

Volume delivery during high frequency oscillation

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Abstract

Aim—To examine the delivered volume during “high volume strategy” high frequency oscillation, used as rescue treatment in preterm infants; and to identify factors, other than frequency and oscillatory amplitude, influencing the magnitude of volume delivery.

Method—Twenty infants (median gestational age 29 weeks) were studied on 45 occasions. Two oscillator types were used (SensorMedics and SLE). Delivered volume was measured under clinical conditions with the arterial blood gases within a predetermined range. A specially calibrated pneumotachograph system was used.

Results—Overall, the median delivered volume was 2.4 ml/kg (range 1.0 to 3.6 ml/kg); on 32 occasions the delivered volume was greater than 2.0 ml/kg and on seven greater than 3.0 ml/kg. The delivered volume related significantly to disease severity; there was an inverse correlation between delivered volume and both the oxygenation index (OI) ($r=-0.51$) and $AaDO_2$ ($r=-0.54$).

Conclusion—Delivered volume during HFO may, in certain infants, exceed the anatomical dead space, permitting some direct alveolar ventilation.

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Keywords: high frequency oscillation; prematurity; delivered volume

Gas exchange is maintained during high frequency oscillation (HFO), yet it has been claimed that the delivered volume is small.^{1 2} Although in an animal model delivered volumes of about 2–3 ml/kg have been recorded,³ in another study⁴ the volumes were as low as 10% of the anatomical dead space. This would mean that during HFO mechanisms of gas exchange, other than those occurring during normal tidal breathing, must take place.⁵ It is, however, difficult to measure volume delivery accurately at fast frequencies. We have already shown that recording devices with apparently adequate frequencies of response do not behave linearly as the rate is raised above 5 Hz.⁶ Fortunately, we have been able to construct a reproducible calibration curve, such that it was possible to use a simple pneumotachograph system to measure reliably the delivered volume during HFO. Results from a pilot study⁶ suggested that the delivered volume during HFO could, in certain infants, be as high as 3 ml/kg. The aim of this study was to determine the magnitude of delivered volume during HFO in preterm infants and whether

this was influenced by factors other than frequency and oscillatory amplitude.

Methods

Twenty infants were studied, their median gestational age was 29 weeks (range 24–37), birthweight 1090 g (range 570–2694), and postnatal age when first studied was 2 days (range 1–16). All the infants had respiratory distress syndrome and had received a median of two doses of exogenous surfactant (range 1–3). Six infants were studied on more than one occasion (median 5, range 2–11). None of the infants was paralysed at the time of study. Their median MAP was 12 cm H₂O (range 8–25) and oscillatory amplitude 28 cm H₂O (range 16–65). Their median oxygenation index (OI) (inspired oxygen concentration [%] × MAP (cm H₂O)/paO₂ (mm Hg)) was 8 (range 3–21) and their $AaDO_2$ (FIO₂ × (barometric – water pressure) – paO₂ – paCO₂ (all pressures in mm Hg)) was 201 (range 51–633).

The study was approved by King’s Healthcare Trust’s Research Ethics Committee.

Estimates were made of the volumes of gas delivered to the lungs during HFO. Infants were receiving HFO as rescue treatment—that is, the clinician in charge felt the blood gases to be poorly responsive to conventional treatment. Some infants were measured on more than one occasion, depending on their clinical condition and the availability of the research staff, but always at intervals of at least 24 hours. In all cases, a high volume HFO strategy was pursued—that is, the mean airway pressure (MAP) was increased to optimise oxygenation and facilitate a reduction in the inspired oxygen concentration to a target of 30%. A frequency of 10 Hz was used throughout and the oscillatory amplitude increased until visible chest wall movement was observed. All the infants had indwelling arterial access and subsequent changes in oscillatory settings were made to ensure their blood gases were kept in the range paO₂ 50–100 mm Hg and paCO₂ 25–50 mm Hg (the lower levels of paCO₂ being used only in infants with severe pulmonary hypertension). Two oscillator types, the SensorMedics and the SLE 2000, were used according to their availability. A fractional inspiratory time of 0.3 was used with the SensorMedics.

