MECHANICAL VENTILATION OF THE CRITICALLY ILL PATIENT

CONVENTIONAL AND NEW TECHNIQUES

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Mechanical ventilation of the critically ill patient is a necessity in the practice of contemporary medicine. At Parkland Memorial Hospital there are about 900 patient ventilator-days per month or about 30 patients on a ventilator at any time. The basic techniques with which patients are usually ventilated were derived in the 1970's, but several alterations have been proposed in the late 1980's. This review will cover aspects of methods used in conventional ventilation and will then describe the more recently introduced techniques and compare the new to the old whenever possible. First, however, a brief history of mechanical ventilation will indicate that this branch of medicine has long been controversial.

TABLE 1

A Brief History of Mechanical Ventilation

1555	Vesalius ventilates animals with bellows
1667	Hooke repeats the Vesalius experiments
1744	Fothergill successful in human ventilation
1770's/ 1800's	Mechanical ventilation used in drownings but abandoned due to barotrauma
1838	Beginning of negative pressure ventilation
1927	Drinker iron lung
1800's/ 1900's	Positive pressure ventilators for thoracic surgery and resuscitation
1937	First "contemporary" pressure limited ventilator
1952	Treatment of poliomyelitis patients in Copenhagen establishes value of positive pressure ventilation
1954	First "contemporary" volume limited ventilator (Engstrom) for long term care
1960's	Establishment of intensive or critical care units

Andreas Vesalius is regarded as the originator of positive pressure mechanical ventilation, having demonstrated in 1555 that animals could be maintained alive by making a hole in the trachea into which a tube of reed or cane was placed and air insufflated with a bellows (1). The Vesalius technique was not an instant success, since no further mention of it was made for about a century until Robert Hook of London repeated the experiments in 1667 and obtained similar results (2). It would be an exaggeration to say that even then this technique seized the imagination of contemporary physicians, since almost another century passed before it was mentioned again. In 1744 John Fothergill reported a successful case of mouth-to-mouth

resuscitation and suggested "a pair of bellows might possibly be applied with more advantage in these cases . . . . . ." (3). By the late 1700's positive pressure ventilation was finally used in drowning victims, along with accessory techniques such as the insufflation of tobacco smoke per rectum (2). However, overly enthusiastic ventilation by bellows led to instances of tension pneumothorax, and the method was discontinued following an adverse publication by Leroy d'Etoille in 1827 (4). Shortly thereafter John Dalziel described a body-enclosing, negative pressure apparatus, and a century of negative pressure ventilation began (5). The technique was never successful for prolonged support until the invention of the famous "iron lung" by Drinker in 1929 (6). During the late 1800's and early 1900's positive pressure ventilators were utilized predominantly for anesthesia during thoracic surgery and for acute resuscitation (7).

Ventilators similar to those presently used were introduced in the late 1930's by Barach and his colleagues (8) and were studied by the pulmonary group at Columbia during the 1940's (9, 10). Intermittent positive-pressure breathing (IPPB) machines are categorized as pressure limited ventilators. That is, the operator determines the peak pressure to be applied to the patient's lungs, and the machine ceases inspiration when that pressure is reached. The tidal volume achieved depends not only on the pressure applied but also on the resistance of the patient's respiratory apparatus. By the late 1950's families of Bennett and of Bird IPPB machines were widely used not only in apneic patients, but also for patients with pulmonary edema, asthma, COPD, and postoperatively.

It was events in Europe, however, that firmly established a role for positive pressure ventilation. In 1952 there was a massive poliomyelitis epidemic in the Scandinavian countries. From July 24 to December 3 the Hospital for Communicable Diseases in Copenhagen admitted 2,722 such patients of which 315 required respiratory support (11). There were only seven negative pressure ventilators available. Among the first patients admitted with respiratory difficulty the mortality rate was 87 percent. Faced with these disastrous results, the Medical Director, Professor H. C. A. Lassen, consulted anesthesiologist Bjorn Ibsen who introduced the use of tracheostomies with cuffed tubes through which manual positive pressure ventilation was given (12). During the remainder of the epidemic medical school was dismissed, teams of students were formed, and with the help of technicians of various types these students carried out continual manual ventilation on paralyzed patients, some of whom required support for several months. The mortality rate for paralysis involving muscles of respiration was decreased to 40 percent. Thus, the efficacy of positive pressure ventilation was established. Simultaneously, it was possible for Engstrom to demonstrate his new volume ventilator which was designed for long term support (13). With a volume ventilator the operator sets

the tidal volume desired, and the machine delivers that tidal volume irrespective of the pressure necessary.

After the introduction of poliomyelitis vaccines and the mass immunization of the American population, most polio wards were closed by the early 1960's. However, by the mid to late 1960's, these units were being replaced by the forerunners of present intensive or critical care units to which patients were admitted most commonly because of the need for mechanical ventilation. In the United States many of these units utilized pressure limited machines at the outset. Although IPPB machines had some advantages relative to volume ventilators, predominantly in the area of patient comfort, there were decided disadvantages. The tidal volume and minute ventilation achieved was not known; the IPPB machines were prone to simple mechanical problems which required immediate solutions by the nursing staff; and there were no alarm systems to indicate the difficulties at hand. Thus, the standard of care for acutely ill patients became the volume limited ventilator. Before proceeding with a description of conventional ventilation, however, it should be pointed out that acute respiratory failure may be caused by differing pathophysiologies.

TYPES OF RESPIRATORY FAILURE

Table 2

Types of Acute Respiratory Failure

Failure of ventilation
Respiratory Center
Neuromuscular apparatus
Failure to eliminate carbon dioxide
Failure to oxygenate arterial blood

There are three types of acute respiratory failure. One of these is failure of ventilation. The primary defect is insufficient minute and alveolar ventilation despite lungs that are in most instances entirely normal. The failure may be due to insufficient respiratory center activity to drive an intact neuromuscular respiratory apparatus; this defect usually results from an overdose of narcotics or a myriad of sedatives. Failure of ventilation may also occur with a normal respiratory center when impulses to the muscles of respiration are blocked by a disease of the nervous system or when the muscles of respiration are too weak to respond to normal impulses. Examples include trauma to the cervical spinal cord, the Guillian Barre syndrome, myasthenia gravis, and the muscular dystrophies or atrophies.

Failure to eliminate carbon dioxide is due to an airway obstructive disease, usually COPD or asthma. Although the primary process is airways obstruction, overt respiratory failure

with hypercapnia may be due to failure of the muscles of respiration due to fatigue (14).

Failure to oxygenate arterial blood despite oxygen administration indicates that a parenchymal disease is distributed widely throughout the lungs, usually a form of severe pulmonary edema. Although left ventricular failure or volume overload may lead to failure of oxygenation, and may require mechanical ventilation, these problems are usually relatively transient once recognized. The syndrome leading to protracted failure to oxygenate blood is most commonly the adult respiratory distress syndrome which may be caused by several agents.

Since the mechanisms of respiratory failure are different in each of these types of defects, it is not surprising that the ventilator strategies should also be different. Ventilatory techniques that are appropriate for one type of respiratory failure may be detrimental in another. Unfortunately some articles refer only to "acute respiratory failure" without clearly indicating the basic mechanisms among the patients being treated. I shall attempt to avoid this mistake in this review.

CONVENTIONAL METHODS OF MECHANICAL VENTILATION

Table 3

Conventional Methods of Mechanical Ventilation

Continuous mandatory ventilation	(CMV)
Assisted mandatory ventilation	(AMV)
Positive end expiratory pressure	(PEEP)
Continuous positive airway pressure	(CPAP)
Synchronized intermittent mandatory ventilation	(SIMV)

These methods are listed as conventional because they were all introduced before 1975, and since that time one or more of these techniques used independently or together have been utilized in the overwhelming majority of patients who have required ventilatory support. Some authors prefer the term Control Mode Ventilation and others Controlled Mandatory Ventilation to Continuous Mandatory Ventilation, but all of these are synonymous, and all are abbreviated CMV. Assisted mandatory ventilation is similar to CMV, but the patient triggers the machine to deliver the tidal volumes and thereby determines the respiratory rate. With positive end expiratory pressure the ventilator creates the pressure necessary to deliver the desired tidal volume and then continues to create a lesser positive pressure during exhalation. Thus, the pressure in the patient's lungs remains above atmospheric pressure even at the end of expiration. With continuous positive airway pressure the ventilator delivers a constant pressure during the entire

respiratory cycle which is usually of the same order of magnitude as PEEP. Thus, there is insufficient pressure to totally assist the patient's inspiration and most of ventilation is caused by the patient's respiratory muscles. CPAP was originally termed continuous positive pressure breathing (CPPB), but the name change did not indicate any difference in the therapy. During synchronized intermittent mandatory ventilation the patient is allowed to determine his or her own respiratory rate, and tidal volume is delivered without machine assistance, but periodically at a rate determined by the ventilator operator a mandated tidal volume is delivered by the machine. The mandated breaths are synchronized to occur just as the patient begins a spontaneous breath. Selected aspects of each of these methods of ventilation will be reviewed.

Before proceeding it should be noted that there is considerable variability among ventilators in performing certain functions (15-27). For example, the ease with which a patient may trigger a machine to give an assisted tidal volume or to initiate gas flow for continuous positive airway pressure varies markedly. Thus, differing outcomes of the same modality of therapy may occur when ventilators of different design are used. Each physician should become familiar with the characteristics of the ventilators used at his or her hospital.

Continuous Mandatory Ventilation (CMV)

Continuous mandatory ventilation, or control mode ventilation, is a method of positive pressure ventilation in which the ventilator delivers a preset tidal volume at a preset frequency (28).

Table 4

Operator Decisions While Initiating CMV

Tidal volume (V_T)
Respiratory rate (f)
Inspiratory flow (V_I)
Inspired oxygen concentration (F_IO_2)

Although every mechanical ventilator has a bewildering array of controls, the critical decisions which an operator must make while initiating CMV are the size of the tidal volumes, the respiratory rate, the rate of inspiratory flow, and the inspired oxygen concentration. Of these, the decision concerning the size of tidal volumes is usually the first.

