to meet peak patient demands, and the development of dynamic hyperinflation. The latter gives rise to auto-PEEP, which depresses the *effective* functional triggering sensitivity and may contribute to intermittent failure of the machine to respond to patient effort [98]. Inappropriately low inspiratory flow rates may cause the patient to enter the expiratory phase of the tidal cycle before the volume cycled breath from the machine has been completed, often resulting in conflict between the natural and the imposed breathing rhythms. The magnitude and importance of these effects is a direct function of minute ventilation.

Pressure limited modes of ventilation (e.g., pressure support) are theoretically unlimited with respect to meeting maximal flow demands; however, this ideal is seldom accomplished in practice. Such modes often present important problems of their own for the vigorously breathing patient. Pressure support, for example, although invaluable for overcoming endotracheal tube resistance and for assisting the patient with moderate ventilation requirements, is not well suited to the needs of a patient breathing at a rapid cycling frequency, one with variable ventilatory requirements, or one who has a very high airway resistance (especially from a very small endotracheal tube). Tidal volume can fall dramatically as frequency increases, especially in patients with airflow obstruction. Moreover, a fixed level of pressure support cannot compensate for a change in ventilatory impedance or the development of auto-PEEP. A patient who requires a high level of pressure support when breathing at a rapid rate may find the applied level of pressure excessive when the ventilatory requirement abates.

C. Adverse effects of sedation and paralysis

Sedation and paralysis are often required to allow patient comfort and to facilitate the imposition of ventilatory patterns (e.g. inverse ratio ventilation) which would otherwise conflict with the patient's own ventilatory pattern. Sedation may result in vasodilation that contributes to hypotension and reduced cardiac output. Paralytic agents immobilize the patient, encouraging secretion retention, atelectasis, and muscle wasting. With breathing efforts prevented, such patients are totally dependent on the ventilation set by the clinician and provided by the machine. Inadvertent disconnection of the ventilator circuit can prove rapidly catastrophic in this setting. Certain neuromuscular blocking agents have been recently associated with neuromuscular weakness that persists long after drug withdrawal [99]. At present, it is not certain whether such effects relate primaly to the nature, dose, or duration of the drug, to synergism with corticosteroids, or to the depth of paralysis itself.

D. Other complications

Among the wide variety of non-cardiopulmonary complications which have been described for mechanical ventilation, perhaps the most important involve mental distress, and dysfunction of the renal, gastrointestinal, and central nervous systems. Psychological distress during mechanical ventilation is exceedingly common, for reasons that include (but are not limited to) sleep deprivation and impaired sleep quality, pain, fear, inability to communicate, and the use of drugs (e.g., benzodiazepines) with dissociative properties.

Renal dysfunction during positive pressure ventilation is believed to be a consequence of reduced circulating blood volume. This tends to alter perfusion of the renal parenchyma, redistribute intra-renal blood flow, release anti-diuretic hormone, or inhibit atrial natriuretic peptides. In any event, reduced free water clearance and generalized fluid retention are commonplace during ventilation with high pressures.

Gastrointestinal consequences of mechanical ventilation include gut distension (due to air swallowing), hypomotility and obstipation (due to pharmacologic agents and immobility), vomiting (due to pharyngeal stimulation and motility disturbances), and mucosal ulceration and bleeding. Serious dysfunction of the liver that occurs as a direct consequence of mechanical ventilation is rare. However, PEEP has been associated with hyperbilirubinemia and mild elevations of liver enzymes in the serum, possibly related to altered perfusion and impeded venous and biliary drainage.

Increased intrathoracic pressure can elevate jugular venous and intracranial pressures, and thereby reduce cerebral perfusion pressure. Such effects assume particular importance in the setting of reduced mean arterial pressure and reduced intracranial compliance resulting from head injury or surgical intervention. The risk of intracranial hypertension in patients ventilated with high mean airway pressures is attenuated by conditions that limit transmission of alveolar pressure to the pleural space (low ratio of lung to chest wall compliance).

Section VI. Specific modes of ventilation

A. Standard modes

1. Introduction

Assisted modes of ventilation are those in which part of the breathing pattern is contributed or initiated by the patient. The work of breathing performed by the patient is never abolished, and one of the difficulties for the physician is to determine the appropriate settings to match the patient's demand, both in terms of gas exchange and work of breathing. The main reasons for using assisted modes in the ICU are the following: (a) to synchronize patient and ventilator activity, (b) to reduce the need for sedation, (c) to prevent disuse atrophy of the respiratory muscles, (d) to improve hemodynamic tolerance of ventilatory support, and (e) to facilitate the weaning process.

Significant differences exist between ventilators concerning demand-valve sensitivity and opening delay, the algorithm for pressure support (rise in pressure, mechanism and criteria for cycling from inspiration to exhalation, plateau pressure), and flow-impedance characteristics of the expiratory circuit and equipment. A great deal of data obtained experimentally and in patients suggest that these differences may alter the work of breathing [55, 58, 100]. Many of the proposals listed below may be modified by the quality of the equipment used.

