Special review

Cuirass Ventilation: A Review and Update

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ABSTRACT

Objective: *This review highlights the development and application of modern chest wall cuirass ventilators.*

Data sources: *Initial animal studies and subsequent publications of applications of various modes of noninvasive cuirass ventilation are recorded.*

Summary of review: *Use of the modern cuirass ventilator in continuous negative, intermittent negative or biphasic (negative and positive) modes is described. Techniques of synchronisation of the cuirass ventilation to the patient's inspiratory and expiratory demands, or even to the patient's cardiac cycle are described. Use of noninvasive cuirass ventilation at normal physiological respiratory rates and at high frequency is highlighted in published studies and in the authors' clinical practice in intensive care. Case reports of patients with cardiac, respiratory and neurological diseases having been successfully managed are used in the review to highlight the desirability, versatility and safety of noninvasive cuirass ventilation for optimal patient care in selected cases.*

Conclusions: *Cuirass ventilation is a valid and valuable method of ventilation in a subset of patients as illustrated by the case reports in this review. Future possibilities for the use of noninvasive cuirass ventilation including in emergency situations where expertise for endotracheal intubation is unavailable; or where physicians or paramedics are unlikely to be able to intubate unconscious/paralysed patients quickly enough to save their lives (e.g. in biological or chemical warfare situatuions).* (**Critical Care and Resuscitation 2005; 7: 22-28**)

Key words: Artificial ventilation, Cuirass ventilation, cough assistance, review

Negative pressure ventilation was the most prevalent method of artificial ventilation until the 1960s. Several historical reviews describe the history and the development of negative pressure ventilation and identify the limitations thereof.[1-3] With the development of positive pressure ventilation, the use of negative pressure as a modality was largely abandoned due to the complexity of device handling and monitoring. However, in recent years, advances in ventilator technology, with improved patient-ventilator interaction and the development of more portable devices with comfortable flexible cuirasses, has once again resulted in the use of cuirass ventilation devices in the intensive care unit (ICU). The latest generation of cuirass ventilators are versatile and can apply many of the patterns of ventilation achievable with positive pressure devices. In addition, they can provide respiratory rates from normal to high frequency oscillation, as well as expiratory (cough) assistance. Modern applications of extrathoracic ventilation are best described as "(Noninvasive) Biphasic Cuirass Ventilat-ion" (BCV).

ANIMAL STUDIES

Since 1986 the pediatrician, Dr Zamir Hayek has been one of the most enthusiastic investigators and developers of modern cuirass designs and electronic biphasic cuirass ventilators. He initially studied the use of his biphasic cuirass external high frequency oscillat-ion (EHFO) in cats,[4] comparing this to conventional mechanical ventilation before and after lung injury. His

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co-workers in Edmonton also went on to study the effects of EHFO on the histology, biochemistry, cerebral blood flow and cardiac output on cats and monkeys.[5,6] Dr Hayek has recently designed a small portable battery driven biphasic cuirass ventilator which is being studied as a potential resource for cuirass ventilation support in the field in the event of chemical warfare, where large numbers of soldiers or civilians with respiratory insuff-iciency due to organophosphate or other gas inhalation may occur. This portable machine is currently being studied on animals and volunteers for rapid response ventilatory support. It is interesting to note that biphasic extrathoracic pressure could theoretically replace both standard chest compression and mechanical ventilation in cardiopulmonary arrest.[7]

MODES OF CUIRASS VENTILATION

Ventilation can be applied using a noninvasive chest wall cuirass in as many different patterns as routine positive pressure ventilation can, with the addition of being able to provide chest compression on expiration (forced expiration).

- **Controlled biphasic cuirass ventilation** is akin to intermittent mandatory ventilation (IMV), with the patient able to take breaths easily whenever desired between the mandatory breaths.
- **Continuous negative pressure,** when applied, is akin to CPAP and can be set at any pressure around the baseline to increase the functional residual capa-city (FRC) as required.[8]
- **Non-invasive Synchronised Biphasic Cuirass Ventilation (BCV)**. Cuirass triggered breaths are akin to the spontaneous breaths in the synchronised IMV (SIMV)
- **High frequency oscillation** (HFO) can be applied in frequencies up to 1200 oscillations per minute, for the achievement of oxygenation, reduction of carbon dioxide,[9,10] or for secretion mobilisation from the lung periphery as in occurs with chest physiotherapy. A major benefit of externally applied cyclical negat-ive and positive (biphasic) pressure is the ability to assist in coughing and secretion clearance from the airways.
- **Cardiac synchronised.** A new addition to the various modes of cuirass ventilation is the ability to time the ventilatory cycle to coincide with the cardiac cycle. This is done by sensing of the electrocardiograph signals to drive the negative pressure ventilator rate and timing. This mode of Noninvasive Cardiac Synchronised Biphasic Cuirass Ventilation has reported benefits in specific cardiac disease, enhancing cardiac output.[11-14] An additional use of ECG-triggered BCV is in the radiology department during MRI scanning. In highly sensitive magnetic resonance scanning of the heart and thorax, cardiac and ventilatory interaction often interferes with clear imaging. When the cycling of ventilation coincides with every heart beat the imaging can be more precise and helpful in determining structural disease, especially of the coronary arteries.