Table 5

Tidal Volumes During CMV for Failure of Ventilation Or CO_2 Elimination

	V_T ml/kg of ideal body wt	V_T 70 kg pt ml
Spontaneous	7	500
Sigh	14-21	1000-1500
CMV for vent failure	10-15	700-1000
CMV for CO_2 failure	10-12	700-850

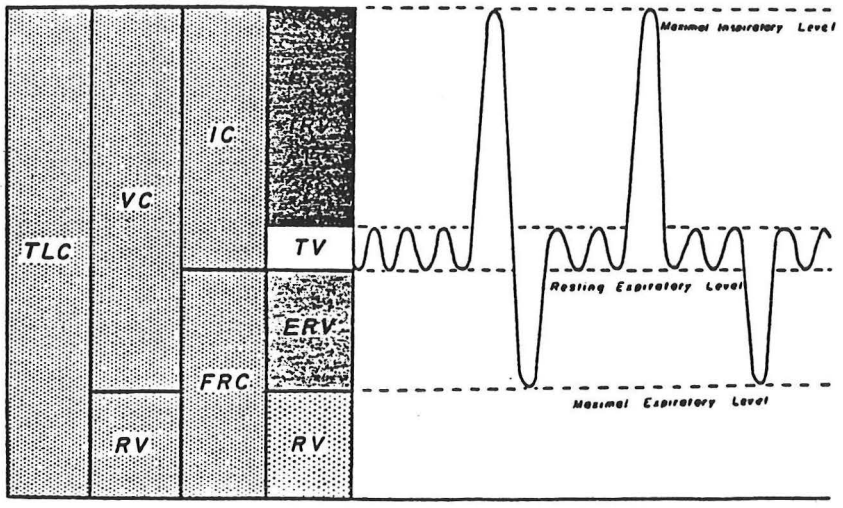
Pontoppidan, Geffin, and Lowenstein: N. Engl. J. Med. 287:690-697, 743-752, 799-806, 1972.

Spontaneous tidal volumes in resting persons vary considerably, but average about 7 ml per kg of ideal body weight. This results in about 500 ml tidal volumes for a 70 kg patient. In a variety of studies it was found that patients mechanically ventilated with normal sized tidal volumes developed progressive hypoxemia and stiffness of the lung. It was also found that these defects could be reversed promptly by periodic hyperinflations with much larger tidal volumes termed sighs. These findings led to the concept of diffuse microatelectasis occurring in lung units which receive little or no ventilation at normal tidal volumes (29). Thus, patients were ventilated with normal sized tidal volumes and given periodic sighs two to three times this volume. Pontoppidan and his colleagues noted in a review article in the New England Journal of Medicine in 1972 that sighs are poorly tolerated by patients. This group initiated the practice of every CMV tidal volume being larger than normal (30). Their article virtually became the manual for the care of patients on ventilators, and continuous large tidal volumes obviating the need for sighs became standard practice. Thus, patients receiving CMV for failure of ventilation usually receive tidal volumes of 10 to 15 ml per kg of ideal body weight resulting in tidal volumes of 700 to 1,000 ml for a 70 kg patient.

Patients receiving continuous mandatory ventilation for failure to eliminate carbon dioxide usually are given smaller tidal volumes than patients with failure of ventilation. A reasonable range is 10 to 12 ml per kg of ideal body weight resulting in a 700 to 850 ml tidal volume in a 70 kg patient (31). The reason for the smaller tidal volumes can best be explained by recalling the static lung volumes (32).

Figure 1

Static Lung Volumes



The total lung capacity (TLC) is the amount of gas contained in the lungs at the end of a maximal inspiration. During a maximal exhalation the majority of this gas is delivered as the vital capacity (VC), but some remains in the lungs, the residual volume (RV). In healthy 20 year old persons the residual volume is about 20 percent of the total lung capacity, but in healthy 50 to 60 year old persons the RV is about 40 percent of TLC (32). An additional important way of visualizing lung volumes relates to the amount of gas in the lungs at the end of a normal tidal volume. At this resting expiratory level no muscular effort is exerted to breathe in or out; the system comes to rest at the volume at which the inward elastic recoil of the lungs is balanced by the outward elastic recoil of the chest wall. The amount of gas contained in the lungs at end expiration is termed the functional residual capacity (FRC) and represents about 40 percent of the potential total lung capacity in a young adult but about 55 percent of TLC in an older adult. Thus from the resting expiratory level a young adult may breathe in about 60 percent of his or her total lung capacity, but an older adult may breathe in only about 45 percent of TLC. Phrased differently, in an average sized adult with a TLC of 6,000 ml a young person may breathe in an additional 3,600 ml while an older person may breathe in only about 2,600 ml.

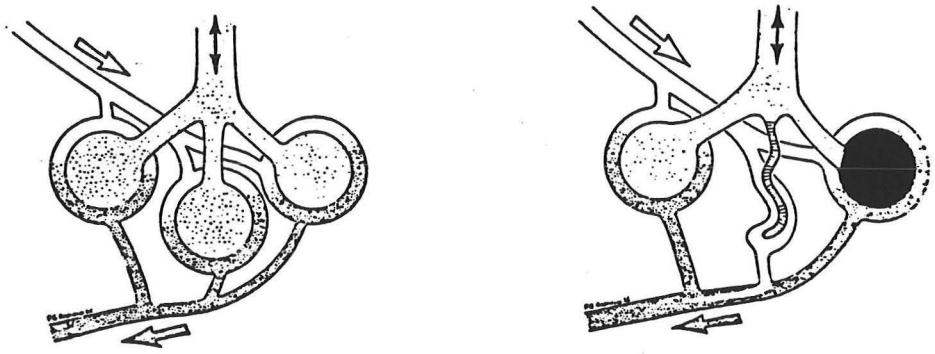
In patients with obstructive airway diseases, especially patients with emphysema in whom the elastic recoil of the lung is diminished, there is air trapping due to closure of airways causing a shift upward in residual volume and functional residual capacity. Thus, the resting expiratory level shifts toward total lung capacity resulting in a diminished inspiratory capacity. Very large tidal volumes delivered by a ventilator might stretch the lungs beyond their capacity for expansion and lead to

barotrauma. Smaller tidal volumes are used during mechanical ventilation of obstructed patients to minimize this risk.

The concept of static lung volumes is also important in understanding the most optimal tidal volumes for patients with failure to oxygenate arterial blood. In these patients the defects are in the opposite direction with small total lung and functional residual capacities.

Figure 2

Schematic Representation of Pulmonary Edema



Modified from: Bendixen, Hedley-Whyte, and Laver: N. Engl. J. Med. 269:992, 1963.

The left side of Figure 2 is a schematic representation of a normal lung in which there is an even distribution of ventilation and a proportionately even distribution of pulmonary arterial blood flow. Thus, there is an optimal relationship in ventilation-perfusion ratios resulting in normal oxygenation. On the right of Figure 2 is a schematic of a lung with pulmonary edema. In this circumstance some alveoli are filled with edema fluid and do not take part in gas exchange. Additional alveoli may have become atelectatic, presumably due to inactivation of surfactant (33). If alveoli with edema or atelectasis retain pulmonary blood flow, the perfusing blood does not come in contact with ventilation and functions as a right to left shunt. Shunting is the major cause of hypoxemia in patients with ARDS (34). Since there is no ventilation to the atelectatic or edema filled areas only unaffected areas take part in ventilation resulting in a low functional residual capacity.

The major strategy in ventilator management of patients with pulmonary edema is to recapture the unventilated areas and optimize their ventilation-perfusion ratios to decrease hypoxemia. In this circumstance it might seem attractive to give very large tidal volumes in order to open areas of atelectasis. This is reasonable to a point, and some areas of additional

ventilation are recruited. However, the critical opening pressure for some closed airways may be quite high. Since the areas of lung filled with edema and the areas whose airways fail to open cannot be ventilated, the path of least resistance for the inhaled gas is to those areas of lung which are normal. This may lead to marked over distention of normal lung units, a phenomenon that has been demonstrated to cause the normal units to develop a high permeability pulmonary edema and the histological picture of ARDS (35-50). This syndrome is usually referred to as high inflation pressure pulmonary edema, but it is clear that the damage correlates with the volume but not the pressure in the previously normal alveoli (38, 41, 44, 45, 47). Indeed, normal alveoli may expand beyond their usual maximal volume by up to twelve fold by encroaching on the space of the lung units which do not take part in ventilation (38). The cause of this high volume pulmonary edema is not entirely clear, but loss of surfactant is most likely involved (36, 42, 50). The damage has also been correlated with an influx of granulocytes (42, 49) but this finding is not consistently reproducible. No matter the mechanism, it is clear that giving excessively large tidal volumes to patients with failure to oxygenate blood is not prudent. To understand a reasonable mechanism for determining an appropriate tidal volume requires that we review the concept of compliance.

Table 6

Measurement of Compliance (▲V/▲P) in Ventilator Patients

Dynamic Comp = V_T/Peak Inflation Pressure = 79 ± 15 ml/cm H_2O
- Chest wall
- Ventilated lungs
- Airway resistance (flow dependent)

Static Comp = V_T/Inflation Hold Pressure = 97 ± 18 ml/cm H_2O
- Chest wall
- Ventilated lungs

Robertson, Johanson and Pierce: Am. Rev. Respir. Dis. 105:979(Abst), 1972.

