HIGH FREQUENCY POSITIVE PRESSURE VENTILATION (HFPPV) IN A NEWBORN INFANT WITH RUPTURED LUNGS

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SUMMARY

A 4.2-kg full-term male infant underwent treatment of acute respiratory distress as a result of gross bilateral pneumothoraces, pneumomediastinum and interstitial emphysema. When a trial of continuous positive airway pressure failed conventional intermittent positive pressure ventilation was instituted, but this also failed to achieve satisfactory ventilation at a respiratory frequency of 60 b.p.m. while producing peak airway pressures of 30 cmH₂O. High frequency positive pressure ventilation was instituted with a Siemens 900C ventilator delivering a minute volume of 3 litre min⁻¹ at a respiratory frequency of 72 b.p.m., while registering peak airway pressures in the range of 20–23 cmH₂O. During the first 30 min of this regimen the patient's condition improved such that FIO₂ was decreased to 0.6. Six hours later FIO₂ was decreased to 0.55 and the inspired minute volume to 2.8 litre min⁻¹ with a further decrease in peak airway pressure. The infant was maintained on high frequency positive pressure ventilation for a total of 42 h, and following weaning made an uneventful recovery. In another newborn infant, weight 1.9 kg, the measurement of airway pressure at the distal end of the tracheal tube and gas flow in the inspiratory limb of the respiratory circuit established that the tracheal peak airway pressure was 10 cm H₂O less that the pressure registered on the ventilator. The 900C ventilator produced a pattern of high frequency low pressure ventilation, with sustained PEEP, which closely resembles the defined pattern of HFPPV.

The frequency of pneumothorax in full-term infants, at birth, is generally thought to be 1–2% (Kempe, Silver and O'Brien, 1980) with a greater frequency in premature infants. In infants with hyaline membrane disease the frequency is considerably greater, and in infants whose ventilation is supported by continuous positive airway pressure (CPAP) (Gregory et al., 1971) it is reported to be between 3.5 and 20%, depending upon the severity of the disease and the intensity of respiratory assistance. A two-fold increase in this frequency is reported in infants whose ventilation is supported with conventional intermittent positive pressure ventilation (IPPV), with or without positive end-expiratory pressure (PEEP) (Berg et al., 1975; Hall and Rhodes, 1975; Ogato et al., 1976).

Pneumothorax, and particularly bilateral pneumothorax with widespread pneumomediastinum and interstitial emphysema, is associated with a significant increase in mortality rate, and has produced a three-fold increase in one series reported (Robertson and Tizard 1975). A variety of approaches to the prevention, and treatment, of this complication has been tried, and considerable attention has focused on the application of prolongation of the inspiratory time, and reversal of the inspiratory/expiratory ratio (Reynolds, 1974). The advent of high frequency positive pressure ventilation (HFPPV) (Heijman, Nilsson and Sjostrand, 1977) and the concept of ventilation with tidal volumes equivalent to, or slightly larger than, the dead-space volume, with correspondingly low peak and mean airway pressures, offers an alternative approach and, while the precise physiological mechanism of action of HFPPV is not clear (Kirby, 1980; Sjostrand, 1980), the principles governing the clinical application of the technique have been defined (Sjostrand, 1980). Its successful use in the treatment of infants with hyaline membrane disease has been described (Bland et al., 1980).

The technique has also been applied successfully to the management of ventilation in the adult with bronchopleural fistula (Carlon et al., 1980), but, paradoxically, does not appear to have been used for this condition in the newborn.

CASE REPORT

A 4.2-kg full-term male infant was admitted in severe respiratory distress at 03.00 h with a presumptive diagnosis of rupture of the trachea or bronchus. His delivery, at 7.30 p.m. the previous evening to a para III mother, had been "extremely difficult; the head was delivered with a Kieland Forceps and shoulder dystocia demanded extreme traction to deliver the shoulders". At birth the patient was noted to have surgical emphysema

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(which subsided when a tracheal tube was inserted) and weakness of the right upper limb. During transfer he was supported by manual ventilation with oxygen administered through the tracheal tube.

On examination the infant was severely cyanosed, with marked surgical emphysema over the chest, suprasternal notch and neck. Air entry to both lungs was very poor.

Chest x-ray (fig. 1) confirmed extensive bilateral pneumothoraces, pneumomediastinum and gross surgical emphysema. Following the insertion of chest drains attached to under-water seals to both pleural cavities, there was an improvement in air entry on both sides. Chest x-rays confirmed that the lungs were expanding, and the arterial blood-gas tensions improved.

