

## Non-invasive and domiciliary ventilation: negative pressure techniques

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### Historical development

Negative pressure ventilation first came into use during the second half of the nineteenth century. 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. When the pressure around the chest wall returned to that of the ambient air, expiration occurred passively owing to the elastic recoil of the lungs and chest wall.

The chest and abdomen are enclosed in an airtight, rigid chamber in all types of negative pressure ventilator, but in most of the earlier designs the whole of the body up to the neck was also contained in the chamber. This had the advantage that chest wall expansion was not limited by contact with the sides of the negative pressure device and that only one airtight seal, that around the neck, was required. The first of these negative pressure ventilators to be of clinical value was that developed at Harvard University Medical School by Drinker, an engineer, in 1928.<sup>1</sup> He designed several modified versions of his tank ventilator or 'iron lung' and these were widely used during the poliomyelitis epidemics of the next 30 years. Tank ventilators were produced that could be constructed rapidly when needed and small enough for children.<sup>2</sup> Most of the early designs were telescopic in that the patient was pulled in and out of the main chamber of the tank on the mattress. In the later designs the upper part of the chamber was hinged towards the foot end and opened upwards (alligator type).

Simpler, non-tank negative pressure ventilators were first developed around the end of the nineteenth century. The most successful of these was Eisenmenger's biomotor, a cuirass designed in 1904.<sup>3</sup> This was superseded by various negative pressure shells or cuirasses introduced from 1930 to 1960. These were not as effective as the tank ventilators or the modern individually moulded cuirasses, but because of their simplicity they became widely used, particularly during recovery from acute poliomyelitis.

In the 1950s the jacket (wrap or poncho) design of negative pressure ventilator was produced,<sup>4</sup> in which the properties of rigidity and imperviousness to air were separated into two structures. The rigidity was provided by an inner framework of metal or plastic and this was covered by an airtight anorak like garment with seals around the neck, arms, and

usually the waist. The jacket, like the tank and cuirass, was connected to a pump, which generated a negative pressure between it and the patient's chest wall.

All these types of negative pressure ventilator were used both in hospital and at home to treat acute and chronic ventilatory failure. Ironically, as substantial improvements in their design were being made intermittent positive pressure ventilation using a trans-laryngeal endotracheal tube or a tracheostomy was shown to be more successful in the poliomyelitis epidemics, such as that in Copenhagen in 1952.<sup>5</sup> The superiority of intermittent positive pressure ventilation was probably due to better protection of the airway from aspiration. Negative pressure ventilators rapidly fell out of favour. In the last decade, however, negative pressure techniques have been used once again for various conditions, particularly neuromuscular and skeletal disorders, and have been shown to have a place, particularly for long term nocturnal ventilation in the home.<sup>6</sup>

### Tank ventilation

Most of the modern tank ventilators are constructed of aluminium, though some, such as the Portalung, are made of plastic and are therefore lighter. The patient's body rests on a mattress within the chamber and a head and neck rest is provided in most designs to ensure comfort and to prevent kinking and obstruction of the upper airway. Most designs have windows that allow some observation of the patient and portholes through which catheters and monitor leads can be passed. They also enable some physiotherapy to be carried out while the patient is in the chamber and procedures such as arterial blood gas sampling to be performed. In several of the models either the head or the feet can be raised and in the Kelleher design the whole tank can rotate through 180° so that postural drainage can be carried out without removing the patient from the ventilator.<sup>7</sup>

The older tank ventilators have a separate bellows pump with a large stroke volume. In some designs this is incorporated into the structure of the ventilator. Newer models have separate rotary pumps of sufficient capacity to evacuate the large volume of air from within the tank chamber.

Tank ventilators are effective, do not need to be constructed individually to fit each patient

