MANAGEMENT OF THE PATIENT ON MECHANICAL VENTILATION

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ABSTRACT

Mechanical ventilation is central to critical care medicine and has far reaching implications for the clinical outcomes of the critically ill. Mechanical ventilation has evolved over years and has become increasingly relevant, particularly as a crucial factor in the management of the novel coronavirus pandemic currently ravaging the world. This paper explores the management of mechanically ventilated patients in the intensive care unit (ICU).

INTRODUCTION

Mechanical ventilation is the most used short term life support technique worldwide[1]. In the United States, 20.7 to 38.9% of ICU beds are occupied by mechanically ventilated patients[2]. The rate of ventilator use in low- and middle-income countries is relatively lower compared to developed countries, a study on intensive care medicine in sub-Saharan Africa revealed a ventilator use rate of 18.7%[3].

Nigeria has an estimated total of 350 ICU beds[4] and as of 17th April 2020, the country only had 169 ventilator units available[5].

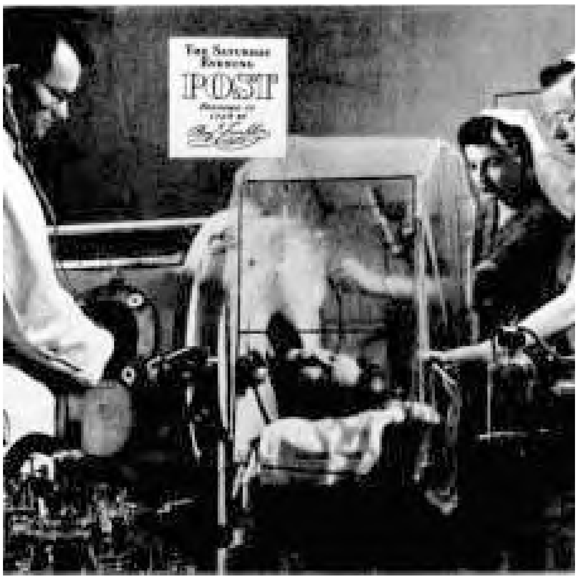
HISTORICAL PERSPECTIVES ON MECHANICAL VENTILATION

Interventions to support ventilation in humans date as far back as biblical times[6]. Mechanical ventilation has evolved through three modes/types: Positive Pressure ventilation, Negative Pressure Ventilation and then back to Positive Pressure Ventilation.

One of the first people to be associated with mechanical ventilation on an individual level was Paracelsus in 1530, when he used fireplace bellows to resuscitate recently dead persons in Europe[7,8]. He was closely followed by Andreas Vesalius who for the first time described positive pressure ventilation in his book “De Humani Corporis Fabrica”[9]

“But that life may be restored to the animal, an opening must be attempted in the trunk of the trachea, into which a tube of reed or cane should be put; you will then blow into this, so that the lung may rise again and take air” is a quote from the book that has popularly been cited as the first reference to positive pressure ventilation.[10]

The 19th century witnessed heightened awareness and thus, criticism of positive pressure ventilation. Evidence of its harmful effects presented by renowned scientists like Jean Leroy d’Eoilles, Dumeril and Magendie resulted in a sharp decline in the acceptance of positive pressure airway ventilation and more physicians gravitated toward the use of negative pressure ventilatation[11]. The iron lung, a form of negative pressure ventilator, was invented in response to the poliomyelitis pandemic[6‘12] that demanded the use of ventilation due to the very high mortality rate[13,14.]



- *Fig. 1. Kay Reiten in an iron lung. (Saturday Evening Post, 21 August 1954, p. 17). Only a few of the images accompanying the published narratives show an individual with polio being attended by medical staff, and this is the only one to show a physician.[15]*

The inability of the iron lung to effectively reduce mortality forced scientists back to the development and use of positive pressure ventilation. The remarkable improvement in mortality rates fostered interest and research in the development of positive pressure ventilation[16].

Positive pressure ventilators have seen four generations of development and continue to be reiterated and optimised for best results in ICU management of critically ill patients.[6]

INDICATIONS FOR MECHANICAL VENTILATION

Mechanical ventilation is indicated in patients whose spontaneous ventilation is not adequate to support life[17]. Physicians place patients on mechanical ventilation for a plethora of reasons based on the clinical assessment of the patient and the nature of the underlying problem[1,18]. Common factors assessed while considering patients for mechanical ventilation include: nasal flaring, tracheal tug, use of accessory breathing muscles and other clinical indicators of increased work of breathing. Because mechanical ventilation provides respiration temporarily and is associated with complications, reversibility of the underlying pathology must be established before mechanical ventilation is initiated[19].