USE IN CARDIAC PATIENTS

Throughout the 1990's Dr Hayek and his co-workers from the Department of Paediatrics at the Royal Brompton Hospital have studied and published on the use of his cuirass designs in paediatric patients before and after open-heart surgery for congenital cardiac malformations.[11-14]

Biphasic cuirass ventilation with external high frequency oscillations has also been shown to improve cardiac function after coronary artery bypass grafting.[15] While positive pressure ventilation is known to support a failing heart, in cardiogenic shock or right ventricular failure, increased intrapulmonary pressure can be detrimental to cardiac function. Oxygenation and optimal alveolar ventilation can be improved by continuous negative pressure.[16] Continuous negative pressure can be used to support the FRC and synchronised biphasic external cuirass ventilation will reduce afterload of the right ventricle and improve pulmonary circulation.

This author often uses cuirass ventilators in adult patients post cardiac surgery with difficult ventilatory weaning due to phrenic nerve injury. In these cases this modality enables rapid weaning and extubation if used regularly nocturnally and whenever the patient needs to lie supine. The cuirass designs used now are more flexible and comfortable, resulting in greater patient and nursing acceptability. As the biphasic ventilators have become more compact, efficient and versatile in the past few years, more applications in post cardiac surgery patients are being found.

USE IN ANAESTHESIA AND ACUTE RESPIRATORY FAILURE

External biphasic ventilation has also been used during general anaesthesia for Ear Nose and Throat (ENT) surgery (e.g. severe tracheal stenosis, micro-laryngeal surgery), failed endotracheal intubation [17-21] and after trauma for adequate ventilation of neuro-surgical patients.[22,23] External chest wall oscillations have been studied in many intensive care units worldwide as a means to avoid intubation or to wean patients from invasive mechanical ventilation while they are still theoretically in acute respiratory failure.[23-]

[25] It has also been used in combination with positive pressure support ventilation to facilitate secretion clearance and support ventilation during temporary disconnections from positive pressure for airway suctioning.[26]

USE IN WEANING FROM INVASIVE VENTILATION

Benefit has been shown from the application of cuirass ventilation in patients who are already intubated and receiving positive pressure ventilation.[24,25] As the biphasic extrathoracic pressures are applied, the requirements for pressure support are easily reduced and physiological improvements in oxygenation and cardiac output are seen.[15] Especially where adaptive positive pressure ventilatory modes are used, the requirements for inspired pressure support can be seen to drop progressively and quickly. It is easy to show that biphasic cuirass ventilation enables rapid weaning from positive pressure support. Spontaneously generated tidal volumes increase with enhanced CO_2 removal and reduced inspired oxygen requirements.[27]

In difficult ventilatory weaning, where pulmonary compliance and airway resistance are relatively normal and the limiting factor for weaning is inspiratory muscle weakness, it makes good sense in any awake, co-operative patient to try cuirass ventilation to achieve earlier weaning from positive pressure ventilation and extubation. This will make the patient's life immediately more pleasant with the ability to talk, eat and breathe freely around the mandatory negative pressure breaths. It should also reduce the incidence of ventilator-associated pneumonia and laryngeal injury. Patients can then be moved to a step down or intermediate care facility, or even home, until muscle strength recovers.

Case Report 1: A 72 year old male with amyotropic lateral sclerosis (ALS) for 9 years was admitted to the ICU in respiratory failure secondary to severe sepsis from a urinary tract infection. His physical function before admission was limited to bed rest without any ability to move his limbs (i.e. essentially tetraplegic). He was able to speak until the sudden development of respiratory failure associated with urinary tract sepsis. On admission to the ICU he needed to be intubated and treated with appropriate antibiotics. On recovery from the sepsis he was fully alert and aware of his condition and was trying to communicate with the medical attendants. Weaning trials revealed a very poor muscle response (Maximum Inspired Pressure (MIP) of -15 cmH_2O, Maximum Expired Pressure (MEP) of +7 cmH_2O). A trial of T-piece weaning resulted in tachypnoea, desaturation and an increase in $PaCO_2$. The patient was put onto BCV (negative pressure of -20 cmH_2O, positive 5 cmH_2O, respiratory rate of 20), which allowed endo-tracheal extubation a few minutes after application. The patient was then able to maintain an oxygen saturation over 95% with nasally sampled end tidal carbon dioxide pressure of 35 mmHg. The patient was able to commun-icate verbally, assisted by the expiratory phase of the cuirass ventilation. Neurological and psychiatric evalua-tion at this time confirmed that the patient had no mental impairment and was fully aware of his condition. The patient repeatedly stated that he wished discontinuation of all modes of mechanical ventilation, and reported that the suffering and hopelessness of his disease was a worse experience than his previous experience in a concentration camp. Therefore cuirass ventilation was discontinued at the patient's insistence and he was given small analgesic doses of morphine for pain relief when he requested them.