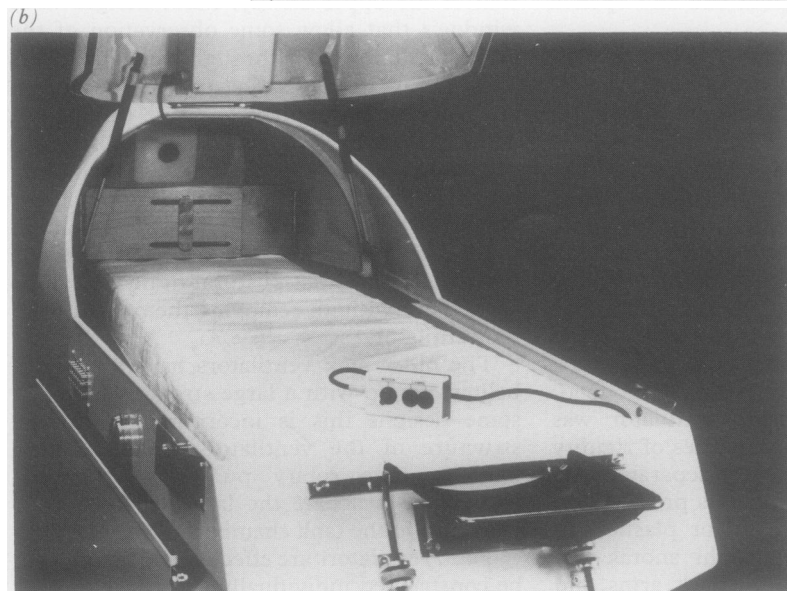
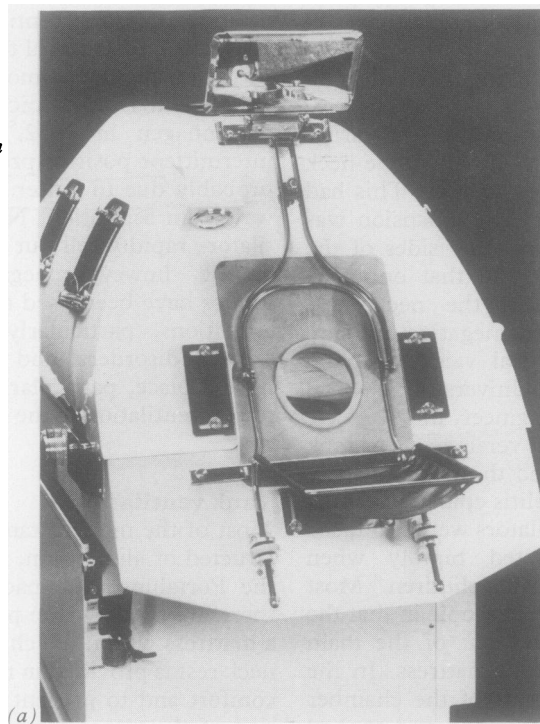
and require only one airtight seal, around the neck. These advantages are, however, balanced by the lack of access to the patient and their size, weight, and cost. In addition, they are available in few centres in the United Kingdom and considerable experience is required to settle an ill patient successfully in the ventilator. An airtight, comfortable neck seal may be difficult to achieve and patients often find it awkward to lie in one position on their back for long periods.

Tank ventilation, like other forms of negative pressure and nasal intermittent positive pressure ventilation, does not protect the airway. Aspiration of material from the pharynx into the trachea and bronchi may occur, but in practice this is uncommon except in neuromuscular disorders associated with abnormalities of the swallowing mechanism. Tank ventilators are capable of maintaining normal blood gas tensions even if there is little or no spontaneous respiratory effort. The

tidal volume is linearly related to the peak negative pressure within the chamber.<sup>8</sup> A pressure of around 30 cm H<sub>2</sub>O is usually required but up to 40 cm H<sub>2</sub>O may be necessary.

The models of tank ventilators that are used most frequently in the United Kingdom are those previously produced by Cape Warwick. There are several models, of which the "alligator" is the most common. A small number of Kelleher rotating ventilators survive and a simplified portable model was introduced in 1986 (fig 1). A few Both tank ventilators are also in use. These were first produced in 1938 and constructed of laminated wood. Most of them were modified in the 1950s but they are less satisfactory than the Cape ventilators. The most satisfactory ventilator of the newer, lighter, and more portable design is the Lifecare Portalung. This polycarbonate tank ventilator is available in three sizes. It is probably as effective as the traditional designs and the current cost is approximately £5000.

*Figure 1 Tank ventilator: (a) closed, showing collar and head rest; (b) open, showing mattress and patient control panel. (Reproduced by permission of Penlon Ltd.)*



### Jacket ventilation

The first effective jacket ventilator was the Tunncliffe jacket, developed in the 1950s.<sup>4</sup> It is still produced in two sizes, but even the larger is too small for many patients, particularly those with scoliosis. Several newer models have been marketed in which the inner framework is made of a metal or plastic grid (fig 2). Some of these designs also have a back plate and they are all enclosed in an airtight synthetic garment. This may cover the legs as well as the trunk but in most designs the garment finishes below the hips. The air within the jacket is intermittently evacuated by a pump similar to those used for cuirass ventilation (see below).

The jackets do not restrain the expansion of the rib cage or abdomen, but they are awkward for many patients to put on and often cold to wear because of air leaks. Pressure areas are not a problem but jackets are invariably larger and more cumbersome than cuirasses. They are preferable to tank ventilators for home use but less satisfactory for treating the more severely ill patients in hospital. The tidal volume that they develop at any given pressure is less than that of a tank ventilator and the peak pressure that patients can tolerate is also usually slightly less.

