Recent advances in mechanical ventilation

JES Park MA MRCP, Specialist Registrar

MJD Griffiths PhD MRCP, Consultant Physician

Unit of Critical Care, Imperial College London at the National Heart and Lung Institute, Royal Brompton Hospital, London

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Mechanical ventilation and critical care have their origins in the polio epidemics of the 1950s which were associated with a high incidence of respiratory failure. During this period, two important aspects of critical care were firmly established:

- mechanical ventilatory support (both invasive and non-invasive) could improve survival in respiratory failure, and
- ventilatory support was better provided by dedicated specialist units.

Since the 1960s, the ability to provide invasive mechanical ventilation has continued to define intensive care unit (ICU) care and in most units at least 50% of admissions will receive such support.

Until recently, the exclusive use of ventilators in ICUs (and theatres) promoted an understandable view that most general physicians needed little working knowledge of these devices. However, the development of non-invasive ventilation (NIV) on medical wards, as well as the widespread use of continuous positive airway pressure (CPAP), has significantly altered the situation. A basic understanding of ventilator and CPAP technology is now important to all those caring for the acutely ill. This article will provide a brief explanation of ventilatory modes and then review ventilatory support in two common conditions that cause respiratory failure on the ICU:

- adult respiratory distress syndrome (ARDS), and
- chronic obstructive pulmonary disease (COPD).

Mechanical ventilators and modes

Ventilator technology can appear bewilderingly complex, a situation not helped by a lack of standardised terminology, with different manufacturers adopting alternative terms for the same mode of ventilation. Table 1 presents a summary of common terms and modes. Like video recorders, modern ICU-based ventilators often have more features than appear strictly necessary. However, this makes them very flexible: for example, it is no longer necessary to have separate machines for pressure- and volume-driven ventilation, with one machine able to fulfil both roles.

A ventilator is best considered as a black box with the internal mechanics irrelevant to the operation of the system. The most important and defining feature of a ventilator is that it can cycle between inspiration and expiration. This distinguishes it from a CPAP machine with which there is no cycling. CPAP machines are therefore not ventilators – despite their similar appearance – and should not be confused with those devices.

Volume or pressure mode

A further important division is in the choice of volume or pressure as the set variable that determines the delivery of the air/oxygen mixture to the patient. In volume cycling modes, tidal volume (V_T) is preset, which then generates an airway pressure (depending on airway resistance and lung compliance). In pressure cycling mode, an inspiratory pressure is preset and V_T is delivered, which again varies depending on airway resistance and lung compliance. Neither method is superior in terms of gas delivery and no study has conclusively demonstrated a better outcome with either mode.

Controls

Few additional controls are needed on a simple ventilator (Table 2). Breath rate per minute needs to be set and some method of controlling the transition from inspiration (I) to expiratory (E) (often an I:E ratio) is required. ICU-style machines have separate oxygen and air supplies, allowing accurate titration of the fractional concentration of oxygen in inspired gas (FiO_2) (up to 100%). Ward-based NIV machines are electrically powered and oxygen is usually entrained from a wall supply, effectively limiting the FiO_2 to less than 50%, at best.

Patient monitoring and alarm facilities

Another important difference between portable and ICU-based machines is the available patient monitoring and alarm facilities. Alarms are fundamental to patient safety and fully ventilator-dependent patients require more complex alarms and monitoring. ICU machines

Key Points

More than 50% of patients admitted to an intensive care unit (ICU) will receive a period of mechanical ventilation

The primary objective of invasive mechanical ventilation is to support adequate gas exchange during the investigation and treatment of respiratory failure

Applying mechanical ventilation to injured lungs exacerbates parenchymal lung damage and inflammation, and contributes to the high mortality of these patients

The short-term outcome of supporting patients with acute respiratory failure complicating chronic obstructive pulmonary disease is generally good

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Table 1. Examples of basic modes of ventilation and respiratory support.

Mode	Description	Comment
CMV or IPPV	All breaths initiated and delivered by the ventilator	No respiratory effort by the patient; this may require full sedation and neuromuscular blockade
IMV	Ventilator provides minimum number of breaths with set parameters (volume or pressure control)	Dyssynchrony is inevitable Rarely used
SIMV	Ventilator senses pressure or flow in the circuit to prevent breath delivery in early expiration Otherwise as above	Useful in early weaning when necessary to ensure minimum number of ventilator-delivered breaths
PSV	All breaths are triggered Ventilator provides flow until target airway pressure reached	Gradual decrease in target airway pressure is effective weaning strategy[1] Under- and over-ventilation possible
CPAP*	Application of positive airway pressure throughout respiratory cycle Aims to prevent decreased functional residual capacity associated with collapse of lung units	May be used at end of weaning from invasive ventilation during trial of spontaneous ventilation *OR* may improve oxygenation in patients with rapidly treatable type 1 respiratory failure, obviating the need for tracheal intubation[2]