Examples of clinical conditions that commonly require mechanical ventilation are listed below:

Hypoxic respiratory failure	Hypercapnic respiratory failure	Perioperative respiratory failure	Shock	Others
Pulmonary embolism, pulmonary hypertension	Central hypoventilation	Upper abdominal surgery	Cardiogenic shock	Intraoperative respiratory support
Pneumonia	Muscle failure	Abdominal distension: obesity, ascites	Septic shock	Reduction of oxygen cost of breathing in patients with circulatory failure
Acute respiratory distress syndrome/ atelectasis	Neuromuscular transmission failure	Preoperative smoking	Hypovolemic shock	Prophylactic ventilation for impending organ failure
Fibrosis	Asthma, COPD	Ascites		Airway protection for patients with reduced consciousness
Alveolar flooding with fluid (blood, pus, aspirate etc)	Chest wall and pleural space failure	Inadequate post operative analgesia		

Figure 2: indications for mechanical ventilation [1,20]

MODES OF MECHANICAL VENTILATION

Modes of mechanical ventilation are the various patterns through which the ventilator assists the patient in breathing[21]. The modes of mechanical ventilation have grown in number and complexity over 30 years from the traditional volume controlled ventilators[22,23,24] to more advanced ventilators such as Neutrally Adjusted Ventilatory Assist(NAVA) and Adaptive Support Ventilation(ASV)[25] with the sole aim of improving patient-ventilator interactions. This has led to the existence of as many as 174 modes of ventilation[26].

The different modes of ventilation can be identified based on their three main components: the ventilator breath control variable, the breath sequence, and the targeting scheme[27].

The ventilator breath control variable is predetermined by the operator of the ventilator and is used as a feedback signal for controlling other variables of ventilation, and ultimately the patient's inspiration[28]. The variables controlled are the Pressure and Volume of delivered air. In advanced ventilators, both variables could be controlled at the same time[21]. Volume controlled ventilators leave pressure as a dependent variable and therefore expose patients with reduced airway compliance to the risk of barotrauma.

The Breath Sequence refers to the pattern through which the breaths of the patient are triggered and terminated. Based on this criteria, modes of mechanical ventilation can be identified under three main groups:
(a) Continuous Mandatory Ventilation (CMV)
(b) Intermittent mandatory Ventilation (IMV)
(c) Continuous Spontaneous Ventilation (CSV)[27].

Mandatory ventilation involves breaths being initiated completely or partially by the machine and spontaneous ventilation involves breaths initiated by the patient. Pressure support ventilation and continuous positive airway pressure are examples of spontaneous ventilation.

The targeting scheme is a model[29] the ventilator uses to achieve predefined outputs, in the form of a feedback control system. There are 7 main targeting schemes. They are: set-point, dual, servo, bio-variable, optimal, intelligent and adaptive[27].

The numerous modes of ventilation available are therefore formed based on different combinations of the breath control variable, breath sequence and targeting scheme.

CARE OF THE PATIENT ON MECHANICAL VENTILATION

Mechanical ventilation usually connotes critical illness demanding individualised care in the ICU. For every patient, ICU physicians work towards reducing work of breathing, optimising oxygenation, preventing complications of mechanical ventilation and ultimately reducing time spent on ventilation while treating the underlying indication for ventilation.
In caring for the patient on ventilation, the following considerations are of high importance

1. Initiation of mechanical ventilation and intubation: after the decision has been made to initiate mechanical ventilation, the mode of ventilation is determined by the physician. Mechanical ventilation could be invasive or non-invasive. Invasive ventilation requires intubation with or without tracheostomy. Tracheostomy is indicated in patients requiring prolonged ventilation and has been associated with shortened duration of mechanical ventilation if instituted early within the first ten days of admission [30]. Complications of intubation such as upper airway and nasal trauma, oropharyngeal laceration, ventilator associated pneumonia among others have encouraged the growing trend towards the use of non-invasive mechanical ventilation. Correct placement of the endotracheal tube, maintenance of proper cuff pressure and adequate suctioning should be ensured in intubated patients.