2. Assist-control (A/C)

This is a mode of ventilation in which every breath is supported by the ventilator. A back-up control ventilatory rate is set; however, the patient may choose any rate above the set rate. Until recently, most ventilators using this mode delivered breaths which were volume cycled or volume-targeted. Using volume-targeted, assist-control ventilation, the tidal volume, inspiratory flow rate, flow waveform, sensitivity and control rate are set. Most of the data in the literature concerning A/C were obtained with this mode [25, 42, 63, 101]. Pressure limited or pressure-targeted A/C, in which pressure level, inspiratory time, control rate and sensitivity are set, is now available on several ventilators.

Advantages: A/C it combines the security of controlled ventilation with the possibility of synchronizing the breathing rhythm of patient and ventilator, and it insures ventilatory support during every breath.

Risks or disadvantages: 1) excessive patient work in case of inadequate peak flow or sensitivity setting, especially if ventilatory drive of the patient is increased (volume-targeted A/C); 2) [25, 42, 101] may be poorly tolerated in awake, non-sedated subjects and can require sedation to ensure synchrony of patient and machine cycle lengths; 3) may be associated with respiratory alkalosis; 4) may potentially worsen air trapping in COPD patients; 5) if pressure-targeted A/C is used, risk of variable (and potentially markedly decreased) tidal volume during changes in lung impedance, patient ventilatory drive or patient-ventilator dys-synchrony.

Patient work of breathing or effort during volume-targeted A/C is dependent upon sensitivity, flow rates (flow rate lower than 40 l/min should probably be avoided), and respiratory drive of the patient. This is dependent upon many stimuli including fever, anemia, hypoxia, pain, hypovolemia, level of consciousness etc. Since patient work is dependent on the ventilator's ability to rapidly recognize patient effort and provide sufficient flow to meet inspiratory demand, the set-up of the venilator may play an important role in the patient's tolerance of this mode [63, 101]. With pressure-targeted A/C, the ventilator, once triggered, provides sufficient flow to allow the set pressure plateau level to be achieved rapidly. As a result, concern with excessive patient work is potentially minimized in pressure-targeted A/C.

3. (Synchronized) intermittent mandatory ventilation [(S)IMV]

(S)IMV is a mode of ventilation and a mode of weaning which combines a preset number of ventilator delivered mandatory breaths of predetermined tidal volume with the facility for intermittent patient-generated spontaneous breaths [102, 103]. Similar to assist-control, several ventilators offer the possibility of delivering pressure-targeted breaths instead of volume-targeted breaths during mandatory cycles. Mandatory breaths can be patient-triggered with SIMV; however, if patient effort is not sensed within a specific period of time, the ventilator delivers a mandatory breath. Pressure support (see below) may be applied during non-mandatory breaths.

Set-up parameters: tidal volume, flow rate and/or inspiratory time, frequency of controlled breaths, and sensitivity. When pressure-targeted breaths are used, pressure level and inspiratory time must be set.

Advantages: 1) the patient is able to perform a variable amount of respiratory work and yet there is the security of a preset mandatory level of ventilation; 2) (S) IMV allows for a variation in level of partial ventilatory support from near total ventilatory support to spontaneous breathing; 3) can be used as a weaning tool [102].

Risks: With IMV, there are risks of dys-synchrony between the patient effort and machine delivered volume.

With SIMV the risks are: 1) Hyperventilation and respiratory alkalosis are possible, similar to assist-control. 2) Excessive work of breathing due to the presence of a poorly responsive demand-valve, suboptimal ventilator circuit (its impedance will vary with the particular ventilator used) or inappropriate flow delivery. In each case, extra work is imposed on the patient during spontaneous breaths. This work can be minimized or abolished with the addition of pressure support. 3) Worsening dynamic hyperinflation has been described in patients with COPD.

The total work (or power) performed by the patient is dependent upon the number of mandatory breaths. It was initially thought that the effort performed by the patient was virtually zero during mechanical breaths. However, recent data suggest that the muscular effort of the dyspneic patient during machine assisted breaths does not vary substantially from the unassisted cycles on a breath to breath basis, i.e., at the same overall level of ventilator support, effort is more or less independent of whether the breath is assisted or not [64]. The work of breathing may also vary with the addition of pressure support during spontaneous cycles and with the use of pressure-targeted mandatory breaths. There has been no demonstrated advantage of using IMV or T-piece trials in terms of reducing weaning duration [104, 105].

4. Pressure support ventilation (PSV)

PSV is a pressure-targeted, flow cycled, mode of ventilation in which each breath must be patient-triggered. It is used both as a mode of ventilation during stable ventilatory support periods and as a method of weaning patients [55, 65, 106–111]. It is primarily designed to assist spontaneous breathing and therefore the patient should have an intact respiratory drive.

With PSV, at the onset of inspiration the pressure rises rapidly to a plateau which is maintained for the remainder of inspiration. The patient and ventilator work in synchrony to achieve the total work of each breath. On most ventilators, termination of inspiration occurs when a flow threshold is reached during the decelerating phase of inspiratory flow. That is, the breath is flow-cycled to exhalation (this has been made possible by incorporating pneumotachygraphs in the ventilators). To avoid confusion, it should be stressed that the difference with pressure-targeted A/C, described above, is that termination of inspiration is different: it is *time* cycled for pressure-targeted A/C (i.e., the inspiratory time is fixed), whereas it is flow cycled for pressure support, i.e., airway pressurization always stops before reaching the zero flow, and inspiratory duration is dependent upon patient's effort.