It was noted that any attempt at instituting IPPV rapidly produced severe skin mottling and cyanosis, but the infant maintained a good colour while breathing spontaneously if \( F_{O_2} \) was maintained at 1.0. Therefore the infant’s ventilation was supported by establishing CPAP of 1–2 cm H\(_2\)O with \( F_{O_2} \) 1.0, by administering a gas flow of oxygen 3 litre min\(^{-1}\) through a T-piece system incorporating a pressure manometer (Vickers Ltd) and a water “blow-off” valve. The infant maintained a satisfactory colour for 3 h, at which time his arterial oxygen tension was 9.8 kPa, carbon dioxide 5.1 kPa and pH 7.24 unit.

Throughout the period of ventilatory support the infant received i.v. fluids, with dextrose, potassium and calcium supplements as indicated, and antibiotics i.v.

Over the following 5 h his colour remained good but the development of a tachycardia of 170–180 beat min\(^{-1}\), hypotension of 50/40 mmHg and arterial gas tensions of pH 7.2 unit, \( P_{CO_2} \) 10.2 kPa, \( P_{O_2} \) 4.4 kPa indicated that this regimen was failing and active intervention was required.

Bronchoscopic examination (Storz 3-mm Bronchoscope with 0° and 30° telescopes) yielded copious mucopurulent secretions and showed some excoriation of the trachea and right main bronchus, but revealed no fracture or tear of the trachea or bronchi. A 3-mm naso-tracheal tube was inserted and IPPV was instituted with a Siemens 900B ventilator with neuromuscular blockade and sedation provided by pancuronium bromide 0.5 mg i.v. hourly and morphine 0.5 mg i.v. 3-hourly respectively. In an effort to achieve satisfactory arterial gas tensions with a peak airway pressure of 20 cm H\(_2\)O (or less), the ventilator was set initially at its maximum cycling rate of 60 b.p.m. and the inspired minute volume was gradually increased from an initial setting of oxygen 1.5 litre. In the event, increasing the inspired minute volume to 1.7 litre min\(^{-1}\) incurred a peak airway pressure of 20 cm H\(_2\)O, which improved the arterial gas tensions (pH 7.28 unit, \( P_{CO_2} \) 7.5 kPa, and \( P_{O_2} \) 6.6 kPa), but there was no improvement in the hypotension or tachycardia. Attempts to improve the situation by further increases in inspired minute volume produced peak airway pressures of 30 cm H\(_2\)O, and it was evident that, with a respiratory frequency of 60 b.p.m., it would not be possible to achieve adequate ventilation without using excessive peak airway pressures and producing continuous bubbling of air through the under-water seals.

The infant was transferred to a Siemens 900C ventilator since it is capable of producing a respiratory frequency of 120 b.p.m. and provides analog and digital displays of peak airway pressure and expired minute volume, and digital displays of inspired tidal volume, expired tidal volume and \( F_{O_2} \).

This ventilator was cycled initially at a rate of 90 b.p.m. with an I:E ratio of 1/2 and an inspired minute volume of oxygen 2.4 litre min\(^{-1}\). The re-
spiratory frequency was gradually decreased and the
inspired minute volume gradually increased, in re-
sponse to a sequence of arterial gas measurements,
until after 30 min it could be established that, at a
respiratory frequency of 72 b.p.m. with an I:E ratio
of 1/2 and an inspired minute volume of 3 litre
min⁻¹, the peak airway pressure could be maintained
in the range 20–23 cm H₂O, and the arterial gas
tensions with $F_{O_2}$ 0.6, were: pH 7.33 unit, $PCO_2$
5.8 kPa, $PO_2$ 11.5 kPa. It was noted also that, with
this pattern of ventilation, PEEP of 2–3 cm H₂O
developed, which was sustained throughout the
period of HFPPV, and there was no further leakage
of air through the underwater seals. When the in-
fant’s condition had been stable for 6 h the inspirat-
ory minute volume was decreased to 2.8 litre min⁻¹
and $F_{O_2}$ to 0.55, which resulted in a peak airway
pressure of 20–21 cm H₂O and a further improve-
ment in arterial gas tensions (pH 7.41 unit, $PCO_2$
3.49, $PO_2$ 11.2 kPa).

