Mechanical Ventilation [MV] is a mainstay of life support in Intensive Care Units. [ICUs] Currently, an estimated 1,00,000 positive pressure ventilators are in use worldwide, approximately half of them in North America. Each year, it is estimated that approximately 1.5 million patients receive MV outside operating rooms in the US.

Although the outcome of patients depends to a large extent on the underlying disease states for which MV is used, a number of complications can occur during MV and can thus make a major impact on the outcome. Besides the complications, MV can contribute significantly due to its physiological effects on major organ systems. The correct, skillful and judicious use of MV is thus a very important factor in the outcome of critically ill patients.

**Indications**

The traditional criteria for MV are shown in Table no. 1

Mechanical ventilation is indicated when there is a need to improve or control the function of the respiratory system thus controlling \( \text{PaO}_2 \) and / or \( \text{PaCO}_2 \). Obviously, good clinical judgment is necessary when deciding about intubation and starting MV, especially when the \( \text{PaCO}_2 \) or the \( \text{PaO}_2 \) are in the normal range.

<table>
<thead>
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<th>Table 1: Criteria for Mechanical Ventilation</th>
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<td>1. Respiratory rate &gt; 35 / min or &lt; 10 / min.</td>
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<td>2. Laboured or irregular pattern of breathing</td>
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<td>3. ( \text{pO}_2 &lt; 60 \text{ mmHg on FiO}_2 0.6 )</td>
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<td>4. ( \text{pCO}_2 &gt; 40 \text{ mm Hg , acutely} )</td>
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<td>6. Severely deranged pH</td>
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<td>7. Tidal Volume &lt; 3 to 5 ml / kg, Vital capacity &lt; 15 ml / kg.</td>
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<td>8. Maximum inspiratory pressure ( \leq -20 \text{ cm H}_2\text{O} )</td>
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Choosing the Settings
The following settings are necessary to initiate the MV.

A. Mode of ventilation: There are various modes of MV, the detailed description is beyond the scope of this article. One needs to be conversant with the modes available on one’s machine before using them.

B. Respiratory Rate:[RR] It varies widely depending on the clinical needs, usually 10-14 per minute is set to start with.

C. Tidal Volume: \[V_t\] In the past, high \[V_t\] were selected to improve the abnormal gases quickly. Current understanding of the pathophysiology of the disease processes and also of Ventilator Induced Lung Injury [VILI], has raised concerns about using higher tidal volumes. Current evidence seems to indicate that smaller \[V_t\] [about 6-7-cc / kg lean body weight] are safe and preferable, in patients with ARDS and in homogeneous pulmonary parenchymal pathologies. Minute ventilation is defined as \[V_t \times \text{RR}\] and some machines require a clinician to set the required minute ventilation. The peak pressures achieved during the delivery of this tidal volume will vary as per the resistance of the airways and the compliance of the lungs.

D. In pressure controlled / limited modes, one needs to set the pressure levels, and as stated above, the volumes delivered at these set pressures will vary as per the resistance of the airways and the compliance of the lungs. The peak inspiratory pressures should be limited to the safe maximum limit of 35-40 cm H\(_2\)O.

E. Fraction of inspired oxygen [FiO\(_2\)]: Once the decision is made to institute mechanical ventilation, the choosing an FiO\(_2\) is no more difficult than picking a number, albeit one based on the patient’s clinical problem and the reason for starting MV. For example, a patient who is ventilated mainly for hypercapnia will usually be adequately oxygenated with an FiO\(_2\) under 0.40. A patient ventilated because of severe hypoxemia or during cardiopulmonary resuscitation may need an initial FiO\(_2\) of 1.00. Blood gas measurements should be obtained in the first half hour after treatment, and adjustments made to keep the PaO\(_2\) between 60 and 90 mm Hg at the lowest FiO\(_2\) possible. Although oxygen toxicity is a concern for patients who are on high FiO\(_2\) [> 0.8] for a prolonged period of time, the correction of hypoxia must take priority. Strategies to keep FiO\(_2\) to minimum, without allowing significant hypoxia to occur are required.

F. Inspiratory flow rates: These are generally set between 60 and 120 l/min. This ow rate determines the inspiratory: expiratory time or I:E ratio. The pattern of gaseous ows [decelerating, sinusoidal, rectangular, exponential] are also set during the volume preset breaths. It is obvious that faster the ow rate, the quicker will be the inspiration and the longer time the patient has to exhale.