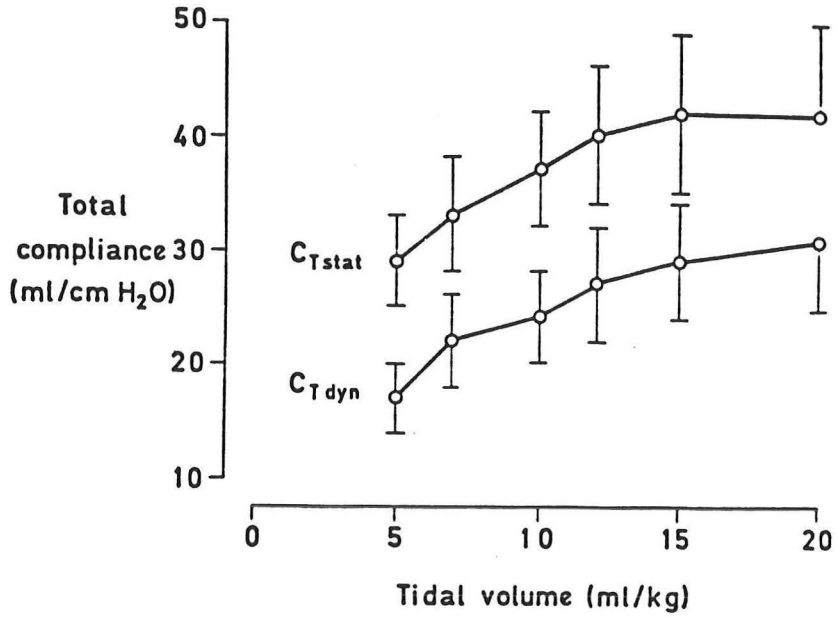
Compliance is a measurement of the elasticity or stiffness of the respiratory apparatus. The measurement of compliance is the change in lung volume (▲V) divided by the change in airway pressure (▲P) which caused the change in volume. For ventilator patients the change in volume which is measured is the exhaled tidal volume, and the change in pressure delivering the tidal volume is recorded from the pressure manometer on the ventilator. Two types of compliance may be determined (51). Dynamic compliance is measured by the tidal volume divided by the peak inflation pressure which caused the tidal volume. The normal value obtained from comatose patients with normal lungs is 79 ml/cm H_2O, but the standard deviation is large. Part of the

inflation pressure is necessary for moving the chest wall and part for inflating the segments of lung which are ventilated. However, during inflation part of the pressure is also dissipated in causing gas to flow from the ventilator through the endotracheal tube and the patient's airways. Thus, the measurement of dynamic compliance includes not only an estimate of chest wall and lung stiffness, but also an estimate of airway resistance. Moreover, the faster the flow of gas from the machine into the patient the more turbulent the gas flow and the more frictional resistance is created. The measurement of dynamic compliance may vary simply due to changing the inspiratory flow control on the ventilator. Thus, a different measurement is more helpful for determining the status of the pulmonary parenchyma.

Static compliance is measured by dividing the tidal volume by the inflation hold pressure and averages about 97 ml/cm H_2O in normal persons. Inflation hold pressure indicates that at the end of inspiration as the ventilator cycles to no gas flow the exhalation valve is held closed so that no gas escapes from the system. Under this circumstance the manometer pressure is equal to alveolar pressure; since no gas is flowing, airway resistance is no longer relevant. This measurement indicates the stiffness of the chest wall and the ventilated lungs. It is not practical to measure the compliance of the lungs alone in a clinical setting. However, unless there is some change in the chest wall, it's compliance does not change over time; thus changes in static compliance may be used to indicate changes in lung compliance. This measurement may be useful in estimating the appropriate tidal volume for patients with failure of oxygenation, as indicated in Figure 3.

Figure 3

Relationship Between Compliance and Tidal Volume



Suter, Fairley, and Isenberg: Chest 73:158, 1978.

This graph by Suter and his colleagues illustrates the usefulness of compliance in determining an appropriate tidal volume for patients with failure to oxygenate blood (51A). The graph plots total compliance against tidal volume in ml/kg, and the asterisks indicate significant differences between adjacent means. In this study the static compliance improved with increasing size of tidal volume from 5 ml/kg through 15 ml/kg. In some patients compliance continued to improve with tidal volumes of 20 ml/kg, but on average compliance did not improve. These data indicate that increasing size of tidal volume recruited areas of lung previously unventilated and thereby improved distribution of ventilation in the functional areas of lung. However, as tidal volume is increased further, a plateau of compliance indicates that the ventilated lung is reaching its limits of distensibility and that it would be unwise to utilize tidal volumes of this magnitude.

In practice we utilize a different plot of the same data, pressure volume curves with tidal volume on the vertical and pressure on the horizontal axes. Tidal volumes are chosen which are well below the plateau indicating lung overdistention.

We shall also use the concept of compliance when discussing PEEP, but for now we shall return to setting up a ventilator to deliver CMV.

Table 7

Respiratory Rate (f) for Patients Receiving CMV

Type of Respiratory Failure	f (V_T/min)	V_T (ml/kg)
CMV for vent failure	5-6	15
CMV for CO_2 failure	8-10	10-12
CMV for O_2 failure	12-14	-
ABG's after 20-30 mins and adjust depending on $PaCO_2$		

Reasonable initial respiratory rates for patients receiving CMV are indicated in Table 7 (31, 52). For conscious patients with ventilatory failure the very slow respiratory rate indicated may be uncomfortable. In such cases additional links of tubing between the patient and the Y connector of the standard machine tubing may be added in order to increase the apparatus dead space which will allow large tidal volumes at a faster respiratory rate. In these instances, however, it is extremely important for all personnel to realize that the tidal volume must not be reduced, since the extra tubing may prevent small tidal volumes from ventilating the patient adequately.

The respiratory rate for patients with failure to eliminate carbon dioxide should initially be quite slow for two reasons. First, patients with chronic hypercapnia should not have their $PaCO_2$ reduced so rapidly that alkalosis ensues and causes a potentially dangerous decrease in cerebral blood flow (53, 54). Second, a protracted expiratory phase is desirable to ensure that exhalation is complete without air trapping.

Respiratory rate for patients with failure of oxygenation cannot be readily estimated, but it is clear that a more rapid rate is necessary than for other types of respiratory failure. The 12 to 14 indicated in the table is a reasonable beginning point.

With all types of respiratory failure arterial blood gases should be performed after 20-30 minutes of ventilation, and the respiratory rate adjusted depending on the $PaCO_2$. If the $PaCO_2$ is not satisfactory, or if conditions change after the first adequate adjustment has been made, subsequent adjustments of respiratory rate are made depending on new determinations of the $PaCO_2$. It usually is not desirable to change the size of the tidal volume to control the $PaCO_2$.

Table 8

Inspiratory Flow (V_I) for Patients Receiving CMV

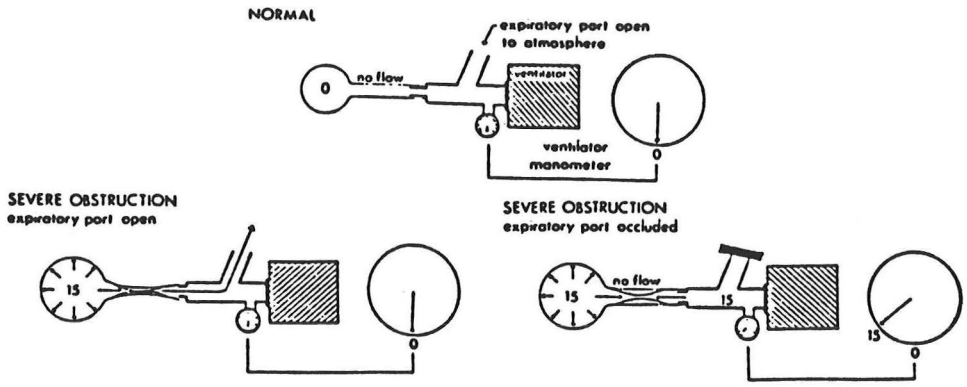
Condition	Peak $\dot{V}_I$ (L/min)
Spontaneous at rest	24
Spontaneous at 20-30 L/min $\dot{V}_E$	90
CMV for vent failure	30-40
CMV for CO_2 failure	100
CMV for O_2 failure	40

Table 8 indicates reasonable settings of the third important operator decision, inspiratory flow ($\dot{V}_I$). For reference I have included peak inspiratory flows for normal persons breathing spontaneously (55). At rest the normal peak flow is about 24 L/min, while at moderate exercise with a minute ventilation of 20 to 30 L/min the inspiratory flow may increase to 90 L/min. In patients on continuous mechanical ventilation three considerations are important in setting the inspiratory flow. First, a slow flow tends to maximize the distribution of ventilation and help improve ventilation-perfusion ratios. Second, a short inspiratory relative to expiratory ratio (I:E) minimizes the cardiovascular effects of positive pressure. Third, the expiratory time must be sufficiently long to ensure complete lung emptying. In patients on CMV for ventilatory failure the respiratory rate is quite slow; a slow inspiratory flow approximating a spontaneous breath in a normal person should equalize distribution of ventilation, allow an I:E ratio sufficiently small to minimize cardiovascular effects, and allow a very long exhalation time for complete lung emptying.

It would be appealing to give slow inspiratory flows to patients on CMV for CO_2 failure since the distribution of ventilation is poor in obstructed patients. Further, a slow inspiratory flow should allow a sufficiently small I:E ratio to minimize cardiovascular effects. However, while ventilating seriously obstructed patients the expiratory time must be as long as possible to ensure complete lung emptying to prevent the phenomenon of auto-PEEP (56-62). Synonyms often applied to this phenomena are dynamic hyperinflation, breath stacking, intrinsic PEEP, and occult PEEP. Auto-PEEP occurs when the time required for complete expiration is longer than the available expiratory time imposed by the ventilator settings. The increase of intrathoracic pressure associated with auto-PEEP may depress cardiac output and may spuriously elevate the end expiratory pulmonary artery wedge pressure (56). The latter may cause an incorrect assessment of the cause of the former and may lead to inappropriate therapy. In addition, the unrecognized auto-PEEP may cause spurious measurements of lung compliance, and may add to the muscular work of breathing of obstructed patients who are being weaned from mechanical ventilation.

Figure 4

Measurement of Auto-PEEP



Pepe and Marini: Am. Rev. Respir. Dis. 126:166, 1982.