With no further change in the ventilator settings
the infant progressed steadily over the next 12 h, by
which time his peak airway pressure had decreased
to 19–20 cm H₂O and he was maintaining an arterial
oxygen tension of 8.47 kPa and carbon dioxide ten-
sion of 4.37 kPa with $F_{O_2}$ 0.4. Twenty-four hours
later the ventilatory frequency was decreased to
50 b.p.m. and the inspired minute volume to 1.9
litre min⁻¹. Once the infant had maintained satisfac-
tory arterial oxygenation on this regimen for 4 h,
synchronous intermittent mandatory ventilation
was introduced at an initial rate of 25 b.p.m. which
was decreased to 10 b.p.m. over a 12-h period.
Throughout the phase of intermittent mandatory
ventilation the infant maintained a spontaneous re-
spiratory rate between 50 and 80 b.p.m. with a peak
airway pressure of 10 cm H₂O. After a further 6 h of
synchronous intermittent mandatory ventilation at a
frequency of 10 b.p.m. and 3 h of continuous posi-
tive airway pressure, the tracheal tube was removed
and the infant made an uninterrupted recovery (fig.
2).

DISCUSSION

The major consideration in the management of
this infant was the avoidance of excessive peak
airway pressures. It has been claimed that a peak
airway pressure of 25 cm H₂O is safe in infants with
hyaline membrane disease (Reynolds, 1974), but it
was felt that, in the presence of the severe damage
sustained by this infant, the peak airway pressure
should be maintained as near to 20 cm H₂O as possi-
bile. Equally, it was considered unwise to rely on the
reflex suppression of spontaneous respiratory
rhythm which may be produced by HFPPV in
certain circumstances (Sjostrand, 1980) and, to pro-
vide maximal compliance, muscle paralysis and se-
dation were provided by pancuronium and mor-
phine. Satisfactory arterial gas tensions were
achieved quickly with a minute volume of 3 litre
min⁻¹ at a respiratory frequency of 72 b.p.m. but at
the expense of using peak airway pressures of

Fig. 2. Chest x-ray of a 4.2-kg male infant after weaning from ventilatory support.
20–23 cm H₂O.

The respiratory frequency chosen, on the basis of the infant’s performance, is in accordance with the rates of ventilation, 60–110 b.p.m., recommended by others (Bland et al., 1980; Sjostrand, 1980) and within the range in which it is claimed that minimal interference with haemodynamic performance may be expected. The tidal volumes (VT) used are of interest. In the initial phase of HFPPV the inspired volume of 3 litre min⁻¹ delivered at a frequency of 72 b.p.m. yielded a tidal volume of 41.6 ml (9.9 ml kg⁻¹), which was decreased to 38.8 ml (9.2 ml kg⁻¹) when the minute volume was decreased to 2.8 litre min⁻¹ 6 h later. Thus, the tidal volumes used are in accordance with the observation that, while VT approaching the deadspace volume (VTₜₐₜ) may be used with high frequency jet ventilation, the VT required at frequencies of 60–100 b.p.m. with conventional systems is of the order usually recommended for IPPV in infants, 10–15 ml kg⁻¹ (Downes and Raphaely, 1975).

Attempts to identify the essential features which distinguish HFPPV from IPPV (Sjostrand, 1980) stress the low peak airway pressures and the positive intratracheal pressure generated throughout the respiration cycle during HFPPV, and emphasize the importance of rapid delivery of gas at the beginning of inspiration, which is claimed to be responsible, at least in part, for improved intrapulmonary gas distribution. It is held that, as a result of circuit compliance and gas compression volume, a similar performance cannot be achieved with conventional respiratory systems, and the conventional paediatric respiratory system supplied with the ventilator (internal diameter 10 mm, internal volume 180 ml) and the large volume humidifier (Bennett, Cascade, internal volume approx. 500 ml), which were used throughout the infant’s treatment, would not usually be described as a low compliance system.

An opportunity to assess these aspects of the system and to clarify the pattern of ventilation established by the 900C ventilator presented when a 1.9-kg infant, who developed respiratory distress 2 weeks after surgical repair of atresia of the oesophagus, required ventilatory support. It was, surprisingly, quickly apparent that in this particular infant the air leak around a 3-mm endotracheal tube was of a magnitude which precluded adequate ventilation. Therefore a 3.5-mm nasotracheal tube was inserted, and using the same respiratory system, the ventilator was cycled to deliver 2.59 litre min⁻¹ at a respiratory frequency of 72 b.p.m. with an I:E ratio of 1/2 (a regime of ventilation which was quickly accepted by the infant without myoneural blockade). A microtransducer (Gould Statham), connected to a pressure module in a Siemens Sirecust 404 monitor, was attached to a 3.5-ch infant feeding tube (Eschmann Ltd) which was inserted through the paediatric swivel mount to the distal end of the tracheal tube (fig. 3).

![Fig. 3. 3.5-ch infant feeding tube, for pressure measurement, inserted through paediatric swivel mount and 3-mm tracheal tube connector.](image)

The resulting tracing of the airway pressure, displayed on the oscilloscope of the monitor in analog and digital forms, was recorded on the linked Siemens 400 pen writer (fig. 4).