Set-up parameters: pressure level, sensitivity. No mandatory pressure support rate is set; however, many ventilators incorporate volume-targeted back-up modes in the event of apnea. In some ventilators it is possible to adjust the rate of rise in pressure at the beginning of inspiration or to adjust the flow threshold for cycling from inspiration to expiration.

Advantages: 1) As a result of the patient's having significant control over gas delivery, overt dys-synchrony is less likely than with A/C or SIMV. When the pressure support level is chosen appropriately, this mode is generally regarded as comfortable for most (but not all) spontaneously breathing patients [65, 106]; 2) PSV reduces the work of breathing roughly in proportion to the pressure delivered, and is associated with a decrease in respiratory frequency and increase in tidal volume with increasing levels of pressure support (PS) [65, 106, 108]. These breathing pattern characteristics may be useful in selecting the appropriate PS level, 3) PSV can be used to compensate for the extra work produced by the endotracheal tube and the demand valve [107, 108], 4) it allows for a wide variation in the level of partial ventilatory support from nearly total ventilatory support (high pressure lev-

els) to essentially spontaneous breathing; and 5) PSV may be useful in patients who are "difficult to wean". Preliminary data suggest either no difference when compared to other modes or a shorter weaning duration and a higher success rate in selected patients using pressure support.

Disadvantages: Tidal volume is not controlled and is dependent upon respiratory mechanics, cycling frequency and synchrony between patient and ventilator. Therefore, careful monitoring is recommended in unstable patients; a back up minute ventilation seems necessary for safety; hypoventilation may develop during continuous flow nebulizer therapy. PSV may be poorly tolerated in some patients with high airway resistances because of the preset high initial flow and terminal inspiratory flow algorithms. This may be improved, however, with adjustment of initial flow rates which is possible on new systems [67, 68].

Work of breathing: Increasing pressure support levels decrease respiratory effort as indicated by a number of changes in breathing pattern. This mode can be combined with SIMV [111, 112] and has been used to compensate for the additional work of breathing due to the endotracheal tube and the demand-valve, adding pressure support ($5-10\,cmH_2O$) during the non-mandatory breaths [107, 108]. Higher levels of PS can also be used, combining mandatory and supported breaths. At the present time clinical studies are lacking to demonstrate the superiority of one mode of partial ventilatory assistance over others. Pressure support has been widely accepted in many ICUs and for some physicians, it seems to be the most useful modality for delivering assisted ventilation either as full ventilatory support or as a mode for gradually withdrawing mechanical ventilation. For others, it is a useful adjunct to existing modes.

5. Continuous positive airway pressure (CPAP)

CPAP is a mode designed to elevate end-expiratory pressure to levels above atmospheric pressure to increase lung volume and oxygenation [113]. A constant positive airway pressure is supplied by the ventilator throughout the ventilatory cycle; all breaths are spontaneous. It is also proposed as a means of reducing the pressure gradient between the mouth and the alveoli in patients with air trapping [41, 59]. It is designed to assist spontaneously breathing patients and therefore requires an intact respiratory drive.

Until recently, two main types of CPAP systems were used. Those offered by most mechanical ventilators work via a demand-valve which needs to be opened to deliver the gas to the patient. This demand-valve is pressure-triggered or flow-triggered. Other specially designed systems work on the principle of a continuous high flow of pressurized gas in the external circuit from which the patient can breathe spontaneously. The advantage of the first system is that ventilator monitoring is still available but the major drawback is that work of breathing is increased by the presence of a demand valve. A continuous flow system is incorporated in some mechanical ventilators in an attempt to combine the advantages of the two previous systems [47, 114]. In this mode, an adjustable, constant flow of gas is continuously delivered in the external circuit during the expiratory phase. Both the inspiratory flow and the expiratory flow are measured and compared by the machine. A difference between these two flow rates indicates to the ventilator that inspiration or expiration is occurring, leading to an adjustment in the delivered flow rate.

Set-up parameters: Pressure level, sensitivity: level of negative pressure (demand valve system) or flow threshold and basal flow rate (continuous flow systems and/or flow-triggered systems).

Advantages: CPAP offers the benefits of PEEP to spontaneously breathing patients. It will improve oxygenation if hypoxemia is in part secondary to decreased lung volume; it may recruit collapsed lung units, minimizing the work of breathing and improving oxygenation. It may help to reduce the work of breathing in patients with dynamic hyperinflation and auto-PEEP.

Recent data suggest that the work of breathing is reduced with systems incorporating a continuous flow system in comparison to demand valve systems [47, 114].

Risks: Hyperinflation and excessive expiratory work may result if excessive CPAP levels are used. Poor clinical tolerance may increase inspiratory work of breathing, if hyperinflation is produced or if non-threshold PEEP devices are used. There will be increased expiratory work if hyperinflation is produced, or if PEEP devices with large flow resistances are used. The use of demand valves with intubated patients receiving CPAP may lead to patient ventilator dys-synchrony.

