Mechanical ventilation and the injured brain

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Introduction

Ventilatory management of a brain-injured patient is challenging. Injury to the brain initiates an inflammatory cascade that may result in secondary brain injury and extracranial organ dysfunction. The lung is often the most compromised in this process, and at multiple stages of brain injury. Lung pathology can be part of the initial injury process, or result from sequelae of the brain injury and critical care course. Principles of lung protection and brain-directed therapies are often in direct conflict. There are limited randomised controlled trials from which clinicians can draw conclusions regarding management of this controversial cohort of patients. Physiological interactions between the brain and lung should be clearly understood. Injurious ventilation should be avoided. Secondary brain injury should be prevented. Risk factors for this must be identified early and treated promptly. Hypoxaemia should be avoided. Arterial CO_2 tension should be managed. Hyperventilation should be reserved for intractable intracranial hypertension. There is no role for prophylactic hyperventilation as primary therapy. Hypocarbia can precipitate cerebral ischaemia. Novel ventilatory strategies are in the infancy stages. By using these therapeutic modalities, more positive outcomes are hoped for.

Traumatic brain injuries are associated with significant morbidity and mortality. Management of a brain-injured patient is complicated by the high incidence of extracerebral complications,[1] in particular pulmonary, making ventilatory management extremely challenging. Secondary brain injury, from hypoxaemia/hypoxia and hypercarbia, requires prevention and prompt management. This needs to be balanced with lung-protective strategies.[2]

Indications for endotracheal intubation and mechanical ventilation in brain injury

Twenty per cent of brain-injured patients require endotracheal intubation and ventilation.[3]

Neurologic indications:

- Altered level of consciousness/airway protection.
- Brainstem dysfunction.
- Intracranial hypertension.
- Anticipated neurologic deterioration.

Respiratory indications:

- Hypoxaemic respiratory failure may be due to aspiration, pneumonia, atelectasis and pulmonary embolism. Twenty to 45% of patients with traumatic brain injury and subarachnoid haemorrhage develop ventilator-associated pneumonia (VAP).
- Acute lung injury/acute respiratory distress syndrome (ALI/ARDS). This presents in 10-30% of patients with brain injuries and aneurysmal subarachnoid haemorrhage. ALI/ARDS is an independent predictor of poor outcome in the setting of brain injury. Distribution is bimodal in ALI/ARDS. Early ALI/ARDS occurs at day two to three and late at day seven to eight post-initiation of mechanical ventilation.[4]
- Neurogenic pulmonary oedema. Mechanisms for this are not clearly understood. Two theories predominate,[4] the hydrostatic and capillary leak theories. The hydrostatic theory postulates that, at the time of cerebral injury, there is a sudden massive adrenergic surge which induces intense

pulmonary vasoconstriction. This is followed by capillary vasoconstriction and capillary leak resulting in pulmonary oedema. This has also been termed the "blast injury theory".[4] The second theory is the capillary leak theory which postulates pulmonary oedema formation on the basis of inflammatory injury. Acute brain injury, contrary to what was previously thought, is a major producer of pro-inflammatory cytokines. This leads to a double-hit effect of secondary brain injury and extracerebral organ injury and dysfunction.

Intracranial physiology and mechanical ventilation

The goals of positive-pressure ventilation (PPV) in brain-injured patients are primarily aimed at improving oxygenation and controlling arterial CO_2 tension to minimise intracranial hypertension. PPV increases functional residual capacity (FRC) by improving alveolar recruitment, thus optimising oxygenation.

Increased intrathoracic pressure (ITP) increases intracranial pressure (ICP) via these mechanisms:

- Direct transmission of ITP to the intracranial cavity via the neck.
- Increased ITP decreases venous return to the right atrium, and increases jugular venous pressure, thereby increasing cerebral blood volume (CBV) and ICP.
- Decreased venous return decreases cardiac output and mean arterial pressure (MAP). This results in decreased cerebral perfusion pressure (CPP) leading to compensatory cerebral vasodilation, increased CBV and potentially increased ICP, if cerebral autoregulation is impaired.

