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CURRENT TOPIC

The role of negative pressure ventilation

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In the 3rd century BC Erasistratus of Chios recognised that breathing depended on muscular action. By 1555 Vesalius had described assisted positive pressure ventilation and in 1667 Hooke used a pair of bellows to keep a dog alive in his demonstration to the Royal Society. By the mid-1800s it was recognised that air would be drawn into the lungs through the mouth and nose if a subatmospheric pressure could be developed around the thorax and abdomen, and the first body enclosing negative pressure ventilators developed. These experimental devices were gradually refined and the first negative pressure ventilator to be of clinical value was described by Drinker in 1928.[1] This tank ventilator or 'iron lung' in its many modifications was widely used in the polio epidemics from 1930 to 1960 and saved many lives.

The iron lung has many disadvantages. It is bulky, cumbersome, and limits access to the patients. Simpler non-tank negative pressure ventilators were developed in the 1950s and 1960s, with cuirasses, negative pressure jackets, or wraps, all of which fitted over the trunk and abdomen.[2] In all of these designs inspiration was controlled, but expiration relied on passive recoil of the lung and so this was a rather inefficient form of ventilation. By the 1950s the greater efficiency of positive pressure ventilation delivered through a tracheostomy or endotracheal tube had been demonstrated and negative pressure ventilation fell out of favour, with its use largely restricted to chronic ventilatory support in neuromuscular disorders. Over the past 10 years, however, the development of newer forms of negative pressure ventilators which overcome in large measure the drawbacks of their predecessors has seen a resurgence of interest in this mode of ventilation for children.

The principles of negative pressure ventilation

The principle of negative pressure ventilation is that inspiration is initiated by an intermittent negative pressure produced outside the thorax, resulting in the expansion of the lungs and drawing in of air. In traditional negative pressure ventilation the expiratory phase relies on passive recoil of the thorax and this limits the frequency of ventilation to around 30 breaths per minute. Modern negative pressure ventilators can control both inspiration and expiration by providing a negative pressure during inspiratory phase and a positive pressure to compress the torso during expiration, thus no longer relying on the passive recoil of the chest. In such ventilators both the inspiratory and expiratory phases are fully controlled and high frequencies of ventilation can be achieved, thereby enabling their use in individuals with underlying lung disease.

In general terms the tidal volume achieved is linearly related to the peak to trough pressure span generated during inspiration[3] (inspiratory peak pressure −20 cm H_2O; expiratory pressure +6 cm H_2O; ΔP 26 cm H_2O). Newer models of negative pressure ventilation produce intermittent swings of pressure upon a background of constant negative expiratory pressure. Constant negative pressure throughout the respiratory cycle increases the patient's functional residual capacity (FRC) and is equivalent to a positive end expiratory pressure produced inside the airway.

Types of ventilators

IRON LUNG/TANK VENTILATION

Iron lung or tank ventilation is still occasionally used in childhood.[4] The entire body excluding the head is placed in a chamber with an airtight seal around the neck. Most designs have windows that allow observation of the patient and portholes through which monitor leads can be passed. Tank ventilators are robust but problems can occur with the seal at the neck causing jugular venous obstruction or skin damage. The constant flow of air can cause significant body cooling.

A modified version of tank negative pressure ventilator developed for use in infants and children overcomes some of these drawbacks.[5] This chamber comes in different sizes and provides a latex seal at the neck without circumferential pressure. It has portholes to provide access to the patient, entrances for monitoring leads, and lines which do not disrupt the seals, and it has servo controlled ambient air temperature within the chamber. It can provide a continuous negative pressure and superimposed intermittent larger negative pressure breaths with a respiratory rate up to 60 breaths per minute. These modifications permit the use of this negative pressure chamber in preterm, term, and older infants.