* Not a ventilation mode as no inspiratory/expiratory cycling occurs.
CMV = controlled mandatory ventilation; CPAP = continuous positive airway pressure; IMV = intermittent mandatory ventilation; IPPV = intermittent positive pressure ventilation; PSV = pressure support ventilation; SIMV = synchronised IMV.

will continuously monitor expiratory gas and so have a 'dual circuit'. This allows rapid detection of circuit/tube occlusion as well as disconnection. Portable machines in general have only an inspiratory circuit. Expiration is by a deliberate leak introduced into either the mask or circuit. While disconnection is readily detectable with this system, occlusion alarms are less reliable. With nasal masks, this is not usually an issue (the patient's mouth provides a safety valve). However, with full-face masks an occlusion can in theory occur. Lack of sophisticated alarms also prevents many portable machines from being suitable for patients with artificial airways (eg patients with tracheostomies).

Indications for ventilation

Assessing the need for intubation and ventilatory support is complex and should be performed by experienced practitioners. It involves both subjective assessment of the patient (how tired are they?), the speed and reversibility of the underlying cause (will it become worse in the next few hours?) and changes in physiological parameters including arterial blood gases. Patients with multiple organ problems (eg sepsis) often benefit from early ventilation in an attempt to control at least one failing organ system and prevent sudden catastrophic respiratory decline from alveolar oedema. Issues about patient choice of advanced support, based on a realistic assessment of survival and recovery prospects, also need to be addressed at an early stage.

The acute respiratory distress syndrome and acute lung injury

Acute lung injury (ALI) is a generic term whilst ARDS is distinguished by having the most severe defect in oxygenation.[3] ARDS was first described in 1967 in patients exposed to major trauma and severe haemorrhagic shock. The process is characterised by acute inflammation of the lung parenchyma and disruption of the alveolar-capillary membrane, resulting in non-cardiogenic pulmonary oedema and respiratory failure with refractory hypoxia.[4]

The pathophysiology of ALI/ARDS presents particular challenges for mechanical ventilation in maintaining adequate gas exchange without causing further lung damage – so-called ventilator-associated lung injury (VALI).[5]

Low tidal volume ventilation

Experimental studies have clearly established that mechanical ventilation can cause lung injury. Using a combination of negative and positive pressure ventilation in the presence and absence of thoracic wall restriction, the damaging effects of high pressure and overdistension on the

Table 2. Common range of ventilator controls, with examples of typical settings.

Parameter	Values/Comment
Inspired oxygen (FiO_2)	21–100%
Inspiratory airway pressure	Usually <30 cmH_2O
Expiratory airway pressure (PEEP)	0–20 cmH_2O
Pressure support of spontaneous breaths	Usually 10-30 cmH_2O
Tidal volume (V_T)	6–12 ml/kg
Respiratory rate	Usually 10–14 mandatory ventilator-delivered breaths/min
Inspiratory:expiratory time	Typically 1:2; increased ratio needed in obstructive lung disease and inverse ratio (eg 1:1) may improve recruitment of units with slow time constants in injured lungs
Trigger sensitivity	To flow or airway pressure
Inspiratory flow rate	20–120 l/min

lung have been differentiated. It has been concluded that high-volume VALI (or volutrauma) is the major culprit.[6] Controlled hypoventilation or permissive hypercapnia has been advocated by some authorities for several years,[7] but the recent ARDS Network study finally demonstrated the survival benefit of a 'protective' ventilation strategy based on a V_T of 6 ml/kg rather than 12 ml/kg.[8]

The importance of this study and the implied impact of VALI cannot be overstated as low-volume tidal ventilation is the only intervention that has reduced the mortality of patients with ARDS. Normal lungs are resistant to the injurious effects of overdistension,[9] but retrospective data suggest that injurious ventilation is associated with the development of ALI in patients subjected to mechanical ventilation for acute respiratory failure.[10]