2. Ventilator settings and lung protective ventilation: mechanical ventilation is associated with barotrauma and other forms of ventilator induced lung injury; thus, initial ventilator settings should prioritise lung protection. The lung protective strategy focuses on low tidal volume and recommends an initial setting of 6-8ml/kg of ideal body weight in healthy lungs and 4-6ml/kg in unhealthy lungs as in acute respiratory distress syndrome (ARDS) for example[31,32]. Limiting driving pressure, flow rate, positive end-expiratory pressure (PEEP), and frequency have also been listed as lung protective measures[33].

3. Positioning: Prone positioning has been found to improve ventilation and is associated with better outcomes. A study comparing prone and supine positioning in mechanically ventilated healthy individuals demonstrated a more uniform perfusion in the prone position[34,35].

4. Sedation and paralysis: in mechanically ventilated patients, a level of sedation is required to prevent unplanned extubation[31]. Sedation has however been associated with prolonged stay on mechanical ventilation and deep sedation should be avoided whenever possible[1,36] Minimising sedation through the use of sedation scales has been associated with better patient outcomes[37]. Paralysis of the diaphragm and respiratory muscles through the use of neuromuscular blocking drugs has traditionally been employed to completely eliminate the patient's work of breathing, improve chest wall compliance and ultimately prevent patient ventilator dyssynchrony[37]. A recent study however shows no significant difference in mortality between patients that received continuous infusion of cisatracurium and heavy sedation and those who were managed under lighter sedation protocols[38].

5. Patient monitoring: constant monitoring is required for every mechanically ventilated patient in the ICU. The pain and sedation needs and patency of airway should constantly be evaluated[31]. Pulse oximetry, ventilator pressure, ventilator traces and diaphragmatic electromyography are parameters that are continuously monitored[39]. It is particularly important to monitor and adjust ventilator pressures as needed to prevent barotrauma. Plateau pressure should be checked every 30 to 60 minutes, values exceeding 30cm H_20 predispose the patient to alveolar injury[32].

6. Nutrition: Critically ill patients undergo a lot of metabolic stress resulting in catabolism and altered gut absorption, this coupled with pre-existing malnutrition predisposes patients to nutrition deficits and muscle wasting. Inability to take food orally necessitates enteral nutrition in mechanically ventilated patients[40]. Energy and protein

needs of patients should be strictly monitored to prevent underfeeding and hyperglycaemia from overfeeding both of which result in prolonged time on ventilator[40].

Indirect calorimetry is the recommended tool for determining energy needs but is not available to most clinicians[41]. Predictive equations, which have a high potential for error, are used instead to approximate caloric needs of the patient.[40] Feeding protocols are optimised for patients based on underlying conditions and individual needs. Micronutrient and vitamin supplementation have been traditionally employed with evolving views on their effectiveness; a study has shown that vitamin D supplementation has no effect on patient outcome[42], while another study demonstrates that vitamin C supplementation shortens duration of mechanical ventilation[43,44]. Enteral feeding in prone positioned patients might seem daunting but is feasible, safe and not associated with increased risk of gastrointestinal complications[45].

7. Oral hygiene: Ensuring oral cavity hygiene with chlorhexidine washes as much as is technically possible is encouraged and has been the standard practice for years, however, studies have shown no impact on the rate of ventilator associated pneumonia or time of mechanical ventilation[31].

COMPLICATIONS OF MECHANICAL VENTILATION

Although a lifesaving intervention, mechanical ventilation is associated with several severe complications that prolong ICU stay, increase healthcare cost, reduce quality of life or result in death.[46] The following table summarises common complications of mechanical ventilation:

Ventilator induced lung injury	**Ventilator associated pneumonia**	**Ventilator induced diaphragmatic dysfunction**	**Others**
Pulmonary oedema resulting from barotrauma and volutrauma	Pneumonia in a patient that has been on mechanical ventilation for more than 48 hours	It results from diaphragmatic atrophy due to reduced inspiratory efforts, administration of neuromuscular blockers and steroids, and acute diaphragmatic injury.	Intubation injury
Risk factors include raised ventilator flow, tidal volume and pressure	It is the second most common nosocomial infection and leading cause of death from nosocomial infections in critically ill patents	It causes weaning failure, prolonged ICU admission and higher risk of complications	Oxygen toxicity
	Staphylococcus aureus and *Pseudomonas aeruginosa* are the most common causative organisms	The use of anti-oxidants may be beneficial in prevention of diaphragmatic atrophy	Auto positive end expiratory pressure
	Patients with COPD, burns, neurosurgical procedures, ARDS and a history of aspiration and reintubation are at increased risk for pneumonia		