TRADITIONAL CUIRASS AND JACKET VENTILATORS [2]

Jacket ventilators such as the Tunnicliffe jacket and the Pulmo-wrap provided an inner framework of metal or plastic which was covered with

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an airtight anorak-like jacket with seals around the neck, arms, and thighs. The air within the jacket was intermittently evacuated, providing the ventilator action. Patients often needed help to put on and seal these jackets but they were suitable for home use. Cuirass negative pressure ventilators were particularly useful in children with neuromuscular disorders. Children had their own cuirass constructed from a plaster of Paris model of the thorax and abdomen. This was possible even when there was a severe thoracic scoliosis. The cuirass consisted of a plastic model of the front and sides of the trunk, the edges were padded with air tight material and the cuirass attached to the patient with a back strap. Pressure sores with cuirasses were common and new cuirasses were required as the patient grew. Cuirass ventilators were easy to wear and suitable for home use with a variety of negative pressure pumps which provided a preset negative pressure within the cuirass.

HAYEK OSCILLATOR

The Hayek oscillator[6] is currently the most versatile negative pressure ventilator. The patient end is a development of the old fashioned cuirass. It is a lightweight flexible chest enclosure with large soft seals to fit around the chest and abdomen, and rests on either a backplate or a flexible cushion forming an airtight enclosure around the chest and abdomen. There is a range of sizes suitable for preterm infants to adults. This cuirass is attached to a piston pump which can provide ventilation up to high frequencies and baseline negative pressure is produced from a vacuum pump. This machine can behave as a conventional negative pressure ventilator at frequencies to 2 Hz. Tidal volume increases in proportion to the negative pressure span generated within the cuirass and minute ventilation is related to the tidal volume and frequency. At above a frequency of 2 Hz, however, the Hayek oscillator behaves more as a high frequency oscillator and oxygenation is achieved largely by diffusion.[3] Frequencies of up to 15 Hz can be obtained with this machine and frequency, inspiratory and expiratory pressures, and I:E ratio are dialled in for individual patients. Adjusting the expiratory pressure permits ventilation above, at, or below the patient's FRC.

Effects of negative pressure on physiology

HAEMODYNAMICS

There have been some elegant studies comparing the haemodynamic effects of positive pressure ventilation with negative pressure ventilation in animal models.[7–10] These initially appear to give conflicting results but further examination reveals that there is a real physiological difference between the effects of continuous negative extrathoracic pressure applied to the whole body with an iron lung or chamber negative pressure ventilator in comparison with techniques where negative pressure is applied only to the thorax and abdomen, that is, cuirass type negative pressure ventilation. Cuirass ventilation maximises the gradient of venous return to the heart by lowering mean intrathoracic pressure, resulting in an improved cardiac output compared with positive pressure ventilation at matched FRC and tidal volumes. In contrast, when the whole body up to the neck is enclosed in a negative pressure chamber, the ambient pressure around the body is subatmospheric, the airway opening is atmospheric, and this is haemodynamically equivalent to the ambient pressure being atmospheric and the airway opening pressure above atmospheric; hence there is no haemodynamic difference between continuous negative expiratory pressure and positive end expiratory pressure in this model. In keeping with these animal findings, cuirass negative pressure ventilation increases pulmonary blood flow after a Fontan procedure.[11] In the absence of underlying cardiac disease, haemodynamic effects of negative pressure ventilation are unlikely to be of clinical significance.

Effects on cerebral blood flow and volume in infants have only been considered in chamber type negative pressure ventilation. In comparison with positive pressure ventilation, Palmer *et al*[12] reported a decrease in cerebral blood volume and a decrease in both oxygenated and deoxygenated haemoglobin, measured using near infrared spectroscopy, suggesting increased venous drainage from the cerebral circulation during negative pressure ventilation. Raine *et al*[13] found no change in cerebral blood flow velocity examined by pulse Doppler ultrasound from the middle cerebral artery, but a small decrease in systemic blood pressure on changing from positive end expiratory pressure to continuous negative expiratory pressure. Removal of the neck seal had no effect on cerebral volume, suggesting that it did not cause significant jugular venous occlusion when correctly applied[14]; however, unilateral thalamic bleeding with associated intraventricular haemorrhage has been attributed to jugular vein compression by the collar of a negative pressure ventilator in a term infant.[15]