Mechanical ventilatory strategies: conventional ventilation

Current practice guidelines for ventilatory management advocate protective lung strategies to prevent volutrauma, barotrauma, atelectrauma and biotrauma.[2,4,5] The principles are to use low tidal volumes (Vt) (5-6 ml/kg ideal body weight), maintenance of low mean airway pressures ≤ 30 cmH_2O, judicious use of positive end-expiratory pressure (PEEP) with Δ pressure ≤ 18 cmH_2O, higher respiratory rates and permissive hypercapnia. This is in direct conflict with the previous "brain-directed" ventilatory strategies that used Vt of 10 ml/kg, high FiO_2 and low PEEP or zero end-expiratory pressure. There is proven mortality benefit with the use of low Vt, but permissive hypercapnia may precipitate intracranial hypertension.[2,6,7] Animal studies indicate a higher incidence of severe pulmonary oedema and haemorrhage after exposure to injurious ventilation in the presence of brain trauma. High Vt independently predicts ALI/ARDS and poor outcome in brain injury.[8]

Mechanical ventilation predisposes to potentially significant haemodynamic fluctuations. These may be detrimental in brain injury due to impaired auto-regulation, rendering the brain extremely vulnerable to CPP fluctuations. Prompt initial intravascular expansion and vasopressor initiation may be necessary.

The role of PEEP

Brain-injured patients are at high risk for associated pulmonary pathology, as part of the initial injury (pulmonary contusion, haemopneumothorax) or as sequelae of the brain injury (secondary pulmonary complications). Maintenance of adequate brain tissue oxygenation is paramount for a favourable outcome.

PEEP improves oxygenation by recruitment of atelectatic alveolar units, improving FRC and preventing atelectrauma. However, it may have detrimental neurologic effects in certain clinical circumstances.[9]

In normal pulmonary compliance, PEEP is associated with increased ITP, decreased right atrial volume, decreased MAP and thus compromised CPP. This situation is not similar to non-compliant lungs, where there is a comparatively low ITP transmission to the cranium, therefore lesser effects on cerebral blood flow (CBF) and ICP. CPP may be indirectly affected by systemic effects of PEEP, but these effects still remain quantitatively modest. PEEP is therefore safe to apply as part of a ventilatory strategy to improve oxygenation. Alveolar overdistension should be avoided and stable haemodynamic parameters should be maintained.

Head position also needs attention. At least 30° head elevation promotes intracranial venous drainage via anterior neck veins, as well as the vertebral venous system - which is not majorly affected by ITP. Jugular veins collapse and act as resistors to some of the ITP transmitted. Tight endotracheal tube ties around the neck and extremes of neck rotation should be avoided.

Role of $PaCO_2$ control

Arterial CO_2 tension is a powerful modulator of cerebral vascular calibre, CBF and ICP.[10,11,12,13] The mechanisms are incompletely understood, but CO_2 relaxes pial arterioles via interactions between the

endothelium, vascular smooth muscle, pericytes, adjacent neurons and glial cells. At physiological $PaCO_2$ ranges, 20-60 mmHg, the relationship between $PaCO_2$ and CBF is linear.

Experimental data show that cerebral vessels are sensitive to changes in extracellular pH, rather than a direct response to CO_2 or bicarbonate. Therefore, increased $PaCO_2$ results in vasodilation, increased CBF, increased CBV, decreased intracranial compliance and increased ICP. The reverse is true for low CO_2 tension. This has been the basis for hyperventilation in intracranial hypertension, but cerebral vasoconstriction may precipitate cerebral ischaemia as pericontusional areas are sensitive to hyperventilation-induced ischaemia. The Brain Trauma Foundation management guidelines do not recommend hyperventilation for initial management of raised ICP, unless ICP is unresponsive to first-tier therapy or hyperventilation is for very brief periods of time.[6,10] Maintaining normocarbia is the best practice.

Role of brain monitoring during ventilatory support in brain injury

It is prudent to monitor intracranial pressure, CPP, and brain oxygenation during ventilatory support in brain injury. It is pathophysiologically sound to associate high ICP and low CPP with adverse neurologic outcome. However, there is no proven mortality benefit in continuous ICP monitoring.

Brain oxygenation may be monitored via jugular venous saturation, near-infrared spectroscopy and microdialysis catheters. Availability and cost of these devices are limiting factors to their use. Brain tissue metabolism may be monitored with microdialysis techniques.

Non-conventional ventilatory strategies

Prone ventilation[14,15,16]

Benefits are:

- Recruitment of atelectatic lung units.
- Improved ventilation-perfusion matching.
- Improved drainage of secretions.
- Even distribution of mechanical ventilatory forces.