G. PEEP: Addition of PEEP is often used to improve the patient’s oxygenation status. It is not a stand alone “mode”, and is rather applied as a strategy in conjunction with the given mode. PEEP rein ates collapsed alveoli and maintains alveolar ation during exhalation. Once recruitment of these alveoli has occurred, PEEP facilitates gas diffusion and oxygenation. PEEP therefore is indicated in refractory hypoxemia especially with intrapulmonary shunting and decreased FRC and lung compliance. Complications and hazards associated with PEEP include barotrauma [due to increased alveolar distending pressure], decreased venous return resulting in decreased cardiac output and hypotension, and increased intracranial pressure.

Mechanical Ventilation for ARDS
The only therapy proven to improve survival in ALI / ARDS is the application of low tidal volume ventilation, demonstrated by the ARDS Network in 2000. In this well designed trial, it was shown that there is a survival benefit for patients of ARDS treated with low TV [6-8 ml / kg of IBW] as compared to those with traditional high TVs [10-12 ml/kg of IBW]. In trying to keep the TV down below the injurious
levels, the MV is likely to be inadequate and pCO$_2$ is likely to rise. Although patients ventilated with lower tidal volumes may experience hypercapnia and respiratory acidosis, and thus require higher respiratory rates, there was no clinical significance to these findings. This rise in pCO$_2$ is accepted till pH falls below 7.2. This strategy is also termed as permissive hypercapnoea. If the compliance of the lungs is very low and pressure limited modes are being used, it is ideal to keep the plateau pressures below 32 cms and the peak pressures below 35 cms of water.

As we understand more about mechanical ventilation and the potentially injurious effects when it is applied incorrectly, it is apparent that low tidal volume ventilation may accrue even greater benefits. Injurious ventilation and ventilator-induced lung injury increase plasma cytokine concentrations in the systemic circulation and correlate with organ failure and cellular apoptosis downstream. Additional data from the low tidal volume trial confirm that cytokine elaboration was reduced with this ventilatory strategy, suggesting that failure of other organs may also be affected simply by providing a “protective” mode of ventilation.

Lower TV strategy using 6 - 8 ml / kg of ideal body weight may now be considered as standard supportive treatment for patients with ALI / ARDS until another ventilatory strategy is demonstrated to be superior. There is no question that this report has elucidated the key principles to be applied in the treatment of patients with the ARDS i.e. these patients need a gentler form of mechanical ventilation

Improving Oxygenation

Maintenance of adequate oxygenation has always been a principle aim of mechanical ventilation, no matter what the underlying disorder and the condition of the patient is. In patients of ARDS, refractory hypoxia is traditionally corrected by one of various approaches viz.

- High FiO$_2$,
- High PEEP,
- Inverse I : E ratios.

The initial O$_2$ dialed is always 100% in these hypoxic patients. Restriction of high FiO$_2$ to less than 0.6, after a period of time of 24 to 48 hours has become standard with reports of O$_2$ toxicity in humans. These include resorption atelectasis, and impaired gas exchange after breathing 100% O$_2$ at sea level for ~40 hrs. The O$_2$ toxicity may be more prominently seen in these patients especially because the diseased lung may be more susceptible to injury from moderate hyperoxia.

Utility of PEEP to improve oxygenation has been recognized by Petty et al in 1971. The mechanism of its action is to increase the FRC probably as a result of recruitment of collapsed alveoli. As a strategy to improve the oxygenation, PEEP was used very enthusiastically when it was introduced. Soon with the documentation of its adverse effects on hemodynamics and on the incidence of barotrauma, it was realized that the beneficial effects of PEEP must be weighed carefully in relation to potential adverse effects. Thus the best strategy for using PEEP and FiO$_2$ in appropriate balance has not yet been defined.

ARDS Net has set up a trial to study the efficacy of High PEEP + Low FiO$_2$ Vs. Low PEEP + High FiO$_2$. The initial results of this ALVEOLI study has not been able to specify any difference in the approaches or an optimum PEEP.

Pending evidence for a better approach, the ARDS network strategy as defined in the low TV study is recommended as standard therapy.