Several jacket designs are currently available, costing about £500 plus the cost of the negative pressure pump. The most commonly used are the Tunncliffe jacket, the Lifecare Pulmo-Wrap, and the Lifecare Nu-mo Garment.

### Cuirass ventilation

Many of the earlier designs of cuirasses were ineffective because they were a poor fit and badly designed. Standard sized models rarely fit individual patients well enough both to be comfortable and to provide an airtight seal around the chest wall. Attention to detail in

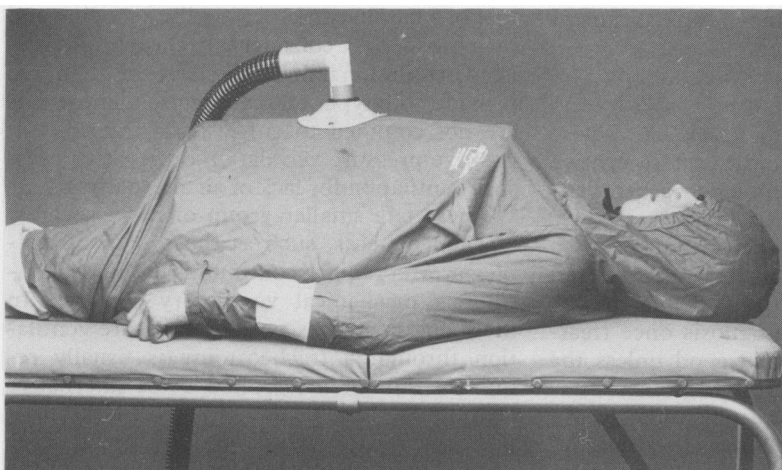


Figure 2 Jacket ventilator showing rigid internal framework surrounding thorax and abdomen, garment, and connecting tubing leading to negative pressure pump.

constructing the cuirass is important so that, for instance, the anterior abdominal wall is free to expand during inspiration and the movement of the lateral aspect and the upper chest is not restrained.

Standard sized designs of cuirass are still available but should seldom be used. Some suppliers will produce a cuirass from an individual patient's chest and abdominal dimensions, but these are rarely satisfactory.

It is usually best to construct the cuirass from a cast of the patient. This can be made of plaster of Paris, from which the cuirass is moulded.<sup>9</sup> The cuirass itself is constructed of light, airtight, synthetic material, such as vitrathene or fibreglass. The edges are padded and covered with airtight material such as neoprene (fig 3). A back strap may be needed to maintain an airtight seal between the cuirass and patient.

Cuirasses can be made to fit patients even if there is a severe thoracic deformity. The construction of individually moulded cuirasses is

analogous to the use of individually moulded nasal masks, which are widely used, particularly in Europe, for nasal intermittent positive pressure ventilation. The cost of the materials for a cuirass is less than £50.

Disadvantages of cuirass ventilation are that pressure areas may develop at the points of contact between the cuirass and the patient, and that if the patient grows or changes in weight a new cuirass may be needed. The patient has to sleep on his back or tilted slightly to one side and, particularly in patients with scoliosis, extra padding may be needed around the spine. Cuirasses are light and durable, and most patients can put them on without assistance.

The tidal volume achieved with a cuirass is linearly related to the peak negative pressure within it<sup>10</sup> and is considerably greater if the abdomen as well as the thorax is enclosed within the cuirass. Respiratory muscle activity is reduced<sup>11</sup> unless the patient is unable to coordinate with the pump.

Various negative pressure pumps are available in the United Kingdom and are suitable for jacket or cuirass ventilation. The Cape cuirass pumps are still in use but are no longer manufactured. The most suitable are the Newmarket pump and the Lifecare 170-C pump. The Newmarket pump is a rotary pump and able to compensate for variable air leaks between the cuirass and the patient so that any preset pressure within the cuirass can be maintained.<sup>12</sup> The standard form provides controlled ventilation but there is also a patient triggered model.

### Indications for negative pressure ventilation

#### ACUTE RESPIRATORY FAILURE

*Neuromuscular and skeletal disorders* Negative pressure ventilation may be invaluable in avoiding the need for endotracheal intubation during acute episodes of respiratory failure in these conditions.<sup>13</sup> Cuirass or jacket ventilation may be sufficient but many patients require treatment in a tank ventilator either continuously or at least overnight for a few days.