A pneumotachograph (Mercury F10L) was inserted between the infant’s endotracheal tube and ventilator circuit. This was attached to a Validyne pressure transducer (± 2 cm H₂O). The flow signal was electronically integrated to volume (Gould Integrator 13-4615-70). The flow and volume signals were recorded simultaneously on a Gould polygraph (2800S). Only recordings made when the infant was apnoeic

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Table 1 Comparison of the infants' demographics, oscillatory settings and delivered volume according to oscillator type, data are median (range)

	SensorMedics (n=28)	SLE (n=17)
Gestational age (weeks)	29 (24–33)	31 (27–37)
MAP (cmH ₂ O)	12 (10–25)	11 (8–17)
Oscillatory amplitude (cmH ₂ O)	24 (16–39)	33 (20–65)
OI	9.5 (3–21)	7 (4–15)
PaCO ₂ (mm Hg)	39 (27–50)	45 (27–37)
PaO ₂ (mm Hg)	61 (50–99)	63 (53–89)
Delivered volume (ml/kg)	2.2 (1.3–3.1)	2.6 (1.0–3.6)

were used for the calculation of delivered volume. The volume waveform of the SensorMedics, unlike that of the SLE 2000,⁷ is not truly sinusoidal and the inspiratory fraction was limited to 0.3 of the cycle. Thus the frequency content of the two phases of ventilation differed, the uncorrected inspiratory volume being less than the expiratory volume. To compensate for this, for all traces, the mean value of the inspiratory and expiratory volume was determined. This value was then converted to the actual volume delivered using the previously published calibration curve.⁶ The calibration curve was devised by connecting the variable volume/variable speed sine wave pump and the pneumotachograph system to a dummy lung consisting of a 50 cm length of tube that was attached to the end of a 3 mm endotracheal tube. The endotracheal tube was sealed through a cork that was inserted into the neck of a 5 litre bottle, so that the tubing lay within the body of the bottle. A Validyne pressure transducer (± 2 cm H₂O) was connected to the bottle by a second 2 mm (internal diameter) tube which also passed through the cork; this measured the pressure changes within the bottle which thus functioned as a reverse plethysmograph. The frequency response of this system is flat to within 5% from 2 to 30 Hz. The pressure transducer was calibrated by inserting and withdrawing 10 ml volumes from the bottle, via the pneumotachograph, at about 2 Hz using a syringe and measuring the deflection produced by the pressure transducer and the pneumotachograph. The syringe was then replaced by the sine wave pump set at 4 ml delivery and recording of pneumotachograph flow and volume obtained at 2 Hz intervals from 2 to 30 Hz. This produced a bell shaped calibration curve with maximum augmentation at 12 Hz and subsequent damping. To assess whether it was valid to use the mean of the inspiratory and expiratory volume trace and the mean oscillatory frequency when inspiration only took 30% of the cycle time, the sine wave pump was then replaced by the SensorMedics oscillator set at 10 Hz and 30% inspiratory time. The tidal exchange measured over 10 oscillations by the pressure transducer was 3.54 ml, the pneumotachograph tidal volume after correcting against the calibration curve was 3.56 ml. The equivalent results at 50% inspiratory time were 5.23 ml and 5.61 ml, respectively. For the studies on the infants, the mean volume delivered in one cycle was calculated using the calibration curve and related to body weight.

Differences were assessed for significance using the Mann Whitney U test and the

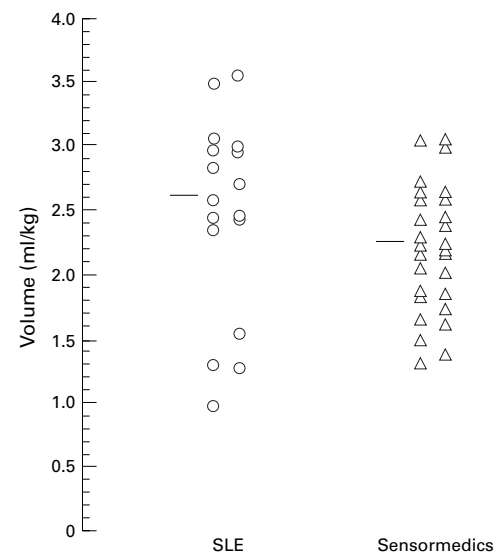


Figure 1 Delivered volume (individual data shown).