This mode can be used in intubated patients as well as nonintubated patients (e.g. patients with sleep apnea). Although inspiration is not really assisted, modern ventilators deliver a small level of pressurization, i.e., a 1 to 3 cmH_2O level of pressure support, to avoid negative airway pressure relative to the end expiratory level during inspiration. It is not clear, however, whether this has a significant clinical effect [58].

6. Servo-controlled modes

Servo-controlled modes are used both for ventilation and for weaning patients. The basic principle is the use of a feedback system to control a specific variable within a given narrow range [115–117]. The ventilatory mode is either SIMV or PSV. The targeted parameter is set by the physician and can be either minute ventilation, or a component of the breathing pattern (respiratory rate, tidal volume). Examples of servo-controlled modes include:

(i) Mandatory minute ventilation (MMV). MMV relies on a patient's spontaneous breathing to meet a predetermined minute ventilation (V_E). If this goal is not met, mechanical breaths at predetermined volume are delivered with a rate sufficient to supply the required minute ventilation. Here the targeted parameter is V_E. In some

ventilators used to implement MMV the basic mode is SIMV, in others can be PSV.

(ii) Servo-controlled PSV (with the exception of MMV). The underlying mode is PSV and the targeted parameter is respiratory rate or tidal volume. If the targeted value is not met, the ventilator can either modify the pressure target level or the way the breath is cycled. The regulation of the targeted variable varies among ventilators. It can take different forms: volume assured pressure support, pressure augmentation, volume support, pressure supported and volume assisted breaths.

(iii) Knowledge-based systems. More complex systems have been implemented in microcomputer-driven ventilators and are being studied or are already used for the routine management of patients in specialized centers [9, 118–120]. These systems have been proposed to help in the management of patients with ARDS or to automatically wean patients from mechanical ventilation. At the present time none of these systems is commercially available.

Advantages: adaptation of the ventilator to the needs of the patient. These systems try to combine the advantages of a partial ventilatory support with the variability in the needs of the patient.

Disadvantages: 1) the algorithm may induce non-physiological breathing patterns; 2) the adequate target value can be difficult to adjust (e.g. adequate level of V_E for MMV); 3) measurement of V_E may give false information if breathing pattern is not considered (rapid shallow breathing may go unrecognized). The published data and clinical experience with these modes are minimal.

A. Alternate modes of ventilation

1. Introduction

During the last decade, a new concept has emerged regarding acute lung injury. In severe cases of ARDS, only a small part of lung parenchyma remains accessible to gas delivered by the mechanical ventilator. This is widely known as the *"baby lung" concept.* As a consequence, tidal volumes of 10 ml/kg or more may overexpand and injure the remaining normally aerated lung parenchyma (see Section V-B-1) and could worsen the prognosis of severe acute respiratory failure by extending non-specific alveolar damage [121]. Because lung volumes and airway pressures relationships are determined by the respiratory P-V curve, and because the apparent "stiffness" of ARDS lung appears related to the fraction of aerated lung, rather than to a generalized increase in elastic recoil – *the specific compliance of the remaining aerated lung parenchyma may be nearly normal.* High airway pressures may result in overdistention and local hyperventilation of more compliant parts of the ARDS lung [39]. Overdistention of lungs in animals has produced diffuse alveolar damage [75, 122]. There are also data in the literature suggesting that ventilation using relatively low end-expiratory pressures (less than the inflection point (opening pressure) of the pressure-volume curve) causes progression of lung injury in animal models of ARDS [123]. This is the reason why alternative modes of mechanical ventilation – all based on a reduction of end inspiratory airway pressures and/or tidal volumes delivered to the patient and some based on ventilation between the lower and upper inflection points of the pressure-volume curve – have been developed and are clinically used by many physicians caring for patients when severe forms of acute respiratory failure. Three of them, high frequency ventilation, inverse ratio ventilation and airway pressure release ventilation will be described in this section. Since there are no data demonstrating the superiority of these non-conventional ventilatory modes in terms of morbidity and mortality, only their physiological rationale and their putative advantages and disadvantages will be presented.

2. High frequency ventilation (HFV)

High frequency ventilation is the administration of small tidal volumes – 1–3 ml/kg – at high frequencies – 100–3000/min [124]. Because it is a mode of mechanical ventilation based on a marked reduction in tidal volumes and airway pressures, it has the greatest potential for reducing pulmonary barotrauma. Mechanisms of gas transport change from conventional bulk flow ($V_A = f \times (V_T - V_D)$) to other types when $V_T < V_D$. Proposed mechanisms include coaxial flow, Taylor dispersion, pendelluft and augmented molecular diffusion. Under these conditions, the $f \times V_T$ product is usually much higher than during mechanical ventilation and V_A appears to be more influenced by V_T than f. There are a number of different types of high frequency ventilation. The three most common are high frequency oscillation (HFO), high frequency positive pressure ventilation, which is used in anesthesia, and high frequency jet ventilation (HFJV) which is used both in anesthesia and in critically ill patients with acute respiratory failure. HFJV is the only high frequency mode routinely used to ventilate ARDS patients, mainly in Europe. Convincing comparative data concerning the advantages of HFJV over conventional mechanical ventilation (CMV) have been presented in the following limited number of clinical studies. There is no agreement, however, that HFJV is better than CMV in these situations: in ARDS patients with circulatory shock [125], in cardiac patients with low cardiac output state [126] and in patients with tracheomalacia, bronchopleural fistula and tracheoesophageal fistula [127].