Recruitment maneuvers have been used recently in order to open the lungs and improve oxygenation. Reduced tidal volume ventilation or high-inspired oxygen concentrations may contribute to atelectasis, with consequent hypoxemia. Similar to prone positioning, recruitment maneuvers have been shown to improve oxygenation in many patients with ALI/ARDS, presumably by recruiting additional collapsed lung to participate in gas exchange. The predominant physiologic effect recognized from recruitment
maneuvers is the increase in functional residual capacity of the lung, representing additional alveoli being opened and available for gas exchange. The effects of these are quite dramatic and can be seen immediately either on oxygenation or structurally on the X-Ray Chest / CT scan. The advantages of recruitment are in the form of improved oxygenation, reduced oxygen toxicity, and minimizing VILI. The response to recruitment maneuvers may depend on the timing of its application and the etiology of ALI/ARDS, such that subtle physiologic differences between direct and indirect causes of lung injury may result in disparate results from recruitment maneuvers. The disadvantages of recruitment are also seen and include hemodynamic compromise, increased risk of diffuse alveolar damage and / or barotrauma and no evidence of improvement in clinical outcomes.

A lot of questions regarding these recruitment maneuvers remain unanswered. These include:

- Is recruitment beneficial?
- How do we measure recruitment at the bedside?
- How do we perform Recruitment maneuvers?
- What pressure, to use and at what time and frequency?
- Do all ARDS patients have similar potential for recruitment?
- Are recruitment maneuvers equally effective or even indicated in all patients?
- Should CT scans become necessary as a routine to document atelectasis and the recruitment?

We will need the answers to all these before recruitment maneuvers become recommended as standard therapy.

It has been shown that prone positioning improves oxygenation for 60% to 70% of ALI/ARDS patients, though the patients most likely to respond are not readily identified in advance. Furthermore, the mechanisms responsible for oxygenation improvements are similarly uncertain. There are 3 primary mechanisms likely responsible:

1. Improved ventilation-perfusion matching,
2. Changes in lung mass and shape, and
3. Alterations in chest wall compliance.

Ventilation-perfusion matching may be severely impaired in patients with ALI/ARDS, partially related to their inability to normally produce hypoxic pulmonary vasoconstriction. In turning a patient from supine to prone, more homogeneous gas distribution is achieved, thus contributing to improved ventilation-perfusion matching. Also, in the process of turning from supine to prone, the heart is no longer compressing the posterior aspects of the left lung, allowing for better aeration. Furthermore, the majority of lung tissue is posterior, and prone positioning allows this large amount of lung tissue to function as anterior regions with better aeration (though perfusion may not improve or worsen). Finally, the anterior chest wall is expanded during respiration, but cannot be to the same degree in the prone position. As such, the anterior chest wall (much like the posterior chest wall with the spine) becomes stiffer. These changes force the diaphragms to contribute a greater percentage to the overall change in thoracic cavity shape, and thus may contribute to less atelectasis and better aeration in dependent lung regions.

Concerns regarding prone positioning remain, primarily related to the safety of performing the prone maneuvers and providing patient care for patients in this position. Knowing that oxygenation is rarely a cause of death in patients with ALI/ARDS (rather, they often succumb to multiple organ failure),Gattinoni and colleagues conducted a large, randomized trial to evaluate whether outcomes may be improved. In this trial, ALI/ARDS patients were randomized to undergo prone positioning for 6+ hours each day for 10 days. There were 152 patients enrolled into each group. Oxygenation improved in approximately 70% of prone positioning patients, and no significant difference was noted in adverse events related to the prone positioning. Relative risk for mortality in the prone group at the end of the study period (0.84), at discharge from the intensive care unit (1.05), and at 6 months (1.06) did not
differ among groups. A post-hoc analysis suggested that prone positioning may be beneficial in the most severely ill patients, as characterized by severity of illness scores and oxygenation, though reductions in mortality at the end of the study period did not persist to the point of intensive care discharge.

Mechanical Ventilation for Severe Asthma

In the past, use of mechanical ventilation for acute respiratory failure was associated with significantly high mortality. This has now changed and the mortality has reduced to 6-10%. However, the figures of mortality still continue to vary.

Respiratory failure in asthmatic patients is a direct consequence of critical increase in airway resistance. Airway narrowing and increased resistance lead to two important mechanical changes. First the increased pressures required for airflow may overload the respiratory muscles, producing a ventilatory pump failure and respiratory muscle fatigue. This will result in spontaneous minute ventilation being inadequate for gas exchange and resulting in increasing pCO$_2$. The narrowed airways create regions of lung that cannot properly empty and return to their normal resting volumes. This is called air trapping and produces elevated end expiratory pressures [Intrinsic or auto PEEP]. Airway obstruction severe enough to require mechanical ventilation is invariably associated with some degree of dynamic hyperinflation.