Any of the three types of negative pressure ventilator may be effective in weaning patients from translaryngeal positive pressure ventilation. Once a tracheostomy has been constructed, however, use of a cuirass is preferable to the other techniques as these may cause obstruction of the tracheostomy. After the acute episode has been effectively treated it is important to assess whether long term ventilatory support is needed and, if so, what form this should take.

*Chronic lung disorders* The place of negative pressure ventilation in acute infective exacerbations of chronic airflow obstruction has not been definitely established. There is some evidence that tank ventilation combined with energetic treatment of the underlying condition is effective and may avoid the need for endotracheal intubation.<sup>14</sup> Jacket and cuirass ventilators are much less effective in these circumstances. There have been no com-

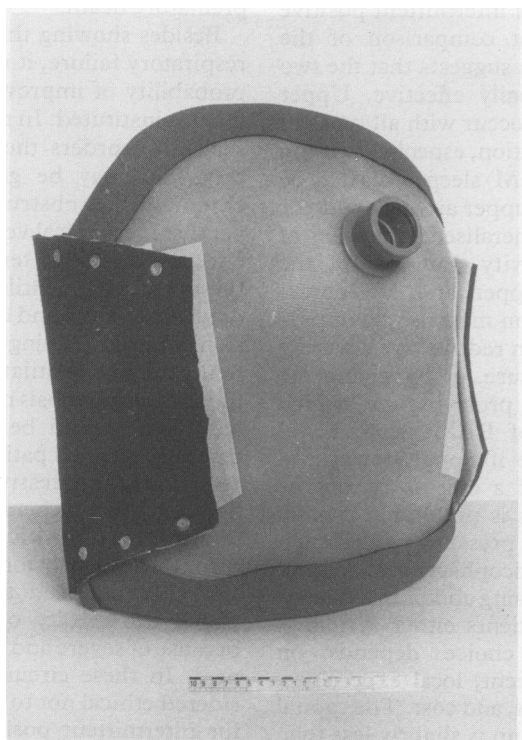


Figure 3 Cuirass constructed of vitrathene, with back strap attached and connector for tubing leading to negative pressure pump.

parative studies of the value of tank and nasal positive pressure ventilation.

#### CHRONIC RESPIRATORY FAILURE

*Neuromuscular and skeletal disorders* These disorders are the main indication for negative pressure ventilation. Tank and jacket ventilators are effective but in most cases their inconvenience outweighs this advantage and a cuirass is preferable for long term use. Arterial blood gas tensions improve both during the day and at night,<sup>10</sup> and the prognosis once treatment is instituted is usually good unless the underlying disease is progressive.<sup>15</sup>

*Chronic lung disease* Recent studies have indicated that respiratory muscle strength<sup>16</sup> and endurance<sup>17</sup> may be increased by regular negative pressure ventilation. The evidence, however, is conflicting and the clinical importance of the physiological improvements that have been found is still uncertain.<sup>18</sup> There are no studies of the effectiveness of this type of treatment in improving prognosis but, as with intermittent positive pressure ventilation,<sup>19</sup> the results would seem likely to be no better than long term oxygen treatment.

#### Negative or positive pressure ventilation?

Many patients requiring mechanical respiratory support in the home need this only during sleep. When they are awake their respiratory drive is sufficient to maintain more or less normal blood gas tensions. In more mildly affected patients mechanical assistance may be required only during acute illnesses or post-operatively. Some patients with severe ventilatory failure, however, require mechanical support for their breathing for part of the day as well as each night.

There have been no comparative studies of cuirass and nasal positive pressure ventilation in these groups of patients. Less experience has been obtained with nasal intermittent positive pressure ventilation but comparison of the results of reported series suggests that the two methods are about equally effective. Upper airway obstruction may occur with all types of negative pressure ventilation, especially during rapid eye movement (REM) sleep. This may be due to inhibition of the upper airway abductor muscles as part of a generalised inhibition of inspiratory muscle activity, but loss of the normal sequence of upper and lower respiratory muscle activation may also be important. Obstruction is often reduced by lowering the peak negative pressure, or by giving the tricyclic antidepressant protryptiline, which reduces the duration of REM sleep. Nasal ventilation is preferable if upper airway obstruction during use of a cuirass cannot be overcome, and a cuirass is preferable if nasal intermittent positive pressure ventilation forces air through the cricopharyngeal sphincter into the stomach, causing abdominal distension. In most other patients either system is satisfactory and the choice depends on acceptability to the patient, local experience, availability of equipment, and cost. The capital cost of a cuirass and pump is slightly less than

that of a nasal ventilator, and the servicing and maintenance are considerably cheaper. An assisted ventilation unit should have the facility to provide both types of treatment so that patients are not confined to either nasal intermittent positive pressure ventilation or negative pressure ventilation for lack of an alternative.