In one well-controlled multi-centered clinical trial (the HIFI trial), HFO was found not to be superior to CMV in ventilation of neonates with infant respiratory distress syndrome, but this study has been criticized because of the lack of a volume recruitment protocol [84]. In a number of animal studies ventilation above the inflection point is required for the beneficial effects of HFV [128, 129], HFV may need to be implemented early in the course of the disease to be effective.

Because of the risk of gas trapping related to expiratory flow limitation, HFV is generally contraindicated for asthma and chronic obstructive pulmonary disease. Al-

though some European groups routinely use HFJV in combination with low tidal volume conventional ventilation to treat patients with severe forms of ARDS (8–10 tidal volumes per minute of 3–4 ml/kg superimposed on HFJV), there are no convincing data demonstrating the superiority of this method of mechanical ventilation in terms of pulmonary barotrauma and mortality. It must be pointed out that the only prospective randomized study comparing HFJV to conventional ventilation which was performed in a nonhomogeneous population of cancer patients with ARDS, did not demonstrate any significant advantage for one or the other method [130]. HFJV can be safely administered in the clinical setting of the intensive care unit according to the following guidelines:

(i) Clinicians must be very familiar with the technique (ventilatory settings, types of injection, humidification).

(ii) Like all other forms of HFV, high frequency jet ventilation, when administered for periods longer than 8 hours requires adequate humidification of delivered gases or severe necrotizing tracheobronchitis can occur [131]. Because the pressure drop across the injection system is very large (*the operating pressures are between 1 and 3 atmospheres, whereas mean airway pressure is between 1 and 30 cmH_2O*), gas expansion occurs within the trachea causing cooling. Therefore specially designed devices for providing adequate humidification during HFJV are required. One such device is a specially constructed high temperature vaporizer [127]. Many detrimental effects of high frequency ventilation, are in fact due to inadequate humidification.

(iii) The effects of ventilator parameters related to airway pressures and tidal volumes are reasonably well understood. Respiratory effects of changing ventilatory settings are markedly influenced by the patient's respiratory mechanics. Increasing I:E and driving pressure increase functional residual capacity and tidal volume. Increasing respiratory frequency markedly decreases tidal volume and increases $PaCO_2$ and has minimum effect on functional residual capacity in patients with stiff lungs [132]. The more compliant the respiratory system, the larger the increase in functional residual capacity induced by increasing I:E, driving pressure and respiratory frequency.

(iv) Mean airway pressure should be continuously monitored using an intratracheal catheter located at least 5 cm below the injection site. It has been demonstrated in experimental [133] and clinical conditions [134], that mean airway pressure measured during HFJV is a reasonably good reflection of mean alveolar pressure, in patients *without* significant obstruction.

(v) There is a large body of evidence in various animal models that HFV is most effective in diseases with stiff lungs when applied following a volume recruitment maneuver. The aim is to ventilate the lung at a pressure above the inflection point, yet at pressures sufficiently low not to cause high pressure (or volume) damage to the lung [135]. This approach has been used in neonates with success, but to date these clinical trials have been relatively small.

Potential risks: Due to the large flow rates used and the fact that gas transport is less well understood, HFV is inherently more dangerous than conventional mechanical ventilation. Outflow obstruction can rapidly lead to increases in lung volume and attendant hemodynamic compromise and barotrauma. Air trapping due to the high flow rates is always of concern, especially in patients with compliant lungs and airways obstruction. Air trapping can be assessed by measuring airway opening pressure under static conditions after airway occlusion, by monitoring esophageal pressure, or by measurements of lung volume obtained at the chest wall (e.g. inductive plethysmography). Inadequate humidification can induce severe necrotizing tracheobronchitis as described above.

3. Inverse ratio ventilation (IRV)

IRV is the use of I:E ratio $>1:1$ during conventional mechanical ventilation [87]. There are 2 different types of IRV: pressure-controlled (pressure limited) IRV, where the ventilator generates a servo-controlled square wave of pressure to the airways via a decelerating inspiratory flow; and volume-cycled IRV, where the ventilator generates a predetermined tidal volume via a constant or a decelerating inspiratory flow. Flow profiles of appropriate length or inspiratory "holds" or "pauses" are applied as necessary for the desired I:E. Pressure-controlled IRV is more widely used than volume-cycled IRV in patients with ARDS. Since mean airway pressure is a major determinant of PaO_2, a major part of the rationale for using IRV in ARDS is to maintain mean airway pressure relatively high but to hold peak alveolar pressure within a safe range. The second theoretical concept underlying IRV is the prolongation of inspiration to allow for recruitment of lung units with long time constants. If air trapping does not develop, mean airway pressure will increase without a change in peak airway pressure or tidal volume. On the other hand, if inspiratory time is so prolonged that air trapping does develop, the resulting auto-PEEP will either raise peak airway pressure (volume-cycled IRV) or decrease tidal volume (pressure limited or pressure-controlled IRV). Indeed, it appears that many of the reported advantages of IRV in improving PaO_2 are related to air trapping (auto-PEEP), and that similar beneficial effects on oxygenation or O_2 transport may be obtained by using conventional I:E with sufficient PEEP to obtain the same increase in mean lung volume [136, 137]. Deep sedation and/or paralysis are nearly always required. At present, there is a lack of convincing data to support the advantage of IRV over conventional ventilation. No study has evaluated the outcome or the comparative incidence of pulmonary barotrauma in ARDS patients treated with IRV as opposed to conventional ventilation. Nevertheless, if IRV is used, it can be safely implemented in the critically ill with ARDS, according to the following guidelines:

(i) Volume-controlled IRV may be more easy to implement than pressure-controlled IRV since volume-cycled

modes are often more familiar to many clinicians. This ventilatory mode guarantees a preset tidal volume and is available on all ICU ventilators.