It was apparent that the peak airway pressures produced, at the distal end of the tracheal tube, were of the order of 5–6 mm Hg (6.7–8 cm H₂O) with a sustained PEEP of 1 mm Hg (1.34 cm H₂O), which, as no PEEP had been added, was generated by the pattern of ventilation.

To assess the accuracy of these findings a heated Fleisch flow head, inserted into the inspiratory limb of the system 50 cm from the tracheal tube, was...
attached to a pneumotachograph (Mercury VPS), the pressure transducer of which was attached to the swivel mount at the proximal end of the tracheal tube; and the pressure and flow measurement were recorded on an ink-jet writer (Siemens Mingograf 803) at paper speeds of 25 mm s\(^{-1}\) (fig. 5) and 100 mm s\(^{-1}\) (fig. 6). The peak airway pressures produced in the swivel mount at the proximal end of the tracheal tube (with no probe in the tube) were consistently of the order of 8–8.5 cm H\(_2\)O, with a sustained PEEP of 2 cm H\(_2\)O.

In repeated measurements, throughout the period of HFPPV, the endotracheal probe recorded consistently peak airway pressures of 5–7 mm Hg (6.7–9.38 cm H\(_2\)O), while pressures of 18–20 cm H\(_2\)O registered on the ventilator. Despite the size of the probe (external diameter approx. 1 mm) and expectations to the contrary, there was no difficulty in maintaining adequate ventilation and, as the pressure traces in figures 4 and 5 show, no interference with the pattern of ventilation.

It is of particular interest that the patterns of airway pressure, in figures 4 and 5, were produced by the airflow pattern in figure 6; and, while the record shows that VT was delivered in approximate-ly 270 ms (and 4/5 of VT in 200 ms, the peak flow recorded, 18 litre min\(^{-1}\), was well short of the peak flows (175–200 litre min\(^{-1}\)) which, it is claimed, are necessary to produce HFPPV (Sjostrand, 1980).

Nonetheless, it is apparent that a pattern of ventilation which closely mimics the described pattern of HFPPV—high frequency, with low peak airway pressure and sustained PEEP—is established when the Siemens 900C ventilator, with the conventional paediatric system and a large volume humidifier, is cycled at a respiratory frequency of 72 b.p.m. in newborn infants. Equally, from the striking improvement in the condition of the infant with ruptured lungs during the first 30 min of this regimen (his arterial PC\(_{\text{O}_2}\) decreased from 8.13 to 3.49 kPa, and arterial PO\(_2\) increased from 6.01 to 11.24 kPa, while FIO\(_2\) was reduced from 1 to 0.6) it is evident that the technique is extremely efficient. The sustained PEEP generated by the technique was seen to be of particular value because, as the tracheal pressure measurements demonstrated, the addition of PEEP by conventional means invariably produced a commensurate increase in peak airway pressure.

REFERENCES


Un nouveau-né à terme, de sexe masculin, pesant 4,2 kg, dut être traité pour une détresse respiratoire aiguë pour pneumopathie bilatérale et emphysème interstitiel. Lorsqu'une tentative de pression continue cuta échoue, une ventilation conventionnelle en pression positive intermit- tente fut mise en route mais elle ne permit pas davantage d'ob- tenir une ventilation satisfaisante à une fréquence respiratoire de 60 min⁻¹, tout en provoquant des pics de pression dans les voies aériennes de 30 cm H₂O. Une ventilation en pression positive à haute fréquence fut alors instaurée grâce à un respirateur Siemens 900C apportant un débit de 3 litre min⁻¹ à une fréquence respiratoire de 72 min⁻¹, avec des pics de pression dans les voies aériennes, de l'ordre de 20–23 cm H₂O. Pendant les premières 30 min de ce mode de ventilation, l'état du patient s'améliora tant que la F₁O₂ put être abaissée à 0,6; 6h après, la F₁O₂ put être abaissée à 0,5 et le débit d'inspiration à 2,8 litre min⁻¹, ce qui provoqua une nouvelle diminution de la pression de crête. Le nouveau-né fut maintenu en VPPHF pendant 42 h au total et après sevrage présenta une guérison sans incident. Chez un autre nouveau-né de 1,9 kg, la mesure des pressions dans les voies aériennes, à l'extré- mite distale de la sonde trachéale, et celle du débit de gaz dans la branche inspiratoire du circuit de ventilation ont montré que la pression de crête dans la trachée était inférieure de 10 cm H₂O aux pressions enregistrées par le respirateur. Le respirateur 900C fournit un mode de ventilation à basse pression et fréquence élevée, en pression positive continue, qui ressemble de très près au mode défini comme VPPHF.