Auto-PEEP should be suggested when a patient is still exhaling at the time the machine cycles into inspiration. The method of determining the presence and magnitude of auto-PEEP is indicated in Figure 4 (56). The top schematic represents the exhalation phase of a ventilated patient with normal lungs. The alveolar pressure has equalized with atmospheric pressure through the open expiratory valve. The ventilator manometer indicates atmospheric pressure in the system. The second schematic indicates a patient with airways obstruction during expiration. The gas flow is so slow from obstructed airways that alveolar pressure does not equalize with atmospheric pressure and remains positive at the end of expiration. The ventilator manometer is open to the atmosphere and does not record the supraatmospheric pressure in the obstructed lung units; i.e. there is no indication of the auto-PEEP. The third diagram indicates a similar circumstance, while the operator occludes the expiratory port immediately before the next inspiration. The pressure throughout the system now equalizes at the positive alveolar pressure existing in obstructed lung units and the auto-PEEP is reflected on the ventilator manometer.

Although in carefully controlled experiments low levels of ventilator applied PEEP may be beneficial in decompressing auto-PEEP, in a clinical setting ventilator applied PEEP is likely to be deleterious (63). It is preferable to give a more rapid inspiratory flow to allow a longer time for exhalation. Indeed, high inspiratory flow has been demonstrated to improve several parameters of ventilation in obstructed patients compared to lower levels of inspiratory flow (64).

A slow flow is indicated for patients on CMV for oxygen failure. However, auto-PEEP may also occur in this type of patient when the patient requires a high minute ventilation with a rapid respiratory rate. In addition, the inspiratory to

expiratory ratio may approach or exceed one indicating a continuous high intrathoracic pressure which may be deleterious to cardiac output. Thus, choosing the appropriate inspiratory flow for a patient on CMV for oxygen failure must be by trial and error.

Table 9

Inspired Oxygen Concentration (F_IO_2) for Patients Receiving CMV

Begin CMV with F_IO_2 of 1.0
Decrease F_IO_2 to lowest level compatible with satisfactory oxygenation of arterial blood
Initiate PEEP if F_IO_2 exceeds 0.4 - 0.5

It is reasonable to begin a patient who has just been intubated and placed on CMV on a F_IO_2 of 1.0 (100% oxygen) until oxygen parameters can be determined. Unfortunately, however, 100% oxygen is toxic to the lungs causing histological and ultrastructural lesions that are indistinguishable from those of ARDS (65-69). Normal persons have severe enough symptoms to discontinue exposure to 100% oxygen after 53 to 75 hours (70). Clinically it is rarely necessary to administer 100% oxygen, but the highest O_2 concentration that is tolerable for prolonged exposure is not known. It is clear that normal subjects can tolerate a F_IO_2 of 0.35 indefinitely (71), and additional evidence suggests that 0.40 to 0.55 is tolerable for normal humans (72, 73). Experimental evidence, however, suggests that preexisting lung damage may increase susceptibility to oxygen toxicity (74). Thus, no definitive dose-time relationship is possible for patients with ARDS. A reasonable compromise is to initiate PEEP in conjunction with CMV if the F_IO_2 exceeds 0.4 to 0.5.

Assisted Mandatory Ventilation (AMV)

We shall now turn our attention to assisted mandatory ventilation (AMV). In clinical practice most ventilators do not have an isolated AMV setting. Instead, there is an AMV/CMV control indicating that the machine will shift to CMV if the patient does not provide sufficient inspirations to reach a preset backup rate. Thus, AMV is a mode in which the ventilator provides tidal volumes of a preset size in response to patient-initiated efforts which determine the respiratory rate. A backup rate of mechanical tidal volumes begins if no patient effort occurs within a preselected time (28).

Table 10

Operator Decisions While Initiating AMV

Tidal volume (V_T)
Trigger sensitivity
Inspiratory flow ($\dot{V}_I$)
Backup rate
Inspired oxygen concentration

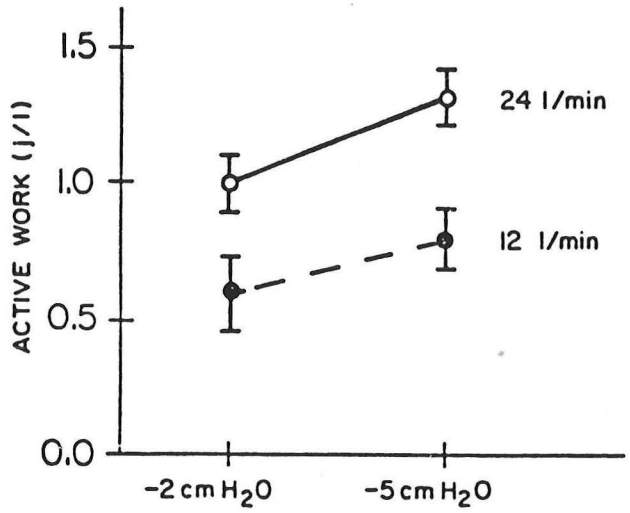
The critical decisions for the operator while initiating AMV are indicated in Table 10. Decisions concerning tidal volume and inspired oxygen concentration are similar to those for CMV. The new or different decisions include trigger sensitivity, inspiratory flow, and backup rate.

The underlying assumption behind the use of AMV is that the ventilator will provide not only a preset tidal volume but also provide an adequate ventilation which is set by the patient. This is accomplished while relieving the work of breathing in a manner similar to CMV. However, this supposition depends to a major degree on the setting of trigger sensitivity and inspiratory flow (75-80).

On AMV the patient must create a negative or subatmospheric pressure at some point in the ventilator to trigger a tidal volume. The amount of negative pressure necessary to trigger inspiration is one determinant of the work performed by the patient.

Figure 5

Influence of Trigger Sensitivity on Work of Breathing



Marini, Capps, and Culver: Chest 87:612, 1985.

In a study by Marini and his colleagues, the patient's muscular work of breathing was quantitated in units of joules/L (75). It is clear that the patient exerts less active work when the machine is set more sensitively indicating a lesser amount of negative pressure necessary to trigger the ventilator. Moreover, the graph indicates that the amount of respiratory work is in part dependent on the patient's minute ventilation. It should be noted that no matter how sensitive the control is set, there is an unavoidable delay between the time that the patient attempts to initiate respiration and the time that the machine responds. In this study it was found that the delay was 0.15 seconds at -2 cm H_2O sensitivity and 0.25 seconds at -5 cm H_2O sensitivity. Thus, at best the machine is always slightly behind the patient's inspiratory effort. Clearly, the machine must be set as sensitive as possible to decrease patient work.

Table 11

Patient Work of Breathing During AMV at Two Inspiratory Flows (n=5)

AMV Minute Ventilation (L/min)	Unassisted Breathing M Flow (L/min)	Peak Flow	Work of Breathing on AMV Joules/L $\dot{V}_{40}$	$\dot{V}_{60}$
22.4 ± 4.9	45 ± 6	69 ± 8	1.83 ± 0/69	1.30 ± 0.64

Marini, Rodriguez, Lamb: Am. Rev. Respir. Dis. 134:902, 1986.

The setting of inspiratory flow is also critical in determining the amount of respiratory work of a patient on AMV. Table 11 illustrates this point. Five patients with CO_2 or oxygenation failure were studied. The average minute ventilation of these patients was about 22.4 L/min, a value that is common in patients with respiratory failure on AMV. During brief trials of unassisted breathing the patient had an average inspiratory flow of 45 L/min and an average peak flow of 69 L/min. As might be predicted, when the patients were ventilated with AMV at an inspiratory flow of 40 L/min the amount of respiratory work performed by the patient was significantly more than at an inspiratory flow setting of 60 L/min. Indeed, since inspiratory flow by the machine always lags slightly behind the initiation of flow by the patient, one would predict that even with optimal settings patient work could not be totally obviated unless inspiratory muscles relaxed immediately after machine flow is initiated. Data from Marini in 20 patients with respiratory failure indicate that the required muscle relaxation does not occur. Patient work on AMV averaged 62.6 ± 24.2% of total work of breathing (76). Indeed, it is possible for the patient's work of breathing while receiving AMV to be greater than that while breathing spontaneously when ventilator settings are inappropriate.

The backup respiratory rate set on the ventilator should be less than the patient's spontaneous respiratory rate but sufficiently high to provide an adequate minute ventilation should the patient's respiratory efforts fail.

Positive End Expiratory Pressure (PEEP)

PEEP is a positive pressure applied throughout exhalation. It may be used in conjunction with any other form of conventional ventilation. When applied during spontaneous breathing with the same positive pressure maintained throughout the entire breathing cycle, the term CPAP is used.

There are no experimental or clinical data of which I am aware that indicate that PEEP decreases the amount of lung water or in any other way fundamentally changes the course of ARDS (81-92). Thus, the indication for the use of PEEP is to achieve adequate arterial oxygenation at a F_IO_2 which is not toxic. An attempt is made to accomplish this with the lowest level of PEEP so as to prevent a decrease in cardiac output (91-95).

Table 12

Mechanisms of Improved PaO_2 with PEEP

Increase in FRC
Recruitment of closed alveoli
Prevention of alveolar collapse
Redistribution of lung water from alveoli to interstitial spaces
Improvement in ventilation-perfusion ratios

The mechanism of improvement of PaO_2 with PEEP is an increase in the functional residual capacity, presumably due to recruitment of previously closed alveoli and prevention of further alveolar collapse (51A, 96, 97). Additionally there may be some redistribution of lung water from alveoli to interstitial spaces allowing some ventilation in these areas (98, 99). The recruitment of additional ventilating lung allows an improvement in ventilation-perfusion ratios with a redistribution in blood flow from shunts to regions of normal or low ventilation-perfusion ratios (34, 100-102).

Table 13

Potential Detrimental Effects of PEEP

Decreased Cardiac Output
Decreased venous return
Compression of heart by stiffened lungs
Renal Function
Blood flow cortex ↓; Medulla ↑
↑ Aldosterone, ↑ Antidiuretic hormone
↓ Atrial natriuretic factor
Increased intracranial pressure
Barotrauma

The potential detrimental effects of PEEP are indicated in Table 13. The most common of these, and the one from which other complications may ensue, is decreased cardiac output (103-108). There are several physiological changes induced by PEEP that may lead to a decreased cardiac output. I shall not review these but instead refer you to the Grand Rounds presented on this subject by Dr. Sharon Cassidy (103). The general consensus is that the most important cause is a decrease in venous return associated with the increased pleural pressure caused by PEEP. The second most important cause is probably the direct compression of the cardiac fossa by the lungs further inhibiting biventricular filling. No matter what the causes, PEEP of less than 15 cm H_2O usually does not lead to this complication, while higher levels of PEEP are likely to do so. Venous return and cardiac output can usually be restored by administration of intravenous fluids, although the administration of catecholamines is sometimes necessary. I have seen no good study indicating the fraction of patients who do not respond to this therapy and in whom the PEEP must be decreased or discontinued.