(ii) Deep sedation is required in most patients under IRV to avoid dys-synchrony with the ventilator.

(iii) Careful monitoring of peak airway pressure and end-inspiratory plateau pressure is required during volume-controlled IRV. The high pressure alarm should be set at 10 cmH_2O above the intended peak airway pressure.

(iv) Careful monitoring of minute ventilation is required during pressure-controlled IRV because tidal volume is markedly dependent on the patient's respiratory mechanics.

(v) The auto-PEEP level, which may develop as the I:E increases, should be regularly measured (see Section IV-A-6).

(vi) Hemodynamic status should be assessed using Swan-Ganz catheter when IRV is implemented.

These guidelines should help minimize the two major complications associated with the use of IRV, pulmonary barotrauma and hemodynamic deterioration.

4. Airway pressure release ventilation (APRV)

Airway pressure release ventilation increases alveolar ventilation by intermittently releasing a continuous positive pressure generated by the ventilator. In passive patients, APRV is identical to pressure-controlled IRV, however, the patient's ability to breathe spontaneously during APRV creates a markedly different intrapleural pressure waveform [90, 138]. The rationale for APRV is to limit peak airway pressures, thereby limiting barotrauma. APRV is not intended for patients with severe airflow obstruction.

There are 2 types of pressure release ventilation: APRV during which pressure release time is preset [139], and intermittent mandatory pressure release ventilation (IMPRV). Both are specifically designed for assisting spontaneously breathing patients [90]. In these modes ventilatory assistance is provided by intermittent changes in FRC related to changes in PEEP. Comparative experimental and clinical studies have shown that APRV and IMPRV can improve alveolar ventilation of animals and humans breathing with CPAP, without a deterioration in arterial oxygenation or an increase in peak airway pressure [90, 138]. When compared to conventional mechanical ventilation, APRV was shown to produce similar hemodynamic effects at similar mean airway pressure in patients with acute respiratory failure [140]. Whether this type of ventilatory support has any advantage over conventional mechanical ventilation with PEEP in terms of pulmonary barotrauma is not known. APRV can be provided by a CPAP breathing circuit in which the CPAP level can be modified by opening or closing a release valve connected to a timer.

IMPRV, which has been integrated in an ICU ventilator [90], provides end-expiratory pressure changes according to the patient's spontaneous breathing activity. Respiratory monitoring and alarms are available and each spontaneous inspiration can be assisted by pressure support. If the patient's respiratory frequency increases above 30/min, auto-PEEP becomes a limiting factor and IMPRV is no longer an efficient method of ventilatory support.

During APRV, the following respiratory parameters are preset: upper and lower airway pressure levels, frequency of pressure release and pressure release time. During IMPRV, the following respiratory parameters are preset: upper and lower PEEP levels, frequency of PEEP changes and sensitivity of the trigger. Ventilatory assistance is maximum when PEEP is changed each 2 spontaneous respiratory cycles and can be progressively decreased by spacing PEEP changes (PEEP release every 2, 3, 4, 5, 6 cycles etc... spontaneous expiration). Whether this type of ventilatory assistance can facilitate weaning of patients with acute respiratory failure is not known.

Section VII: Discontinuation of mechanical ventilation

A. What is it, and when does it begin?

Weaning has been defined as the process whereby mechanical ventilation is *gradually* withdrawn and the patient resumes spontaneous breathing [141]. Within the daily vernacular of the ICU, most clinicians do not employ the term weaning in the strict sense, but rather they use it to include the overall process of discontinuing ventilator support. To enhance communication between investigators and clinicians it may be wise to drop the term *weaning*, and replace it by a term such as discontinuation of mechanical ventilation. This, in turn, could be subdivided into different categories depending on the pace of the discontinuation process – these terms could replace older less precise terminology such as the "fast wean" and "slow wean". Alternatively, the term *discontinuation* could be used to describe disconnecting the patient from the ventilator over a short, predefined time limit, while *weaning* refers to the more gradual process; unfortunately, the dividing line between these two processes is arbitrary with no obvious basis.

It has become increasingly difficult to define the precise time at which the discontinuation process commences. It was relatively easy to define this time in the past when volume cycled assist-control (AC) ventilation and T-tube trials were the sole or predominant method of managing patients. With the widespread use of IMV and PSV in modern ICUs, it has become increasingly difficult to define the precise time at which these modes are no longer being used as the primary mode of ventilator support and are being adjusted to assist with the discontinuation process. In an ICU setting, ventilator support is typically initiated because of an episode of acute respiratory failure. In general, most clinicians would consider it imprudent to start a discontinuation process until there is evidence of significant resolution of the initial precipitating illness. Unfortunately, rigorous physiological or clinical indices have never been proposed to help to define this time. This largely relates to the lack of data characterizing

the changes in respiratory function from the time that ventilator support is instituted until the time that it can be safely withdrawn. Until this time can be defined in clear-cut objective terms it is going to be extremely difficult to conduct trials comparing the efficacy of different techniques of discontinuing mechanical ventilation.