There is a smaller group of more severely affected patients, such as those with quadriplegia, who require continuous or almost continuous mechanical ventilatory support. In these circumstances positive pressure ventilation through a tracheostomy is usually required, though in selected cases alternative techniques, such as mouth intermittent positive pressure ventilation or phrenic nerve pacing,<sup>2</sup> may be of value for some or all of the time. Intermittent positive pressure ventilation through a tracheostomy with a cuffed endotracheal tube is also indicated if aspiration into the tracheobronchial tree is a problem owing to disordered swallowing, a poor cough, or both. Long term treatment in the home may be difficult to organise in these severely disabled and highly dependent patients.

#### Indications for long term domiciliary assisted ventilation

The decision to institute mechanical assistance to ventilation is an important one because this is usually a long term treatment. It is essential to establish that respiratory failure is present and that all conventional methods of treatment of the underlying cause have been tried. Unfortunately, there are no firm guidelines for judging whether respiratory failure is severe enough to require long term mechanical support. In general, however, this should be considered if respiratory failure has caused troublesome symptoms or potentially serious complications such as polycythaemia or pulmonary hypertension, or is likely to lead to these problems or to premature death.

Besides showing that the patient has severe respiratory failure, it is important to assess the probability of improving the outlook if treatment is instituted. In many neuromuscular and skeletal disorders the quality of life and the prognosis may be greatly improved but in chronic airflow obstruction there is no evidence yet that mechanical ventilatory support is more effective than long term oxygen treatment. In these patients ventilatory support does not prevent the slow and often inexorable progression of the underlying airway disease. The need to use a home ventilator reduces the quality of life and, as prognosis may not be improved, this treatment should be recommended only for carefully selected patients.

In some progressive neuromuscular disorders, such as Duchenne's muscular dystrophy, intermittent positive pressure ventilation through a tracheostomy may prolong life considerably but lead to a long period during which the quality of life is extremely poor because of severe and widespread muscle weakness. In these circumstances it may be considered ethical not to construct a tracheostomy for intermittent positive pressure ventilation

but to provide a negative or nasal intermittent positive pressure ventilation system, neither of which protects the airway.

### Funding and organisation of a home ventilator service

There are wide geographical differences in the use of domiciliary ventilatory support in the United Kingdom. These are due partly to variations in awareness of the value of treatment but also to the patchy availability of a home ventilator service.

The initiation of home ventilator treatment requires much more than simply providing suitable equipment and discharging the patient into the community.<sup>20</sup> A successful outcome requires explanation, education, and support for both the patient and the family or attendants. An understanding of the underlying cause of the respiratory failure and the equipment that has been provided, and what to do if problems arise, is needed. The choice of whether a negative or a positive pressure system is preferable often depends as much on the patient's personality and the degree of support in the home as on purely medical factors.

It is also essential that a rapid replacement service is available in case equipment fails. Within the supervising hospital there should be facilities and trained staff available continuously in case emergency readmission is needed.

At present there is no consistent pattern of NHS funding for domiciliary ventilatory support. Studies in the United Kingdom, France, and the United States have all shown that it is considerably cheaper than hospital care and just as safe.<sup>19</sup> The British government's proposals in the NHS and Community Care Act 1990 may rectify this once hospitals are reimbursed for the cost of treating individual patients. There is, however, the risk that the inevitable pressure to reduce costs will also reduce the standards of care and support, and limit the range of techniques available for treating this vulnerable group of patients.

### Appendix: Suppliers of negative pressure equipment

#### TANK VENTILATORS

*PortaLung*, available from Medicaid Ltd, Hook Lane, Pagham, Sussex PO21 3PP.

#### JACKETS

*Tunncliffe jacket*, available from Watco Services (Basing Instruments Ltd), PO Box 86, Basingstoke, Hants RG24 0GZ.

*Lifecare Pulmo-Wrap*, available from Medicaid Ltd, Hook Lane, Pagham, Sussex PO21 3PP.

*Lifecare Nu-mo Garment*, available from Medicaid Ltd, Hook Lane, Pagham, Sussex PO21 3PP.

#### CUIRASS

Should be individually constructed.

#### PUMPS

*Newmarket pump*, available from Si-Plan Electronics Research Ltd, Avenue Farm Industrial Estate, Birmingham Road, Stratford-on-Avon, Warwicks CV37 0HP (about £2500).

*Lifecare 170-C pump*, available from Medicaid Ltd, Hook Lane, Pagham, Sussex PO21 3PP (about £5000).

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