The patient was given food and water when requested and no further blood gas analyses were performed. He died comfortably 36 hours after ventilation was discontinued. An ALS patient's will is often not known before a respiratory crisis occurs. External biphasic cuirass ventilation can serve as a non invasive method of ventilation in such patients, enabling medical staff and family members to communicate verbally with the patient requiring ventilatory support. Cuirass ventilation should be tried more frequently in ALS patients and other patients with muscle weakness especially when bulbar function is preserved.[28,29]

USE IN CENTRAL ALVEOLAR HYPOVENTILATION

Central alveolar hypoventilation (CAH) syndrome with sleep apnea ("Ondine's curse"), can be congenital, acquired or trauma-induced and is rare.[30,31] Patients who suffer from this syndrome are generally ventilated by invasive positive pressure ventilation by tracheostomy at night only. The cosmetic defect of the tracheostomy, which is not used by day, is most detrimental in younger patients, when physical appearance can pose a psychological stress. Negative pressure ventilation (NPV) is possible in these patients, but there are scarce reports of its use.[32-34] Cuirass negative pressure, specifically, has not been successfully reported in such patients. The author recently converted two patients with "Ondine's curse" from positive pressure ventilation via a tracheostomy to biphasic cuirass ventilation with non-invasive monitoring of SaO_2 and end tidal CO_2. This allowed closure of the tracheostomy in these patients. Both patients were placed in the ICU for a trial of conversion from the tracheostomy-based positive pressure ventilation to biphasic cuirass ventilation. Both patients were observed for any upper airway obstruction, and were monitored during sleep for oxygen saturation and end tidal CO_2.

Case report 2: A nineteen-year-old female, who sustained base of skull and cervical spine trauma in a motor accident at the age of 15, was initially tetraplegic. A gradual motor response developed and after prolonged rehabilitation the patient's tetraparesis improved to enable her to perform most of her daily activities independently. Her weakness was more profound on the left side and she had a neurogenic bladder and bowel. She had central alveolar hypo-ventilation with no respiratory activity during sleep. She was therefore ventilated at night with positive pressure ventilation through a permanent tracheostomy.

During the day she required no ventilatory support and was able to walk about unaided with a cane. She presented to our department with the specific request to have her tracheostomy removed, if this was possible, so that she would look "normal". The patient was placed on BCV with a size 7 cuirass with the following parameters: negative pressure -20 cmH_2O, positive pressure + 5 cmH_2O, I:E ratio 1:1, rate 15 per minute. On these parameters the patient maintained an oxygen saturation of 94%, with an end tidal CO_2 of 35 mmHg. The patient underwent bronchoscopy, which revealed that her trachea was normal with no evidence of tracheomalacia. Her trachea was subsequently decannulated and the tracheostomy scar allowed to heal naturally. After a period observation in the ICU she was allowed to go home. A cuirass ventilator was supplied for home use. This patient has now been ventilated at home by BCV for three years without any major respiratory complications.

The most prevalent method of ventilation for patients with Ondine's curse is positive pressure ventilation via tracheostomy.[31,32] Although this method has proved to be highly effective, it has some disadvantages. Tracheo-stomy allows recurrent aspiration and pulmonary infections, as well as the aesthetic problem. In the past cuirass ventilation for this condition was limited by the size of the machinery and the cost of replacement cuirasses as the child grew. The new generation of cuirass ventilators simply need cuirass changes with child growth, without changing the central unit.

Upper airway obstruction, more common in neonates,[33,34] and tracheomalacia after prolonged intubation must be excluded prior to conversion to cuirass ventilation and permanent removal of the tracheostomy. As in the two cases described above, conversion to biphasic ventilation can be achieved by non-invasive monitoring of O_2 and CO_2 during the application of cuirass ventilation both in hospital and later at home.[35,36] Apart from the obvious cosmetic benefit of removal of the tracheostomy cuirass ventilation allows more physiological ventilation, reduces the risk of infection via the tracheostomy and allows the patient to speak, eat, smell and breath more normally.[36,37]

USE IN CHRONIC LUNG DISEASE (COPD and Cystic Fibrosis)