B. Relative importance of pathophysiological determinants of the discontinuation process

There are four major factors that determine the ability to discontinue ventilator support: (i) respiratory load and the capacity of the respiratory neuromuscular system to cope with this load; (ii) oxygenation; (iii) cardiovascular performance; and (iv) psychological factors.

Systematic studies have never been conducted to determine the relative importance of these pathophysiologic mechanisms. However, many clinicians and investigators suspect that respiratory muscle dysfunction resulting from an imbalance between respiratory neuromuscular capacity and load is the most important determinant. Unfortunately, measurements of each of the components included in this balance have not been systematically obtained in patients at the time that ventilator support is being discontinued. Measurements of respiratory center output indicate that a depressed respiratory drive is rarely responsible for the inability to discontinue ventilator support [142, 143]. Phrenic nerve function is usually satisfactory, except for a small proportion of patients who develop problems following coronary artery bypass surgery. Respiratory muscle strength is reflected by measurements of maximal inspiratory pressure ($P_I$max) [144]. Available evidence suggests that this, *on its own,* is not an important determinant of the ability to resume and sustain spontaneous ventilation after a period of mechanical ventilation [145]. A number of techniques can be used to assess respiratory muscle endurance or fatigue in a research laboratory. None of these have ever been reliably applied in ventilator-supported patients. Thus, we do not know if respiratory muscle fatigue ever occurs in patients who are unable to resume spontaneous ventilation and, if it occurs, how important it is in determining clinical outcome or patient management? Respiratory muscle fatigue has been defined in dichotomous terms (present or absent), but the impairment in contractility is more likely to exist in the form of a continuum. Thus, it is quite conceivable that "mild fatigue" *per se* may not seriously interfere with the process of discontinuing ventilator support. This is an area where additional research is sorely needed.

The load on the respiratory system is primarily determined by an increase in respiratory resistance, a decrease in respiratory compliance, and the presence of auto-PEEP, which poses an additional threshold load. Each of these factors could produce a marked increase in respiratory work and interfere with the process of discontinuing the ventilator. Although measurements of respiratory work have been obtained in patients at the time of discontinuing mechanical ventilation, most studies contain significant methodologic flaws [141]. Even allowing for these limitations, it is doubtful that a single threshold value of respiratory work can reasonably discriminate between patients who are able to successfully sustain spontaneous ventilation and those requiring continued ventilator support. In particular, there is a tremendous need for research defining the precise interplay between respiratory load and respiratory muscle performance in such patients. Such knowledge would be important not only in elucidating the mechanisms responsible for the inability to resume spontaneous ventilation, but it would also help in guiding optimal ventilator support prior to the discontinuation attempts.

Although mechanical ventilation is commonly instituted because of problems with oxygenation, this is rarely a cause of difficulty at the time that mechanical ventilation is being stopped, largely because ventilator discontinuation is not contemplated in patients who display significant problems with oxygenation.

Research into the discontinuation of ventilator support has primarily focused on factors affecting the respiratory system. Although impaired cardiovascular performance has significant impact on the respiratory system (decreasing O_2 supply to the respiratory muscles, increasing respiratory work secondary to pulmonary edema, and hypoxemia as a result of a low mixed venous O_2 tension), remarkably few studies have examined the role of cardiovascular performance as a determinant of the ability to resume successful spontaneous ventilation [146]. In patients with known coronary heart disease, significant cardiovascular impairment reflected by a marked increase in pulmonary artery occlusion pressure has been documented at the time of resuming spontaneous ventilation. This is another area where much research is required, both in patients who require ventilator support primarily because of cardiovascular problems, and in patients without obvious underlying cardiovascular disease. In particular, it is important to document the time course of significant decompensation in such patients, and to determine if this differs significantly from the pattern occurring in patients with a primary pulmonary disorder.

Psychologic factors are a major determinant of outcome in some patients, especially in those patients who require prolonged ventilator support [147]. Minimal research has been conducted into this important issue, and, thus, it is difficult to state its relative importance in determining the ability to resume spontaneous ventilation.

C. Predictive indices

A wide variety of physiological indices have been proposed to guide the process of discontinuing ventilator support. Traditional indices include the P_aO_2/F_IO_2 ratio, the alveolar-arterial PO_2 gradient, $P_I$max, VC, V_E, and MVV [144, 145]. Newer indices include $P_{0.1}$, the f/V_T ratio, and integrative indices such as CROP, the pressure-time index and V_E40 [143, 148, 149]. In general, these indices evaluate a patient's ability to sustain spontaneous ventilation. They do not assess a patient's ability to protect his/her upper airway. Indices of upper airway function have been developed for managing post-operative patients, but similar indices have not been evaluated in critically-ill patients.