RESPIRATORY MECHANICS

In adults it has been demonstrated that there is inhibition of respiratory muscle activity during negative pressure ventilation, with a decrease in both diaphragmatic electrical activity and mechanical activity of the diaphragm. This occurs with both negative pressure ventilation by chamber[16] and by cuirass (Pneumowrap).[17] Thus there is a significant decrease in the work of breathing. However, positive pressure ventilation by nasal mask is more effective than negative pressure ventilation (Poncho wrap) in reducing diaphragmatic activity.[18]

Changes in respiratory mechanics and timing produced by continuous negative extrathoracic pressure have been assessed in infants recovering from respiratory distress syndrome.[19] The introduction of continuous negative expiratory pressure produced a significant decrease in the respiratory rate due to prolongation of expiratory time. Respiratory system compliance increased in those infants where the baseline compliance was low. There was no change in compliance in those with a normal baseline measurement. There was no change in respiratory system resistance. The authors thought that the marked increase in expiratory time probably reflected increased tonic vagal activity arising from stretch receptor stimulation during the application of continuous negative expiratory pressure.

After careful study of the comparative effects of continuous negative extrathoracic pressure (CNEP) and positive end expiratory pressure (PEEP) on lung mechanics and gas exchange in a neonatal animal model of lung injury it was concluded that CNEP and PEEP were physiologically equivalent when matched for distending pressure.[20]

Problems during ventilation

Some practical problems in using extrathoracic ventilation have been mentioned. It is important to obtain a good seal around the patient but essential to protect the skin at contact points and avoid venous obstruction. There needs to be a means of access to the child or infant for monitoring purposes while maintaining ventilation, and a mechanism permitting rapid release of the patient from the ventilator if necessary.

The biggest problem in the use of negative pressure ventilation, however, is that of extrathoracic upper airway obstruction. This was reported as a problem in the early days of negative pressure ventilation[21] and is thought to be related to suppression of the normal preinspiratory activation of upper airway muscles, rendering upper airway structures floppier and more susceptible to passive closure. Obstruction is more likely during REM sleep when the breathing pattern is irregular and upper airway tone reduced.[22 23] Once the problem with upper airway obstruction is identified it is manageable either by the addition of nasal continuous positive airway pressure[24] or by the application of an alternative method of mechanical ventilation, for example positive pressure ventilation with a nasal mask. It is worth noting that this complication cannot be detected using respiratory inductance plethysmography during negative pressure ventilation as the negative pressure inside the cuirass increases the circumference of the plethysmographic bands even in the absence of air flow.[25]

Monitoring during negative pressure ventilation

During the establishment of negative pressure ventilation it is important to ensure that thereis adequate gas exchange; when there is no arterial line this is best achieved by using oxygen saturation and end tidal carbon dioxide monitoring. For chronic use oxygen saturation monitoring alone is most commonly used.

Indications for use

PAEDIATRIC INTENSIVE THERAPY UNIT OR NEONATAL UNIT

In the paediatric intensive therapy unit or neonatal unit a negative pressure ventilator can be a useful additional facility, in either continuous negative pressure mode or intermittent negative pressure ventilation mode to facilitate weaning from positive pressure ventilation. When used after extubation it can be particularly useful in preventing the need for reintubation in a fragile child (personal observation). In individual children there may be benefits from using continuous negative pressure ventilation delivered by cuirass in combination with intermittent positive ventilation without PEEP. This can avoid the haemodynamic effects of PEEP on the pulmonary circulation. It has been suggested that cuirass negative pressure ventilation has a particular role in the support of children after Fontan type operations.[11] The Hayek oscillator has also been used in its high frequency mode to provide negative pressure high frequency oscillation and hence gas exchange by diffusion on top of intermittent positive pressure ventilation. Such strategies, although rarely used, appear to have improved survival in individuals.

A randomised controlled trial of CNEP in neonatal respiratory failure has been reported recently.[26] A chamber system was used and infants were placed in continuous negative pressure at four hours of age if they required more than 40% inspired oxygen or ventilation. There was a small overall benefit of CNEP but at the cost of increased nursing care and with non-significant increases in mortality, pneumothorax rate, and cranial ultrasound abnormalities in the CNEP group. Since that trial started, new and effective methods of delivering nasal continuous pressure support to preterm infants have been developed and negative pressure ventilation by chamber has become less popular.