Renal function may be altered by PEEP including decreases in urine output and sodium excretion (28, 101, 109-112). This in part results from a redistribution in intrarenal blood flow with a decrease to the cortex and an increase to the medulla. In addition, there is increased aldosterone and antidiuretic hormone and a decrease in atrial natriuretic factor. The net result is retention of fluid. Maintenance of a normal cardiac output may prevent these changes.

PEEP may also cause increased intracranial pressure primarily by decreasing cerebral venous outflow due to increased superior vena caval pressure (109, 113, 114). Increased intracranial pressure is unlikely to occur in patients with normal intracranial dynamics. In persons with CNS dysfunction, PEEP may be used up to 12 or 15 cm H_2O while monitoring intracranial pressure and neurologic function (115). At higher levels of PEEP aortic pressure may be reduced resulting in a fall of cerebral perfusion.

The term barotrauma indicates the occurrence of pneumothorax, pneumomediastinum or subcutaneous emphysema and implies that these phenomenon occur due to excessive pressure in the lung. The incidence of this complication due to conventional mechanical ventilation is about 4% of all ventilated patients (116, 117). Barotrauma is often listed as a potential complication of PEEP therapy (28, 101). However, an association between barotrauma and PEEP per se is not clear. Indeed, an association between inflation pressure and barotrauma is not clear. In the 1940's Macklin and Macklin demonstrated that overdistention of alveoli preceded the development of barotrauma (118). Subsequently, hyperinflation was associated with barotrauma in patients on CMV with PEEP (119). Thus, barotrauma is probably related to overdistention of lung units by the association of excess PEEP plus tidal volume rather than to PEEP alone. Determining appropriate PEEP pressure plus tidal volume size should minimize this complication.

Table 14

Summary of the Effects of "Best PEEP"

Measurement	ZEEP	6 cm H_2O <Best PEEP	Best PEEP	6 cm H_2O >Best PEEP
C_{stat} (ml/cm H_2O)	41±4	41±4	51±4	45±5
PaO_2 (mm Hg)	78±3	82±6	90±4	99±5
Q_S/Q_T	.18±.03	.18±.03	.15±.02	.11±.02
O_2 Transport (ml/min)	841±108	858±90	950±110	794±68

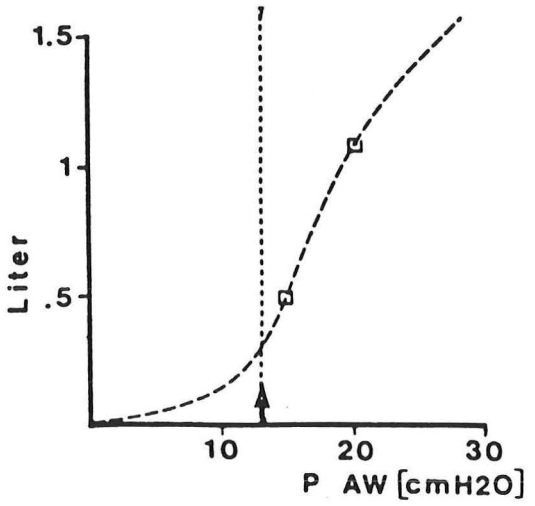
Suter, Fairley, Isenberg: N. Engl. J. Med. 292:284, 1975.

Suter and his colleagues, whose data appear in Table 14, have provided the rationale for an estimate of "best PEEP" utilizing measurements of static compliance (97). In this study tidal volumes were held constant at 12 ml/kg while PEEP was varied by 3 cm H_2O steps from 0 (ZEEP) to values which decreased cardiac output. "Best PEEP" was defined as the positive end expiratory pressure which produced the maximum oxygen transport, (i.e. the oxygen content of blood times the cardiac output). Although "best PEEP" varied widely among patients, it was paralleled by the static compliance; in other words, the best oxygen transport could be predicted by the PEEP which caused the best static compliance.

Suter's data indicate that levels of PEEP above "best PEEP" may improve the arterial PaO_2 and may further decrease the fraction of cardiac output which is shunted. However, the increase in arterial oxygenation was not sufficient to make up for the decrease in cardiac output, and thus oxygen transport fell. These data indicate that following only the PaO_2 and the shunt fraction of patients being given increasing amounts of PEEP is not satisfactory.

Figure 6

Static Inflation Pressure-Volume Curve



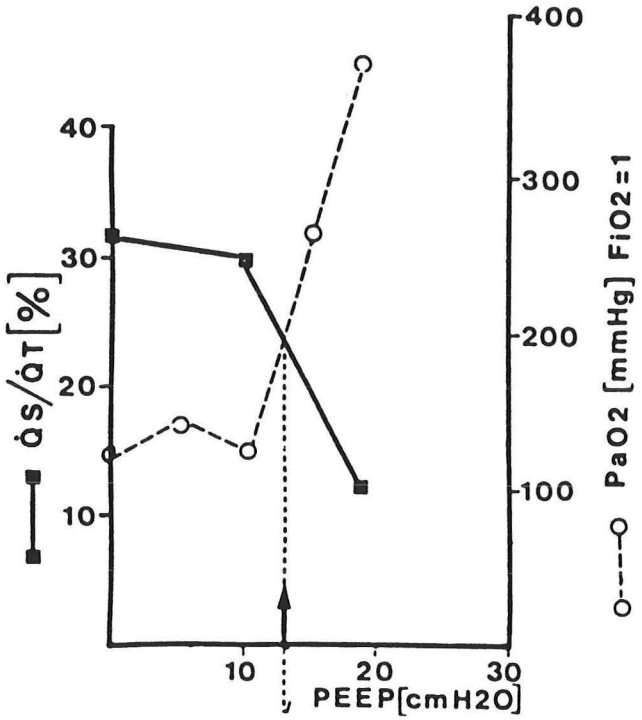
Matamis, D., et al.: Chest 86:58, 1984.

Perhaps the best method of estimating the optimal amount of PEEP plus tidal volume is to plot static compliance in the form of a pressure-volume diagram such as that in Figure 6. To construct the graph one measures static compliance at the smallest tidal volume at which the patient can be ventilated, usually 400 ml. The measurements are then repeated at 200 ml increments. Patients in the course of early ARDS have curves similar to the one indicated in the figure (120-123). The compliance measured is that of the healthy lung within the functional residual capacity (124).

The lower part of the compliance curve indicates that in the patient studied stiffer (less compliant) lung is measured from 0 end expiratory pressure to about 12 cm H_20 of PEEP due to atelectatic areas of normal lung. Above this inflexion point, from 15 to 20 cm H_20 airway pressure, the compliance curve is linear. Above 20 cm H_20 compliance begins to decrease again as the ventilated lung reaches maximal inflation. The level of PEEP should be set just above the lower "inflexion point" of the curve, in this patient at about 12.5 cm H_20. This PEEP pressure leads to the maximal recruitment of relatively normal lung into the FRC. Tidal volumes are delivered above this level as necessary to improve arterial oxygenation, but should be well below the second inflexion to prevent the normal lung from exceeding its limits of expansion.

Figure 7

Results of PEEP Pressure to the "Inflexion Point" of the Pressure-Volume Curve



Matamis, D., et al.: Chest 86:58, 1984.

Figure 7 indicates the effect of applying PEEP just above the inflexion point. The right to left shunting is markedly decreased, and the arterial PaO_2 is markedly increased. Data not shown indicate no decrease in cardiac output. Thus, the inflexion point of the pressure-volume curve is a guide to "best PEEP".

If a patient with ARDS does not improve rapidly ARDS evolves into a stage of interstitial fibrosis over two to three weeks (125). During this stage the pressure-volume curve no longer shows an inflexion point; instead compliance is linear from FRC to near total lung capacity. PEEP is no longer of benefit, and the prognosis for improvement is poor (122, 126).

Continuous Positive Airway Pressure (CPAP)

CPAP is a ventilatory technique used in spontaneously breathing patients in which a positive pressure, of the same order of magnitude as PEEP, is maintained throughout the entire respiratory cycle. CPAP may be used as the primary mode of ventilator therapy for patients with failure to oxygenate blood who are capable of maintaining spontaneous ventilation (tidal

volume above 300 ml and $PaCO_2$ below 45 mm Hg). However, it is more commonly used in recovering patients as a weaning technique (127-131). The potential beneficial effects of CPAP are indicated in Table 15.

Table 15

Potential Beneficial Effects of CPAP

Increase in FRC
Improvement in ventilation-perfusion ratios
Decreased work of breathing
Physiological PEEP for weaning

CPAP causes an increase in FRC and thereby an improvement in ventilation-perfusion ratios in much the same manner as PEEP (132, 133). CPAP is less likely to cause decreases in cardiac output than is A/CMV plus PEEP (128, 134). Since there is a positive pressure during inspiration, one would assume that CPAP should decrease the work of breathing. It does, in fact, do so in a well-designed delivery system which is functioning correctly (132, 133, 135).

Although not all studies report the same results, in my opinion the better studies find that patients weaned on low levels of CPAP (5 cm H_2O) have higher FRCs, better ventilation-perfusion ratios, and better $PaCO_2$'s than patients weaned on T bars (134-138). By 30 minutes after extubation patients weaned with either method have similar lung functions. This led to the suggestion that adults, like neonates, have an upper airway mechanism which creates a positive expiratory airway pressure unless bypassed by an endotracheal tube. In other words, some mechanism in the area of the glottis causes an upper airway obstruction following extubation leading to positive intratracheal pressure during exhalation. One group placed an intratracheal catheter confirmed positive pressures during exhalation (137). However, it is of some interest to look at the order of magnitude of difference between CPAP and T bar.