The general indications for mechanical ventilation are similar to any other acute respiratory failure, with clinical evidence of respiratory muscle fatigue, rising trends of pCO$_2$, and reducing pO$_2$ being of paramount importance. It is obvious that in the face of marked hypopnoea or apnoea the patient will be immediately intubated and ventilated. Rapidly increasing tachypnoea despite intensive pharmacologic treatment even in the absence of blood gas abnormality will perhaps form the major indication in patients of acute severe asthma. No single criterion can dictate the timing of intubation and ventilation, it will be based on careful observation by an experienced intelligent person.

The overall goals of mechanical ventilation are mostly similar to those in other respiratory failure, but differ in certain aspects. In view of the overloaded and fatigued muscles, selecting modes that initially provide substantial muscle unloading is particularly important. The presence of very narrowed airways can result in very high peak airway pressures. The development of intrinsic PEEP can further increase the intra-atomic pressures.

Institution of mechanical ventilation causes pleural pressure to become positive throughout the respiratory cycle. This impedes venous return and a fall in cardiac output, and hypotension should be anticipated as in any initiation of mechanical ventilation. Hemodynamic instability can be further exacerbated by additional lung hyperinflation due to incomplete expiration of machine-delivered tidal volumes.

Ventilator management strategies during positive pressure ventilation in acute severe asthma include

- Selecting modes that initially provide substantial muscle unloading
- Attempts to minimize dynamic hyperinflation
- Attempts to keep peak airway pressures down to minimum.

During mechanical ventilation, critical factors in determining the degree of dynamic hyperinflation are the inspired tidal volume, expiratory time, and severity of airway obstruction. Ventilatory strategies to minimize dynamic hyperinflation utilize a low tidal volume and maximal inspiratory time by increasing inspiratory and decreasing expiratory time.

Thus typical settings for mechanical ventilation will include

- Use of controlled / assist controlled mode: both pressure and volume targeted modes are effective
- Relatively low respiratory rate [10-14/min.]
• Relatively low tidal volumes. : [6-8 ml/kg] In either of the targeted modes, if the peak pressures are kept below 35 cm H$_2$O, the risk of barotrauma is considerably less. Along with low respiratory rates, this will mean low minute ventilation and thus decreasing pH and increasing pCO$_2$ is usually an acceptable trade off.

• Adjustments in I:E ratios and inspiratory air ow rates and patterns so as to maximize the duration of expiration (specifically, high inspiratory air rates using a square wave form);

• Avoidance of ventilator-applied positive end-expiratory pressure. These ventilator settings [low tidal volumes, low respiratory rates, long expiratory time] will result in relative hypoventilation with permissive hypercapnia (pH as low as 7.2). By minimizing the risk of dynamic hyperinflation, these settings help limit barotrauma, especially pneumothorax, which is catastrophic in this setting. Barotrauma was found to complicate status asthmaticus in 14-27% of patients. The monitoring of these settings and the resultant respiratory mechanics can be done by respiratory graphics although measurements of peak airway pressures and auto PEEP have not been found to correlate with complications. The most direct indicators of dynamic hyperinflation are circulatory responses and end inspiratory lung volumes but these are cumbersome to measure. Plateau pressures and level of auto PEEP best reflect the dynamic hyperinflation.

• Adjustments in I:E ratios and inspiratory airflow rates and patterns so as to maximize the duration of expiration (specifically, high inspiratory airflow rates using a square wave form);

These ventilator settings require the patient to be sedated with narcotics, benzodiazepines, or propofol. An interesting choice is ketamine, a general anesthetic with bronchodilating properties. By itself ketamine has potential problems of tachycardia, hypertension, delirium, etc. and hence a clinician will have to weigh the balance before using it. Muscle relaxants are also required at times but should be avoided where possible. Preferred agents are non depolarizing agents like vecuronium and atracurium which have minimal cardiac toxicity. A potential disadvantage of atracurium is its ability to release histamine and worsen bronchospasm. In an interesting study, Leatherman and coworkers found that in intubated asthmatics, the use of corticosteroids and neuromuscular blocking agents was associated with a much higher incidence of muscle weakness as compared with the use of corticosteroids alone. This additional myopathy can contribute significantly to difficulty in weaning and to the prolonged stay in ICU, and hospital. Thus, minimum effective dose of muscle relaxant should be used - if at all, the drug should be withdrawn at the earliest, and myopathic effects should be monitored with laboratory parameters.