• *Figure 3: complications of mechanical ventilation. 46-52*

WEANING

Weaning is the process of withdrawing ventilatory support from a patient on mechanical ventilation47. An estimated 40% of the total duration of mechanical ventilation is dedicated to weaning48 Complications such as ventilator associated pneumonia and ventilator induced lung injury make prompt liberation from mechanical ventilation imperative. Conversely, premature weaning results in complications like loss of the airway48; ventilator weaning is thus delicate and must be handled with as much care, if not more, than the initiation and maintenance of mechanical ventilation.

STAGES OF WEANING

- Assessing readiness to wean: this is carried out on a daily basis after the underlying condition has resolved or improved significantly.
- Spontaneous breathing trial (SBT): carried out over a period of at least 30 minutes and not longer than 120 minutes47.
- Extubation: the patient is extubated if there are no factors predisposing the patient to extubation failure.
- Reintubation: This is associated with prolonged ICU stay and must be prevented.

Subjective criteria:

1. Resolution of disease acute phase for which patient was intubated
2. Adequate cough
3. Absence of excessive trachea-bronchial secretion
4. No sedation or adequate mentation on sedation (or stable neurologic patient)

Objective criteria:

1. Stable cardiovascular status (i.e. HR </=140 beats per min, systolic BP 90–160 mmHg, no or minimal vasopressors)
2. Absence of fever
3. Adequate haemoglobin levels
4. Stable metabolic status
5. Adequate oxygenation as evidenced by:
   a. Tidal volume > 5 mL/kg
   b. Vital capacity >10 mL/kg
   c. Proper inspiratory effort
   d. Respiratory rate ≤ 35/minute
   e. PaO2 ≥ 60 and PaCO2 ≤ 60 mmHg
   f. Positive end expiratory pressure ≤ 8 cmH2O
   g. No significant respiratory acidosis (pH ≥ 7.30)
   h. Maximal inspiratory pressure (MIP) ≤ -20 – -25 cmH2O
   i. O2 saturation > 90% on FIO2 ≤ 0.4 (or PaO2/FIO2 ≥ 200)

- *Figure 4: assessment of readiness to wean*[47]

Respiratory rate < 35 breaths/minute
Good tolerance to spontaneous breathing trials
Heart rate < 140 /minute or heart rate variability of >20%
Arterial oxygen saturation >90% or PaO_2 > 60 mmHg on FiO_2<0.4 (40%)
Systolic blood pressure 80 - 180mmHg or <20% change from baseline
No signs of increased work of breathing or distress *

- *Figure 5: criteria for successful spontaneous breathing trial* [47]

Clinical assessment and subjective indices: Agitation and anxiety;
Depressed mental status,
Diaphoresis, Cyanosis, Evidence of increasing effort:
Increased accessory muscle activity
Facial signs of distress, Dyspnoea
PaO2 </=50–60 mmHg on FIO2 >/=0.5 or SaO2 </=90%
PaCO2 >50 mmHg or an increase in PaCO2 >8 mmHg
pH <7.32 or a decrease in pH >/=0.07 pH units
Resp. rate > 35 breaths/min or increased by >/=50%
Heart rate >140 beats/min or increased by >/=20%
Systolic BP >180 mmHg or increased by >/=20%

- *Figure 6: criteria for failed spontaneous breathing trial* [47]

Simple: Successful SBT after the first attempt
Difficult: Failed SBT at first attempt and required up to three trials or Required <7days to reach successful SBT
Prolonged Required >7days or more than 3 trials to reach successful SBT

- *Figure 7: classification of weaning outcomes*[47]

EXTUBATION FAILURE

Extubation is said to have failed when reintubation is needed within 48 hours of extubation. Airway protection capacity and mental status are factors that should be considered before attempting extubation. Good cough, reduced secretion and need for suctioning (adequate airway protection), high cuff leak values and a GCS > 8 are factors associated with successful SBT. A cuff link value <110ml indicate high risk for post extubation stridor. Post extubation stridor occurs as a result of airway narrowing and can be treated with steroids or epinephrine[49]. Patients with low cuff leak values may receive prophylaxis 24 hours before extubation[48].