Table 16

Effects of "Physiological PEEP" during and after Intubation

Parameter	CPAP (5 cm H_2O)	T Bar (0 cm H_2O)	30 Min After Extubation
Resp rate	22 ± 2	22 ± 2	23 ± 2
V_T (ml)	456 ± 20	471 ± 20	544 ± 33*
pH (units)	7.45 ± 0.01	7.44 ± 0.01	7.45 ± 0.01
$PaCO_2$ (mm Hg)	38 ± 1	40 ± 1	38 ± 1
PaO_2 (mm Hg)	114 ± 8*	106 ± 8	117 ± 5*
FRC (ml)	1864 ± 230*	1600 ± 186	1794 ± 159

* = Significant difference from T bar

Quan, Falltrick, and Schlobohm: Anesthesiology 55:53, 1981.

The data of Quan and his colleagues are representative (138). The significant differences between CPAP and T bar are the PaO_2 and the FRC. The changes, although statistically significant, are not biologically impressive. Moreover, patients weaned with either mechanism are the same 30 minutes after extubation. I interpret these data to suggest that either mechanism is satisfactory in most patients.

Table 17

Potential Detrimental Effects of CPAP

Decreased cardiac output
Prolong weaning
Increased work of breathing

Like other forms of PEEP, CPAP may cause a decreased cardiac output. This is not, however, a frequent problem. It is also possible that CPAP prolongs weaning by adding an additional measure between AMV and extubation; I have no data to support this concern.

Although a well designed and well functioning ventilator system will decrease the work of breathing while on CPAP, until recently there have been no commercial ventilators which are satisfactory in this regard (15-18, 20, 23, 25-27). Of the ventilators used by Parkland only the Bennett 7200 and the Siemens Servo C are capable of satisfactory delivery of CPAP.

Synchronized Intermittent Mandatory Ventilation (SIMV)

Intermittent mandatory ventilation is a mode of mechanically assisted ventilation in which the patient may breathe

spontaneously and additionally receive preset tidal volumes at a preset frequency. The ventilator circuitry is capable of ensuring that each machine delivered breath is synchronized to the onset of an inspiratory effort by the patient.

The technique was originally introduced as a new approach to weaning patients from ventilatory support (139), but soon became a mode of continuous ventilation (140-142). Although it was found that synchronization with the patient's respiratory effort was not necessary, virtually all ventilators remain synchronized IMV (143, 144).

Table 18

Potential Beneficial Effects of SIMV

Prevent respiratory alkalosis (relative to A/CMV)
Maintain adequate cardiac output
Improve ventilation-perfusion ratios
Minimize the work of breathing
Rapid weaning from mechanical ventilation

Downs, J.B.: Respir. Care 28:586, 1983.

Downs, the originator of SIMV, has listed the potential beneficial effects of this mode of ventilation (145). His list is indicated in Table 18. It was thought that SIMV would allow the patient to control his or her alveolar ventilation to a greater degree than AMV and hence prevent the respiratory alkalosis that is almost universal with AMV. However, data by two groups which have addressed this issue do not support a major difference (146, 147).

Table 19

Comparison of AMV and SIMV in Causing Respiratory Alkalosis

Ventilator Mode	pH	$PaCO_2$ (mm Hg)	Vco_2 (ml/min)	VA (L/min)
AMV	7.51 ± 0.04	29 ± 5	301 ± 110	6.7 ± 3.2
SIMV	7.48 ± 0.05*	30 ± 6	323 ± 124*	7.4 ± 6.2
AMV	7.51 ± 0.05*	28 ± 5*	285 ± 97*	6.4 ± 2.2

* = $P < 0.05$

Hudson, L.D., et al.: Am. Rev. Respir. Dis. 132:1071, 1985.

Table 19 indicates the findings of Hudson and his colleagues (146). In this study each patient was changed from AMV to SIMV and then back to AMV. The differences between SIMV and AMV were significant for pH, $PaCO_2$, and CO_2 production. However, it

should be noted that statistical significance may not indicate biological difference, since the values are very similar. Further, it is interesting that alveolar ventilation is not different between SIMV and AMV and that the CO_2 production is higher in patients on SIMV. Thus, differences in pH and PaCO2 are probably not due to decreased ventilation but to higher carbon dioxide production while on SIMV. The most likely interpretation is that patients on SIMV have an increased work of breathing.

Downs also suggested that SIMV would better maintain an adequate cardiac output than other forms of mechanical ventilation. In a study which addressed this issue, no significant differences in cardiac output were found between AMV with PEEP and IMV with CPAP (148). I am unable to find any satisfactory study comparing ventilation-perfusion ratios in patients ventilated with A/CMV versus SIMV.

In studies dealing with the work of breathing on SIMV it has been found that chronic, stable patients may change breathing patterns to permit the ventilator to perform a large percentage of the respiratory work of the mandated breath (149). However, force generated by acutely ill patients differed little for spontaneous or machine-aided breaths, and there was little adaptation to machine assistance (150). Further, estimates of muscle reserve in acutely ill patients suggest that the muscles of respiration continue under stress at all levels of machine assistance. Other investigators have found evidence of respiratory muscle fatigue in many patients during IMV despite acceptable blood gases (151).

Four studies of varying sophistication have compared weaning times for patients treated with SIMV or T-bar (152-155).

Table 20

Total Ventilation and Weaning Times for Patients Treated with SIMV or T-Bar

	Protocol for Weaning 2 h	7 h or 3 d	Total Patients
SIMV (n)	83	15	98
Prewean vent time (h)	29 ± 3	436 ± 284	116 ± 48
Weaning time (h)	2.8 ± 0.2	15.9 ± 5.9	5.3 ± 1.2
T-Bar (n)	85	17	102
Prewean vent time (h)	34 ± 6	205 ± 32	67 ± 10
Weaning time (h)	2.8 ± 0.2	18.3 ± 6.3	5.9 ± 1.4

Tomlinson, J.R., et al.: Chest 96:348, 1989.

The results of the best study are presented in Table 20 (155). This was a prospective investigation with very stringent criteria concerning weaning parameters and weaning protocols. Among the 98 patients treated with SIMV on the 2 hour protocol, 83 (85%) had been ventilated an average of 29 hours and were weaned in 2.8 hours. For the 102 similar patients treated with T-bar 85 (83%) had been ventilated an average of 34 hours and were weaned in 2.8 hours. Patients in either the SIMV or T-bar groups who were ventilated for longer intervals and were on 7 hour or 3 day protocols were weaned in similar intervals. There are no statistically different figures in the table. Thus, there is no apparent advantage in this or other studies for SIMV weaning. It should also be noted that with either mode the vast majority of patients could be weaned from ventilatory support in less than one day.

Results in Ventilated Patients

Table 21

Mortality Rate of Conventionally Ventilated Patients

Series	Date	No. Pts.	Deaths No.	Deaths Pts.	Deaths %	Resp. Failure No.	Resp. Failure Pts.	Resp. Failure %
COPD								
Bone, et al.	1978	29		9	31	0		0
ARDS								
Bell, et al.	1983	141		104	74	2		2
Montgomery, et al.	1985	47		32	68	5		16
Total ARDS		188		136	72	7		5

Bone, Pierce, Johnson: Am. J. Med. 65:896, 1978.
Bell, et al.: Ann. Intern. Med. 99:293, 1983.
Montgomery, et al.: Am. Rev. Respir. Dis. 132:485, 1985.

Mortality rates of conventionally ventilated patients are indicated in Table 21. There are no data for patients who have failure of ventilation, since these patients virtually never die due to respiratory failure, and the mortality rate would indicate that of the underlying disease processes. The study by Bone and colleagues in COPD patients with failure to eliminate carbon dioxide was comprised of 123 patients of whom 29 (24%) required conventional ventilation. Of these 9 or 31% died. However, failure to ventilate was not the cause in any patient (156). The studies by Bell and Montgomery and their colleagues report the results in 188 conventionally ventilated patients with ARDS (157, 158). One hundred and thirty-six of these patients died yielding a mortality rate of 72%. However, in only 7 (5%) patients was an inability to oxygenate arterial blood or serious barotrauma thought to contribute to mortality. Deaths in the first three

days of therapy were thought to be due to the underlying illness or injury, while most late deaths were due to the sepsis syndrome and multiorgan failure.

These data suggest that the very high death rate in patients with ARDS, which has not changed significantly since the initial report using this diagnostic terminology (159), is not directly due to our modes of ventilation. Such may, of course, not be correct, and there may be unrecognized associations between methods of ventilation and detrimental effects to other tissues through mediators not yet appreciated. At the present, however, the information at hand suggests that the underlying disease process and the occurrence of multiorgan failure are the limits to survival.

One of the newer techniques of ventilation to be reviewed shortly has been called a salvage technique. That is, that technique is utilized when conventional ventilation is unable to prevent potentially lethal hypoxemia. If the data from Bell and Montgomery and their colleagues are correct, there should be few cases in which "salvage" is necessary.

Work of Breathing

Table 22

How Much Work of Breathing is Enough?

Patients with severe lung disease or decreased cardiac output may develop inspiratory muscle fatigue.

Too much exercise of a fatigued muscle may cause muscle injury.

Too much rest of a muscle may lead to atrophy.

Respiratory muscles may be trained to increase strength and/or endurance. The principle is to alternate brief periods of fatiguing exercise and rest.

The application of these principles to weaning has not been systematically proven.

As I have reported, the work of breathing imposed on patients by each type of conventional ventilation has been studied, and work is usually discussed in pejorative terms. That is, the work of breathing while on a ventilator is typically considered detrimental. This may not be the case.

It has generally been thought that patients with severe lung disease or decreased cardiac output may develop inspiratory muscle fatigue (14, 160-163), although it has recently been

suggested that this concept needs re-examination (164). Further, too much exercise of a fatigued muscle may cause muscle injury. Thus, resting the muscles of inspiration has frequently been a goal of therapy (165). However, too much rest of a muscle may cause atrophy, leading some investigators to question the goal of rest (145).

It has also been demonstrated that respiratory muscles in chronically ill patients may be trained to increase strength and/or endurance (166, 167). Indeed, it has been demonstrated that endurance training with flow resistors may be of benefit in weaning patients from prolonged mechanical ventilation when standard methods are not successful (168). The principle is to alternate brief periods of fatiguing exercise with rest.