IN THEATRE

Cuirass negative pressure ventilation using the Hayek oscillator (along with total intravenous anaesthesia) has been reported as a preferred means of ventilation for airway surgery including laser procedures.[27 28] It leaves the surgeon a clear field unencumbered by tubes or catheters and avoids the problem of inflammable substances when lasers are used. The only drawback to this method is that it leaves the airway unprotected so there is a potential for inhalation. So far the reports have been in adult patients but the technique seems equally applicable to children.

AT HOME OR IN HOSPITAL FOR MEDIUM/LONG TERM VENTILATION

There are a group of children predominantly with neuromuscular disorders who require medium or long term ventilation. These range from children with phrenic nerve palsies after cardiac surgery where recovery is anticipated in weeks or months to the children with long term muscular weakness such as Duchenne or spinal muscular atrophy. Negative extrathoracic pressure ventilation for phrenic nerve palsy is particularly helpful in permitting the child to come off positive pressure ventilatory support and to leave the intensive care unit for either the ward or care at home. Most children with this postoperative problem will require support for decreasing amounts of time as recovery occurs. Both negative pressure chambers and

Cuirass type ventilators have been used successfully in this condition.[29]

Many other children with neuromuscular disorders have a chronic and often very slowly progressive disorder and require a type of support that is robust and can be easily managed at home. Traditionally children with this type of problem had a made to measure cuirass for their night time ventilation at home. In recent years this has been superseded by other newer methods of non-invasive ventilation such as ventilation by nasal or face mask which is in many cases both easier to apply and more comfortable for individual patients. Negative pressure ventilation, however, retains a role for those in whom nasal or face mask positive pressure support is not suitable.

One final group of patients who require long term home ventilation are those with central hypoventilation syndromes, either congenital or acquired. The majority of such children are managed with intermittent positive pressure ventilation delivered during sleep through a tracheostomy. However, individuals are being successfully managed using negative pressure ventilation, despite some problems with upper airway obstruction.[4 24]

Role *v* other techniques

Improvements in the techniques of negative pressure ventilation have occurred simultaneously with the evolution of other non-invasive methods of ventilatory support and in particular positive pressure ventilation delivered either by nasal mask or face mask. In older children and in adults nasal ventilation has become the preferred route for delivering ventilatory assistance in chronic respiratory failure.[30] It has the advantages of convenience, comfort, and portability compared with negative pressure ventilation. In a study by Simonds and Elliott[31] of long term nasal positive pressure ventilation in 180 adults, there was improved oxygenation and alveolar ventilation on nasal positive pressure ventilation, and in a small subgroup of patients changed from negative pressure to nasal ventilation there were improvements in blood gas tensions following the switch. However, there has not been a controlled study comparing nasal positive pressure ventilation with a negative extrathoracic ventilation.

A problem with nasal ventilation is that nasal pressures are lost if the mouth drops open and face mask ventilation has been used in some individuals as an alternative. Nasal or face mask ventilation has been used in children as young as two years, but it can be extremely difficult to introduce a young child to a nasal mask or face mask and there are certain children for whom this method of ventilation is unsuitable.

Conclusions

There has been a resurgence of interest in methods of non-invasive ventilation recently. The introduction of ventilators which can provide negative pressure ventilation around a negative pressure baseline and the ability to control expiration and respiratory frequency has produced a versatile alternative strategy for intensive care problems. CNEP is physiologically equivalent to PEEP but may have a lesser haemodynamic effect in some circumstances. The additional facility of negative pressure oscillation at high frequency and hence gas exchange by an alternative mechanism (diffusion) has proved beneficial in individual anecdotal cases and its role in paediatric intensive care needs to be explored further.

It is important in long term ventilation to match the mode of support to individual patient needs. The modern negative pressure machines, together with the developments in nasal and face mask ventilators, provide the respiratory physician with a welcome choice.

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