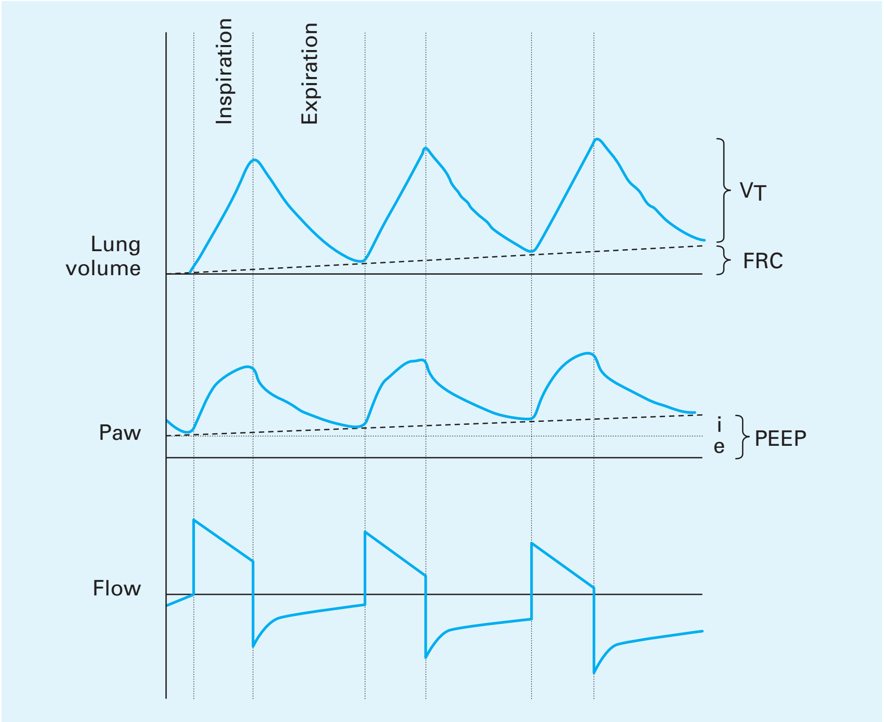

Fig 1. Diagram demonstrating breath stacking in a patient with expiratory airflow limitation. Breath stacking (or hyperinflation) caused by gas trapping occurs when a breath is delivered before expiration of the previous breath has been completed. In this patient with chronic obstructive pulmonary disease, the set ratio of inspiration:expiration is 1:2 (normal) but the retarded expiratory flow results in a progressive increase in airway pressure (Paw) and functional residual capacity (FRC). In addition, the positive end-expiratory pressure (PEEP) increases (e = expiration; i = inspiration; V_T = tidal volume).

Positive end-expiratory pressure

Positive end-expiratory pressure (PEEP) is applied during ventilation to prevent alveolar pressure from returning to atmospheric during expiration. Reported benefits include the:

- prevention of atelectasis
- recruitment of collapsed lung units, and
- improvement in oxygenation in diffuse lung disease.

However, it may also reduce cardiac output by impairing venous return. The best method for setting PEEP remains uncertain, as are the measures for defining its optimum level.[11] In the ARDS Network study[11] PEEP was set by a simple clinical algorithm. However, the more recent ARDS Network ALVEOLI study[12] comparing low (8.3 ± 3.2 cmH_2O) and high (13.2 ± 3.5 cmH_2O, p <0.001) PEEP strategies in 549 patients with ARDS on days 1-4 after admission showed no difference in survival and ventilator-free days between the two groups.

Chronic obstructive pulmonary disease

COPD is common, accounting for 25% of acute medical admissions, over a million bed-days per year and 32,155 deaths in the UK in 1999. During the last decade, NIV has become established in the management of patients with acute exacerbations of COPD complicated by respiratory acidosis (pH <7.35).[13] Even prior to the widespread use of NIV the outcome of patients admitted to intensive care requiring mechanical ventilation was favourable, with over 70% hospital survival recorded in three studies from Australia and the USA.[14–16] Recent data from the 2003 Royal College of Physicians/British Thoracic Society audit of acute COPD admissions are less encouraging. In the total population of patients admitted to hospital, 15% died and 27% were readmitted in a 90-day period.[17] These data may reflect the under-provision of level 2 and 3 beds in the UK and a negative attitude to COPD patients in those controlling ICU admissions.

The ventilatory management of patients suffering an acute exacerbation of COPD may be difficult. Dynamic hyperinflation and high intrinsic PEEP are hallmarks of obstructive airways diseases, including COPD, because of the increased relative resistance to expiration (Fig 1).

Manoeuvres that protect against gas trapping include:

- prolonging the expiratory time such that the inspiratory:expiratory time ratio is 1:3 or higher,
- intermittent disconnection from the ventilator circuit and manual decompression of the chest, and
- setting the level of extrinsic PEEP at two-thirds of the intrinsic PEEP.[18]

Many modern ventilators can estimate the volume of trapped gas and intrinsic PEEP so that the effectiveness of these manoeuvres can be monitored.

Weaning from ventilation can prove difficult and a number of patients will need a prolonged period of ventilatory support (see accompanying article 'Weaning from mechanical ventilation'). A recent meta-analysis suggested that early tracheostomy may improve outcome; a large multi-centre, randomised controlled trial is currently being performed in the UK on this issue.[19]

Future progress in mechanical ventilation

The demonstration that mechanical ventilation can worsen lung injury in man has been a pivotal finding and has already significantly changed clinical practice. Future progress in ventilatory support will depend on achieving a better balance between the organ preserving advantages of maintaining adequate oxygenation and the lung damaging features of current mechanical ventilators.

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