Unfortunately, the study of the muscles of respiration is complex, and the application of these principles to weaning has not been systematically proven. Thus, weaning a patient from a ventilator remains a subject of controversy. Perhaps, however, more has been made of this controversy than is justified. By referring again to Table 20 it may be noted that almost all patients may be weaned by T-bar in less than one day. Thus, one must be cautious in accepting explanations regarding decreased work of breathing as evidence for the superiority of one mode of therapy over another.

RECENTLY INTRODUCED MECHANICAL VENTILATOR TECHNIQUES

Table 23

Recently Introduced Mechanical Ventilator Techniques

Discussed
Pressure support/pressure control ventilation (PSV/PCV)
Inverse ratio ventilation (IRV)
Airway pressure release ventilation (APRV)
Not Discussed
High-frequency ventilation (HFV)
Constant flow ventilation (CFV)
Mandatory minute ventilation (MMV)
Proportional assist ventilation (PAV)

In the 1980's several new ventilator techniques were introduced; these are indicated in Table 23. Pressure support ventilation is a form of pressure limited ventilation in which the operator sets the pressure to be delivered by the machine while the patient determines his or her own inspiratory time and frequency. Pressure controlled ventilation is the same principle, but the operator also sets the frequency with which the ventilator delivers a breath, i.e. the respiratory rate. Inverse ratio ventilation is delivered with either pressure or

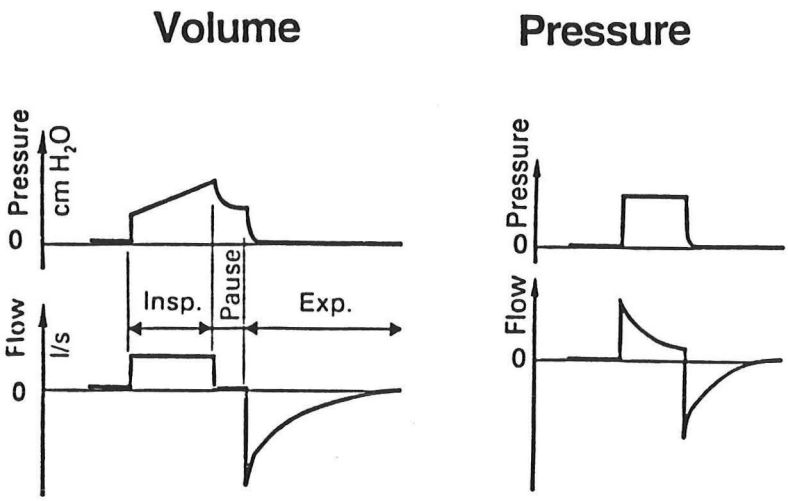
volume controlled machines and indicates that the inspiratory to expiratory time ratio is greater than 1:1; that is, inspiration is prolonged relative to expiration. Airway pressure release ventilation is a form of CPAP in which the positive airway pressure is periodically transiently decreased (released) allowing the patient to exhale to atmosphere or to a lower positive pressure than the CPAP. Each of these newer ventilatory techniques will be discussed.

High-frequency ventilation is a generic term for any type of assisted ventilation at a frequency at least four times the natural breathing frequency of the patient being ventilated. For adults rates may vary between 60 to 3,000 breaths per minute. In addition, high-frequency ventilation usually indicates a tidal volume that is less than the anatomic dead space. High-frequency ventilation has been studied extensively for over 10 years (169-173), but most data suggest that it does not offer any advantage over conventional mechanical ventilation, and it will not be considered further.

Constant flow ventilation uses very high oxygen enriched gas flow through catheters into the main stem bronchi. There is no rhythmic movement of the chest by the patient or by the apparatus (174). There are no clinical data available for this technique. Mandatory minute ventilation is predominantly a weaning technique. The operator sets the expected respiratory rate and size of tidal volumes which produce a normal minute ventilation. The ventilator senses the gas breathed spontaneously by the patient and delivers by a positive pressure breath the added gas necessary to ensure the ventilation goals that have been set (175-177). Proportional assist ventilation is delivered by a sophisticated ventilator which changes pressure at the airway in proportion to inspired volume and flow rather than delivering a target pressure or volume. Thus, the ventilator reduces the total respiratory load by amplifying the ventilator consequences of respiratory muscle activity, while leaving the patient in control of all aspects of the breathing pattern (178, 179). None of the latter three forms of ventilation have substantial data concerning their characteristics or efficacy, and they will not be considered further.

Figure 8

Controlled Ventilation



Each of the new forms of ventilation, pressure support, pressure control, inverse ratio, and airway pressure release have as the main control the pressure which is to be applied to the airway (180). Conventional volume controlled ventilation is compared to pressure controlled ventilation in Figure 8. Volume ventilators generate a constant flow during all of inspiration causing the pressure in the airways to rise linearly until the preset tidal volume has been delivered. At that instant inspiratory flow stops. The exhalation valve may be held shut momentarily, termed a pause, to hold the lungs inflated and better equalize the distribution of ventilation, or the exhalation valve may be opened allowing the patient to expire to either atmospheric or PEEP pressure.

Pressure controlled ventilators have an initial high flow which causes airway pressure to rise rapidly, and the pressure is then held constant during all of inspiration by means of a servo controlled decreasing inspiratory flow. When the flow has fallen to some set limit, usually 25% of peak flow or an absolute flow of 5 L/min, flow ceases and the exhalation valve opens to allow the patient to breathe to atmospheric pressure. During pressure control or inverse ratio ventilation the operator determines the respiratory rate, while with pressure support and airway pressure release ventilation each breath may be patient triggered. The tidal volume that is achieved is dependent on the impedance characteristics (resistance, compliance) of the chest. Thus, the operator cannot be assured of achieving a specific tidal volume or a satisfactory level of ventilation.

Although termed a new modality, it is interesting to note that the same flow and pressure profiles were caused by the IPPB machines incorporating a Bennett valve which were introduced in

the 1950's. These types of ventilators gave way to volume ventilators because of the variability of ventilation at any given pressure. The newer ventilators which have pressure support capability are much more sophisticated with microprocessor controls, various monitoring and alarm capabilities, and perhaps a back up ventilation mode. However, despite the sophistication, some of the problems encountered with the old IPPB machines may exist. For example, if there is a serious airway leak, as around an endotracheal tube cuff, the cut-off flow of the ventilator may not be reached, and the machine fails to cycle out of inspiration (181). Additionally, continuous flow nebulizers between the patient and the sensor in the ventilator may prevent the patient from initiating a pressure support breath (182). As with any mode of ventilation, the operator must be familiar with the equipment which he or she chooses to use.

Pressure Support/Pressure Control Ventilation

Table 24

Current Status of Pressure Support Ventilation

Not considered a primary mode of ventilation
Comparison to SIMV, CPAP Hemodynamics similar Decreased work of breathing
Clinical response
Role in weaning

Interest in the status of pressure support ventilation is indicated by the fact that there are almost as many theoretical and review articles (28, 80, 183-200) as there are articles with experimental data. Although one study has reported PSV to be a satisfactory means of primary ventilation (201), others have reported that patients with severe pulmonary edema are not adequately ventilated by pressure support due to apneas, incorrectable acidosis, and failure to maintain adequate tidal volumes (202, 203). Thus, pressure support ventilation is generally considered to be most useful in carefully monitored patients with failure to excrete carbon dioxide due to COPD (204) and patients with ARDS who have been stabilized with conventional modes of ventilation.

Since pressure support is regarded as a modality used in stable patients, it is most commonly compared to SIMV or CPAP. In these comparisons and in comparisons with CMV, it has been found that PSV to a level of 30 cm H_2O causes similar hemodynamics (205-207). The only alteration in pulmonary

function is a modest increase in the amount of respiratory deadspace (205, 208). There is a consistent decrease in the work of breathing compared to SIMV, CPAP or T-bar (209-216).

The most striking feature of pressure support ventilation compared to volume ventilation is an improvement in patient comfort and acceptance while being ventilated (217-220). This apparently occurs because the patient maintains control of inspiratory and expiratory timing while the ventilator adjusts inspiratory flow to patient demand to maintain a constant airway pressure. It is thought that these features allow pressure support to better synchronize with the patient's ventilatory drive (217, 220). However, the initial flow from machine to patient is fixed by the ventilator. MacIntyre has demonstrated that improved synchronization could be achieved if an adjustable initial flow was permitted (220).

In practical application as a weaning technique it is suggested that the patient be given tidal volumes equivalent to that supplied by conventional mechanical ventilation, e.g. 10 to 15 ml/kg, a level that should reduce the patient's work to near 0 (191). The amount of pressure is then reduced as rapidly as possible while using a slow respiratory rate as an indication of satisfactory ventilation. The best predictor of inspiratory muscle fatigue is an abnormally fast respiratory rate (221-223).

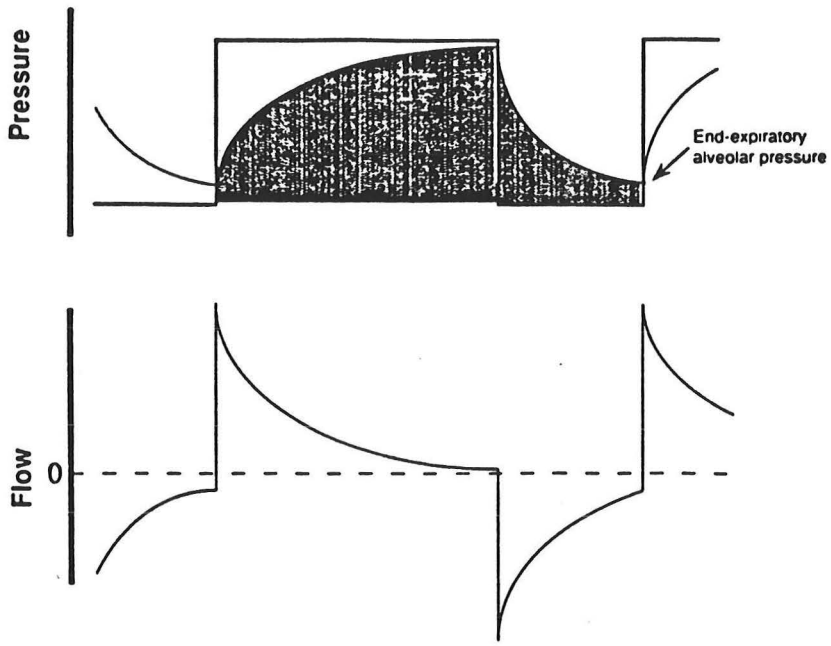
There have been no studies which have compared pressure support ventilation with other methods of weaning to determine which is the most expeditious. It is clear that many patients can be rapidly extubated from AMV. Whether difficult to wean patients can be managed better by PSV cannot be determined at this time.