Although V/Q mismatching does occur in acute airway obstruction, shunts are less of a problem and thus oxygenation can usually be maintained reasonably well without using very high inspired oxygen concentration [FiO$_2$]. Role of Positive end expiratory pressures (PEEP) is thus limited. In fact, PEEP in addition to the over distended auto PEEP only further over distends them. The only role seems to be during patient triggered breaths in situations when intrinsic PEEP produces an imposed inspiratory triggering threshold.

Other considerations in management include the use of anaesthetic gases to reduce airway muscle tone in refractory bronchospasm, use of mixtures of low density gases (Helium:O$_2$ in proportions of 80-20, 70-30, 60-40) to facilitate lung emptying.

Techniques to deliver bronchodilator aerosols through the ventilator circuits must also be employed. This usually means in-line-circuit nebulizers, although metered dose inhalers with inspiratory circuit holding chambers are also effective. Because endotracheal tubes significantly reduce aerosol delivery, doses are usually increased 3 to 4 times. The various patterns and graphs can be used to monitor bronchodilator efficacy.

The median duration of mechanical ventilation is 3 days. Sepsis, GI bleeding, venous thromboembolism remain the potential complications if patients’ stay in ICU gets prolonged.

Non Invasive Mechanical Ventilation:
Invasive mechanical ventilation is associated with substantial morbidity and mortality. Partial ventilatory support can be applied successfully to these patients by using NIPPV. Several studies suggest that
NIPPV may be useful in these patients by improving alveolar ventilation and ameliorating muscle fatigue. Generally these systems use pressure targeted breaths and they can be used both to prevent intubation or to facilitate post extubation management. Indeed some of the strongest data supporting the use of NIPPV has come from studies on patients with asthma.

Although there are very few controlled trials comparing invasive with non invasive mechanical ventilation, non invasive ventilation seems to have a role in selected patients with status asthmaticus, despite reservations.

Ventilator Induced Lung Injury

Mechanical ventilation has been used to support acutely ill patients for several decades. But clinicians are aware that, despite the life-saving potential of this assistance, it has several potential drawbacks and complications. A State of the Art review published several years ago in the American Review of Respiratory Disease recapitulated these complications. What has recently emerged is one of the most serious potential complications of mechanical ventilation, ventilator-induced lung injury (VILI). VILI was, for years, synonymous with clinical barotrauma, the leakage of air due to disruption of the airspace wall. The extra-alveolar accumulation of air causes several manifestations, of which the most threatening is tension pneumothorax. The adverse consequences of these macroscopic events are usually immediately obvious, and this form of barotrauma has been the subject of clinical studies. It is only very recently that the possibility that more subtle physiologic and morphologic alterations may occur during mechanical ventilation has been recognized. This form of injury is now a major preoccupation of most physicians caring for patients needing ventilatory support. Although several fundamental experimental studies were published before 1975, it was only 10 year later that renewed interest in this subject stimulated the major research effort which has considerably expanded our knowledge. Unlike the classic forms of barotrauma (i.e. extra-alveolar air), our knowledge of these alterations has come only from experimental studies. Alterations in lung uid balance, increases in endothelial and epithelial permeability, and severe tissue damage have been seen following mechanical ventilation in animals. The macroscopic and even microscopic damage observed in VILI is not specific. It closely resembles that observed in other forms of experimental acute lung injury. More importantly, it does not fundamentally differ from the diffuse alveolar damage observed during human acute respiratory distress syndrome. Thus, were VILI to occur in humans, it would be indistinguishable from most of the initial acute offending processes that lead to respiratory failure and the need for ventilator assistance. The possibility that mechanical ventilation can actually worsen acute lung disease is now widely accepted, despite the lack of a clear demonstration of a clinical equivalent of the experimental observations. Any demonstration of superimposed VILI during the course of human acute respiratory distress syndrome may be illusive. Thus, this concept derived from animal studies has resulted in complete reassessment of the use of mechanical ventilation for patients with acute lung diseases and underlies current trends in the clinical practice of mechanical ventilation. Indeed, the current orientation is to emphasize the potential importance of easing the stress on acutely injured lungs by using modes of ventilation that limit the pressure and volume of gas delivered to the lungs.

Suggested Reading