The major problems in chronic lung disease, which are amenable to management with modern cuirass ventilation devices are secretion clearance, carbon dioxide retention and muscle fatigue. Each of these problems can be relieved to some extent by the periodic application of Noninvasive Synchronised Biphasic Cuirass Ventilation, much in the same way as intermittent non-invasive positive pressure ventilation is useful. The cuirass can be applied in the sitting position, either in bed or in a chair, for secretion clearance by HFO and cough assist. Studies have been done using periodic, daily or weekly applications of BCV showing improvements of inspiratory muscle strength, blood gases and forced vital capacity.[38-41] The Hayek Oscillator has been shown to be superior to other external ventilators in this regard by Spitzer *et al*.[42] Klonin *et al*, has reported beneficial effects in infants with cystic fibrosis.[43] The author has used the technique as a bridge to lung transplantation in a teenage boy with cystic fibrosis. This patient had a tracheostomy and could not be weaned from mechanical ventilation but was able to be decannuated while on cuirass ventilation. His tracheostomy stoma closed spontaneously while on the cuirass ventilation and he was discharged home on a combination program of intermittent biphasic cuirass ventilation and secretion clearance mode, until transplantation. Bilateral lung transplant was successfully performed a few months later and he has fully recovered.

USE IN CHEST PHYSIOTHERAPY AND SECRET-ION CLEARANCE

Noninvasive cuirass ventilation, when applied in high frequency oscillations followed by larger than normal inspiratory to expiratory excursions is used to enhance the clearing of airway secretions. This sequential procedure can be programmed into the modern day cuirass ventilator and applied at regular intervals to the patient either with or without continuous biphasic ventilation as required. In a randomised, crossed comparative study of 20 patients with stablised bronchiectasis, mechanical high frequency oscillations was shown to be as good as conventional chest physiotherapy, theoretically reducing the need for the specific care of a chest physiotherapist for regular treatment.[44]

USE IN MUSCLE WEAKNESS

In the author's experience modern cuirass ventilation is a useful modality for weaning or for chronic ventilatory support in weak patients in our medical intensive care unit, with excellent patient and nursing staff acceptance. The author has also found these devices to be of benefit in the long term ventilation of selected patients at home.

Most suitable for biphasic cuirass ventilation are patients with atelectasis due to diaphragmatic weakness or paralysis, Multiple Sclerosis, Muscular Atrophy or Dystrophy, Polymyositis, Amyotrophic Lateral Sclerosis, Central Alveolar Hypoventilation Syndrome (Ondine's curse) and patients after major sepsis who are weak due to critical illness polyneuropathy or myopathy. Patients who have retained upper airway protective reflexes and who have reasonable pulmonary compliance, but are too weak to generate adequate tidal volumes and cough and clear secretions, can usually easily be weaned from positive pressure ventilation as long as tidal volume and functional residual capacity are supported by cuirass ventilation. External biphasic cuirass devices also allow the application of positive pressure during expiration which is applied more to the abdomen than the thorax and assists weak patients to cough and clear their secretions. These factors permit the cessation of positive pressure ventilation with extubation or decannulation of a tracheostomy. While on BCV patients are able to speak, eat and sleep comfortably at night.

Chronic ventilatory support with biphasic cuirass ventilation is easily accomplished in patients using the cuirass ventilation devices. The ability of the machines to oscillate in high frequency (up to 1200 cycles per minute) followed by deep breaths and positive expiratory pressure (artificial cough) facilitates clearance of secretions. Lung compliance, lung volumes and gas exchange are well maintained and patients are comfortable using the flexible cuirass. Patients less commonly develop the recurrent pneumonias which usually occur in patients who are weak and need chronic ventilatory support by positive pressure ventilation. The use of cuirass ventilation devices should be considered in selected patients with chronic respiratory failure needing ventilatory support for the reasons outlined above.

USE IN EMERGENCY SITUATIONS

A small portable version of the extra-thoracic biphasic cuirass ventilator has been studied in Israel by 10 physicians of various subspecialities, who all tried both to apply a cuirass to a volunteer and perform endotracheal intubation on a mannequin while dressed in full anti chemical protective gear.[45] In this study the external cuirass was able to be applied on average 70secs faster than conventional intubation with a lower failure rate (1 in 10 versus 4 in 10). In the event of biological/chemical disaster or warfare, large numbers of soldiers or civilians with respiratory insufficiency due to organophosphate or other gas inhalation may require rapid response ventilatory support; then external cuirass ventilation applied by a portable battery driven machine may be more feasible than endotracheal intubation which them requires ventilation by hand or portable positive pressure ventilators. Finally, it is interesting to note that biphasic extrathoracic pressure could theoretically replace both standard chest compression and mechanical ventilation in cardiopulmonary arrest.[7]

Conclusion

Many of the actual and potential beneficial applications of cuirass ventilation have been described. In the author's view, this range of useful applications can only increase.

Received: 11 October 2004
Accepted: 3 November 2004

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