Pressure control is not usually used as a primary mode of ventilation. It is most commonly combined with another of the new ventilatory techniques, inverse ratio ventilation. This mode is used in patients with failure to oxygenate blood only; the short exhalation time precludes patients with airways obstruction.

Inverse Ratio Ventilation

Figure 9

Pressure Control Inverse Ratio Ventilation (PC-IRV)



Marcy, T.W., and J.J. Marini: Chest 100:494, 1991.

Although inverse ratio ventilation may be administered by volume control, pressure control is more frequently used. Pressure and flow during PC-IRV are indicated in Figure 9 from Marcy and Marini (224). During PC-IRV the ventilator delivers a square wave of pressure to the airway which causes alveolar pressure to gradually come into equilibrium during a prolonged inspiration, as indicated by the black area of the figure. The time-cycle is set to deliver an I:E ratio of 2:1, 3:1, or 4:1. This pressure wave form is caused by an initially rapid and then decelerating flow. At the end of the designated inspiration, the machine cycles off and the patient exhales to ambient or to PEEP pressure.

Since the exhalation time is so short relative to the inspiratory time, it may be impossible to exhale the tidal volume completely; that is, it is common for the patient to develop auto-PEEP. For example, if the PC-IRV is set at a respiratory rate of 15, each respiratory cycle will occupy four seconds. At an I:E ratio of 4:1, exhalation will occupy 0.8 seconds. In this example the patient is likely to develop auto-PEEP, and the recognition of this phenomenon cannot be performed by obstructing the exhalation valve at end expiration. Any level of auto-PEEP will decrease the inspiratory tidal volumes, and careful monitoring of exhaled tidal volume and minute ventilation is

mandatory. It should also be indicated that alert patients usually do not tolerate this prolonged inspiration relative to expiration, and it is necessary to sedate and paralyze most patients before beginning IRV.

Table 25

Potential Effects of Pressure Control Inverse Ratio Ventilation

Decrease peak inflation pressure
Increase PaO_2/F_IO_2
Variable effect on cardiac output, O_2 transport
Increase mean airway pressure ($\overline{Paw}$)
Results due to increased $\overline{Paw}$ or inverted ramp flow?

IRV was introduced to adult medicine by Lachmann in 1980 (225). In that initial as well as in subsequent studies it was found that IRV usually decreases the peak inflation pressure and increases the PaO_2/F_IO_2 (226-230). The effect on cardiac output, and therefore oxygen transport to tissues, has been more variable (228, 230, 231). From the data at hand it is not possible to assess this critical feature; one can only suspect that decreases in cardiac output may relate to the presence of unrecognized auto-PEEP. In one careful study, Cole and his colleagues noted that decrease in right to left shunting, cardiac output, and systemic oxygen transport is the same with CMV with PEEP or PC-IRV 4:1 when each causes the same increase in the functional residual capacity (232).

A controversy exists as to whether the results of PC-IRV are due to the increased mean airway pressure or to the inverted ramp flow caused by pressure support (228, 230, 233-236).

Table 26

Comparison of PC-IRV 3:1 to CMV 1:2 Each With Mean Airway Pressure 21 ± 6.2 cm H_2O

Parameters the Same	Parameters Different
F_IO_2, PaO_2, PvO_2, PaCO2, ph	PEEP 6.5 ± 3.7 vs 12.6 ± 4.3
QS/QT, V_D/V_T, VE,	PIP 32.4 ± 9.2 vs 39.8 ± 10.2
CI, $\overline{P}_{PA}$, $\overline{BP}$, P_{PW}, P_{CV}	

In my opinion, the best data in this regard has been generated by Gattinoni and his colleagues which are presented in Table 26 (237). In this study patients were ventilated with PC-IRV 3:1 at a respiratory rate of 20 and tidal volumes adjusted to maintain the $PaCO_2$ normal. The PEEP level was set so that it

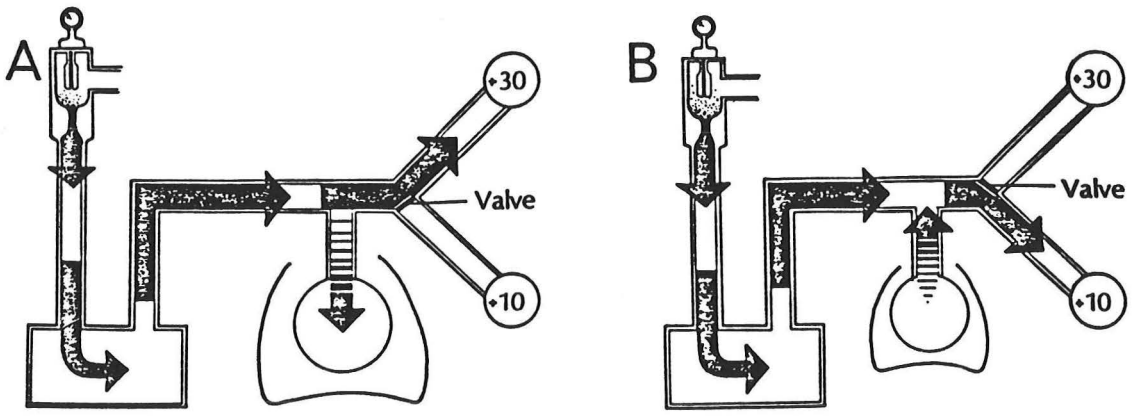
was 2 cm H_2O above the inflexion point identified on a pressure-volume compliance curve. After 30 minutes all parameters were measured, and the patient changed to CMV 1:2 at a respiratory rate of 20 to maintain the $PaCO_2$ normal. The PEEP was raised to a level that caused the same mean airway pressure that had existed on IRV. As indicated in the table all ventilatory and cardiovascular parameters were the same excepting that the peak inflation pressure on IRV was 32 and on CMV was 40. These data strongly support the concept that it is the mean airway pressure that determines the results of either form of ventilation. Additionally, these data indicate that CMV and PC-IRV yield the same results when adjusted to the same mean airway pressure. If the peak inflation pressure on CMV is considered dangerously high, it can be reduced by decreasing the size of tidal volumes and increasing the PEEP (238).

The role of PC-IRV is not yet established, since there have been no controlled trials utilizing this mode of ventilation compared to conventional modes of ventilation. The work of Cole and of Gattinoni suggest that carefully regulated CMV is likely to have the same effects as the newer form of ventilation. However, should one choose to use PC-IRV, cardiac output and oxygen transport should be measured in addition to the measurements of ventilation already suggested.

Airway Pressure Release Ventilation (APRV)

Figure 10

Airway Pressure Release Ventilation



Cane, et al.: Chest 100:460, 1991.

Airway pressure release ventilation has recently been described by Downs, and indeed all of the articles concerning APRV in adults save two case reports and one clinical trial,

include Downs as one of the authors (239-244). APRV is a form of CPAP in which spontaneous ventilation can occur at any time during the respiratory cycle, but it also ensures ventilation by transiently releasing CPAP to a lower preset pressure which leads to exhalation. When the release value closes, the higher preset CPAP inflates the lungs and thereby achieves inspiration. The APRV mechanism is illustrated in Figure 10. Oxygen from a high pressure source passes through a Venturi jet resulting in a flow of 90-100 L/min. The gas passes through a humidifier to the patient and then through a threshold-resistor expiratory valve, set in this example at 30 cm H_2O. The CPAP system allows the patient to breathe spontaneously, and like all well constructed CPAP systems assists inspiration. At preset intervals determined by the operator a valve switches flow from the high pressure threshold-resistor to a separate expiratory channel which may be open to the atmosphere or may provide a positive end expiratory pressure, illustrated here as 10 cm H_2O. The sudden change in pressure at the airway causes the patient to exhale. The exhalation phase usually occupies 1.5 seconds.

The unique feature of this system is that the peak airway pressure never exceeds the CPAP pressure, while in systems like IMV or pressure support with CPAP airway pressure rises above CPAP pressure by the amount necessary to deliver a tidal volume. With APRV the CPAP causes a large FRC, and the expiratory release merely briefly shifts the FRC to a lower volume. The system is somewhat analogous to inverse ratio ventilation; for example, if the respiratory rate is set at ten, the inspiratory phase is three times longer than the expiratory phase. Like PC-IRV, the technique is used only in patients with no airways obstruction.

Cane and his colleagues, who are not members of the Downs group, have reported the only clinical trial in patients with ARDS (245). All ventilatory and cardiac parameters were the same when CMV was compared to APRV except for the peak inflation pressure which was higher with CMV. Further, 13 of 18 (72%) of the patients treated with APRV died. Thus, the role of airway pressure release ventilation is not yet clear.

CONCLUSIONS

Several forms of mechanical ventilation have been reviewed including the conventional modes which have been used for 20 years and three newer modes for which there are fewer data. Although several elegant investigations, and many more which are not so elegant, have been performed in this arena, there are far more physiological and mechanistic studies than outcome studies. For example, we have adequate reassurance that pressure support ventilation is likely to reduce the work of breathing, but we have no knowledge concerning whether this mode of ventilation will shorten or lengthen the patient's time on a ventilator. Thus, one must conclude that there are appropriate and inappropriate ways to use each form of mechanical ventilation,

but whether using one mode appropriately is as good or better as using a different mode appropriately is not clear. Perhaps the observation by George Bernard Shaw is appropriate: "We learn from experience that men never learn anything from experience".

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