ICP and brain tissue oxygenation ($PbtO_2$) should ideally be monitored. There are conflicting results on the effects of prone ventilation on ICP and CPP, but there are consistently improved respiratory mechanics and oxygenation. Care should be taken during prone positioning not to dislodge endotracheal tubes and invasive monitors. Pressure-point necrosis should be pre-empted and prevented. There is no mortality benefit to prone positioning.

Recruitment manoeuvres

Multiple strategies are used to recruit atelectatic alveoli and improve oxygenation. The use of incremental levels of PEEP and high intermittent tidal volumes require brain physiological monitoring.

High frequency oscillatory ventilation (HFOV)[17,18]

This delivers high mean airway pressure and very small Vt of 1-5 ml/kg at a rapid rate. It recruits alveoli, while preventing overdistension. Compared to conventional ventilation, HFOV is safe and effective in preventing ventilator-induced lung injury (VILI) and improving oxygenation in severe ARDS. There may be improved intracranial compliance.

Extracorporeal CO_2 removal ($ECCO_2R$)[3,19]

Extracorporeal membrane oxygenators have been attempted in brain-injured patients to improve oxygenation. There is a drop in intracranial pressure and maintained CPP associated with ECMO use. The concern with this is anticoagulation requirements and the risk of intracranial bleeding.

Pumpless extracorporeal lung assist (pECLA) has recently been utilised in small case series with promising results. Protective respiratory care can be maintained while CO_2 removal is optimised. Use of this device requires stable haemodynamic parameters. Anticoagulation is as for thrombo-prophylaxis in immobilised patients. The risk of the device clotting is not entirely eliminated by impregnation with anticoagulant in the filter. Vascular injury, exsanguination and limb ischaemia are some of the recognised complications.

Nitric oxide

Nitric oxide improves oxygenation in ALI/ARDS with no survival benefit. There is potential to cause harm. Data for its use in ARDS with brain injury are limited.

Liberation from mechanical ventilation in acute brain injury

The plan to liberate the patient from mechanical ventilation should be made at initiation of ventilation. There needs to be recognition of when mechanical ventilatory support can be reduced and ultimately discontinued. Patients with neurological injury are often difficult to assess, leading to frequent extubation delays.

Timely liberation from ventilation has the following advantages:

- Decreased risk of VILI.
- Decreased risk of VAP.
- Decreased airway injury.
- Decreased sedation requirements.

- Decreased delirium.
- Shortened ICU length of stay.

Assessment for extubation readiness can be simplified into three criteria:
- Respiratory criteria.
- Haemodynamic criteria.
- Neurologic criteria including stable neurological status, ICP ≤ 20 mmHg, CPP ≥ 60 mmHg.

Clinicians have to evaluate all risks of premature weaning and extubation. Risks associated with ventilator liberation are:
- Respiratory muscle fatigue.
- Gas exchange failure.
- Loss of airway protection.

There is clear benefit to weaning according to a protocol. There should be frequent assessment of ventilatory support requirement and re-evaluation of factors contributing to ventilator dependence before ventilation is discontinued.

Role of tracheostomy

There is ongoing debate regarding indications and timing for tracheostomy placement.[23]

Advantages:
- Decreased risk of self-extubation.
- Decreased sinusitis.
- Decreased airway resistance, dead space and breathing work.
- Better tolerance.
- Less sedative requirements.
- Potentially-reduced duration of mechanical ventilation.

Risks:
- Surgical site infection.
- Airway haemorrhage.
- Pneumothorax.
- Oesophageal perforation.

Tracheostomy placement leads to earlier liberation from mechanical ventilation, but without any mortality benefit or effect on pulmonary infection rates.[23,24,25]

Conclusion

Management of brain-injured patients requires a multidisciplinary approach. Association of brain injury with extracranial organ dysfunction, particularly pulmonary dysfunction, makes this an even a greater clinical conundrum. Clinicians need to recognise principles of management for each organ system to improve function. In some clinical cases, as discussed, principles of management are in direct contrast. This calls for a strategic clinical approach. Early expert consultation must be sought, risk-benefit ratio principles applied and novel therapies can be attempted if available. The process must be driven towards attaining the best possible patient outcomes from early phases of management.

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