There are enormous discrepancies in the literature on the accuracy of indices in predicting successful discontinuation of mechanical ventilation. Discordance is due, at least in part, to methodologic problems and differences among studies. These include: (a) characteristics of the patient population; (b) the method of making the measurements; (c) reproducibility of the measurement; (d) the method of selecting the threshold value of an index; (e) the method of testing the accuracy of an index; and (f) definition of end points in the evaluation study.

As currently employed, predictive indices are most commonly used in evaluating a patient for extubation. Measurement of these physiological indices may suggest to a physician that ventilator support can be discontinued at an earlier time than he/she might otherwise have thought possible. This may help in decreasing the risk of complications associated with mechanical ventilation. When an index suggests that resumption of sustained spontaneous ventilation is unlikely to be successful, it can provide important information regarding the patient's underlying pathophysiologic state. However, there is no evidence to suggest that a particular set of physiological indices is helpful in guiding the selection of a particular technique to hasten the process of discontinuing ventilator support. Accordingly, at this time, it is impossible to say precisely if, and how, such physiological indices should be used in clinical decision making or in the management of a patient who is still requiring ventilator support.

It is important to remember that the condition of ventilator-dependent patients can vary considerably from day to day. Thus, a patient's ability to successfully resume and sustain spontaneous ventilation should be evaluated on a recurrent basis.

D. Techniques of discontinuing ventilator support

The major techniques of discontinuing ventilator support include T-tube trials, IMV and PSV.

There is considerable variation among clinicians in the manner of applying T-tube trials [141, 150]. Some clinicians continue maximal ventilator support (e.g., CMV with neuromuscular blockade, or A/C) up until the point at which they believe that a patient has a reasonable chance of extubation. This decision is usually based on clinical examination and measurement of physiological indices. At this point, the ventilator is stopped and the patient breathes through a T-tube system. The duration of such a T-tube trial has never been standardized, and it varies from about 30 min to several hours. During the trial, a decision is made to extubate the patient (provided that problems with upper airway protection are considered unlikely) or to reinstate ventilator support. Some clinicians do not attempt another T-tube trial for ≥ 24 h after an unsuccessful attempt. Other clinicians employ intermittent T-tube trials of gradually increasing duration (from 5 to 60 min) at intermittent intervals (e.g., 3–4 h apart); this is conducted on an empirical basis.

IMV was the first alternative approach to T-tube trials [150, 151]. IMV involves a gradual reduction in the amount of support being provided by the ventilator and a progressive increase in the amount of respiratory work being performed by the patient. The pace of decreasing the IMV rate is generally based on clinical assessment and measurement of arterial blood gases, but precise guidelines do not exist. As discussed elsewhere in this consensus conference, breathing through the demand valve of an IMV circuit can produce a marked increase in the work of breathing. (See Section IV-B-3)

PSV can also be used to gradually decrease the level of ventilator support [152–154]. The level of PSV is gradually decreased so that a patient becomes increasingly responsible for a larger proportion of overall ventilation. It is commonly assumed that the level of PSV can be decreased to a low level that will compensate for the resistance of the endotracheal tube and circuit, and that the patient can then be extubated at that level of PSV [108, 155, 156]. Unfortunately, there are no simple parameters that can predict the level of PSV that compensates for this resistance in an individual patient.

A gradual approach to the discontinuation of mechanical ventilation (i.e. IMV or PSV versus abrupt T-tube trials) has two theoretical advantages: (a) the use of less positive pressure (since these are modes of partial rather than full assistance) and, thus, a potential for fewer pressure-related complications, and (b) performance of some level of respiratory work should prevent the development of respiratory muscle atrophy – this is mainly an advantage when contrasted with a patient receiving CMV with neuromuscular blockade, since patients being managed with AC (with or without intermittent T-tube trials) probably perform sufficient work to prevent significant deconditioning.

In addition to the independent use of T-tube trials, IMV or PSV as approaches to discontinuing ventilator support, these techniques are frequently integrated and specific protocols defined for a given patient in an attempt to establish the most optimal approach. That is, PSV and IMV have been combined, with both gradually decreased, or the level of one technique kept constant while the other is gradually decreased. T-tube trials have also been integrated with PSV and IMV.

At the present time, no study has been published that has compared the optimal use of these three major techniques of discontinuing mechanical ventilation.

E. Management of the difficult patient

Discontinuation of mechanical ventilation poses considerable difficulty in a significant proportion of patients. These patients account for a disproportionate amount of health care costs, and they pose enormous clinical, economic and ethical problems. In addition to the factors already discussed, several other issues need to be considered in these patients. Increasing ventilator support at night to ensure maximal rest is recommended. In a recent study, the institution of a ventilator-management team was shown to decrease the number of ventilator and ICU days [157]. Nutritional support needs to be considered since these patients are dependent on a ventilator for a relatively long period of time. Uncontrolled, retrospective studies suggest that nutritional supplementation can ex-

pedite the discontinuation of mechanical ventilation, but this has yet to be examined prospectively [141]. Likewise, respiratory muscle training appeared promising in an uncontrolled study [158], but its benefit has yet to be evaluated prospectively. Finally, a prospective study of biofeedback was shown to be particularly beneficial [147]. However, skilled practitioners are not widely available, and the initial beneficial findings in this study need to be confirmed.

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