Failure of two or more consecutive SBTs
Chronic heart failure
Partial pressure of arterial carbon dioxide > 45 mmHg after extubation
More than one coexisting condition other than heart failure
Weak cough
Upper-airway stridor at extubation
Age ≥ 65 years
APACHE II score >12 on the day of extubation
Patients in medical, paediatric or multispecialty ICU
Pneumonia as a cause of respiratory failure

- *Figure 8: Predictors of extubation failure.* [47]

Prophylactic use of non-invasive ventilation and high flow nasal cannula have been identified to improve extubation success and prevent prolonged ICU stay post extubation[49].

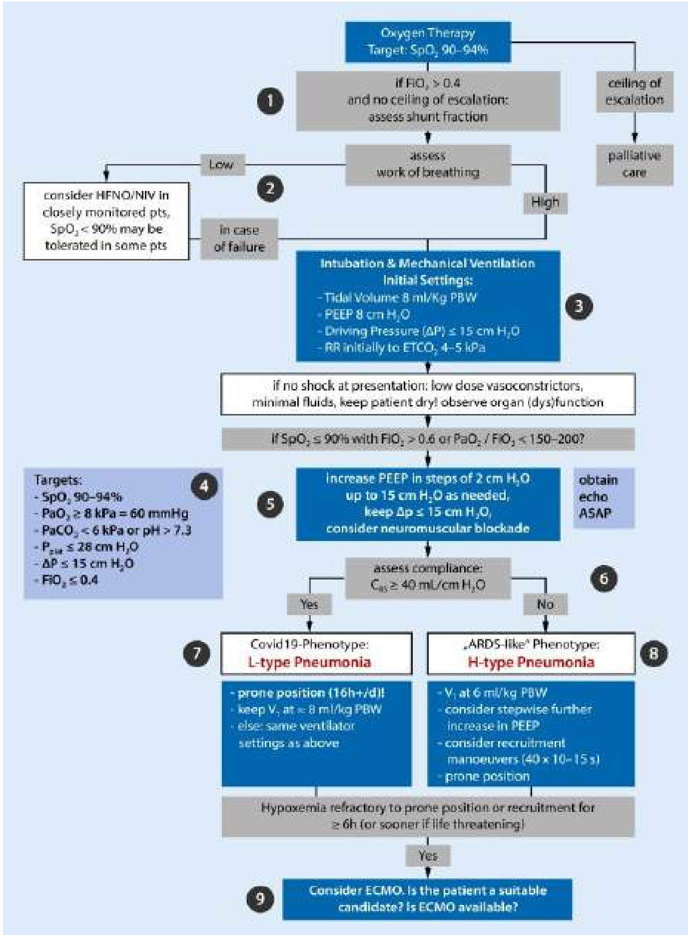
MECHANICAL VENTILATION IN COVID-19 MANAGEMENT

Approximately 5-15% of COVID-19 patients require ventilator support and ICU care[50]. The goal of mechanical ventilation in COVID-19 patients is effective gas exchange while avoiding ventilator induced lung injury through lung protective ventilation.[51]

Ventilator support is recommended for patients with severe hypoxemia of P_2O_2 < 200mmHg[51]; however, the use of invasive mechanical ventilation has been associated with higher rates of mortality and comorbidities such as acute kidney injury[52],thus, non-invasive ventilation with airborne precautions and a low threshold for intubation is recommended for COVID-19 patients with mild hypoxia[50]. Helmet Continuous Positive Airway Pressure (H-CPAP ventilation) has been recommended as a non-invasive respiratory support for COVID-19 patients around the world. Its use has been associated with good clinical outcomes, reduced air leaks and aerosolization and thus improved ICU staff protection; better enteral nutrition, hydration and patient cooperation[53,54]

• *Figure 9: Patient in tripod position during Helmet CPAP [54]*

Invasive ventilation is instituted in patients with worsening hypoxemia, organ failure, and delirium or other contraindications to non-invasive ventilation. Use of single rooms, prevention of unnecessary intubation, reduction of aerosol generating interventions and use of personal protective equipment are measures taken to protect ICU staff from infection.[50,51]



• *Figure 10: ventilation strategy for COVID-19 patents[50]*

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