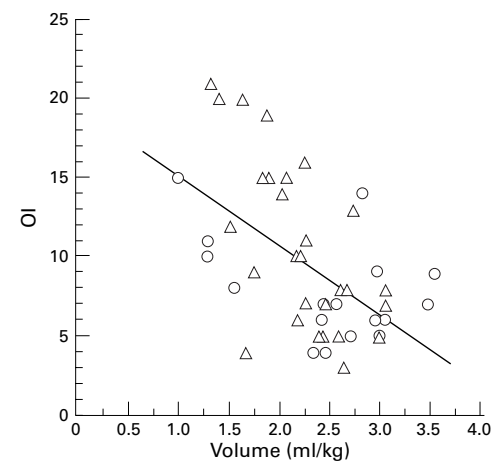


Figure 2 Correlation between delivered volume and OI. Individual data and the regression line are shown.

strength of relations determined by calculating Spearman's correlation coefficients.

Results

The median delivered volume was 2.4 ml/kg (range 1.0 to 3.6). On 32 occasions the delivered volume was greater than 2 ml/kg and on seven greater than 3 ml/kg. The median delivered volume of the infants, whose paCO₂ was within the narrower range of 35 to 50 mmHg, was 2.4 ml/kg (range 1.3–3.5). There was no significant difference in the median volume delivered by the two oscillator types (fig 1) although the oscillatory amplitude was higher ($p < 0.05$) with the SLE (table 1). There was, however, a significant inverse correlation between the delivered volume and both the OI ($r = -0.51$, $p < 0.01$) (fig 2) and the AaDO₂ ($r = -0.54$, $p < 0.01$).

Discussion

It has been suggested that the delivered volume during HFO is between 10 and 100% of the anatomical dead space,⁴ but this study has shown that the median delivered volume was 2.4 ml/kg. The expected anatomical dead space

had been thought to be about 2.2 ml/kg.⁸ A recent study, however, highlighted that the extrathoracic dead space is larger in infants and children because of their relatively large heads. Using a water displacement technique, extrathoracic dead space decreased exponentially with increasing age, and in early infancy the total anatomical dead space was about 3 ml/kg.⁹ In the presence of an endotracheal tube this dead space will be reduced as the nasopharynx is bypassed. Those data⁹ mean that certain infants we studied had a delivered volume greater than the anatomical dead space and in most (fig 1) it was greater than 50% of the dead space. These results have important implications for gas transport mechanisms during HFO as they suggest that a greater number of alveoli are ventilated directly than has been assumed.⁴ Results in a simple physical model suggested that if during HFO the tidal volume related to ventilatory dead space is in the range 0.8–1.2 convective bulk flow causing direct alveolar ventilation is of considerable importance.¹⁰

We measured the delivered volume using a pneumotachograph system, as has been done in other studies.^{11–13} The accuracy of such a system has been compared with simultaneous measurements by plethysmography.³ A good correlation ($r=0.92$) was found and, with a mean delivered volume of about 15 ml, 88% of the differences between the results of the two measurement techniques were within 2 ml of one another when analysed according to the method of Bland and Altman.¹⁴ That correlation¹⁵ required that the system had a suitable frequency of response and was carefully calibrated; those criteria were fulfilled by the device we used⁶ and further validated in this study.

Delivered volume can be affected by frequency. This is due to changes in volume when oscillating at or near the resonant frequency of the respiratory system.¹⁵ The performance of certain oscillators, including the two we used, is affected by frequency.⁷ The delivered volume decreases above 10 Hz,⁷ so we chose to manage our infants only at that frequency. The volume delivery of the SLE is lower⁷ than that of the SensorMedics at similar oscillatory settings, and this may explain the higher oscillatory amplitude used among infants supported by the SLE to achieve similar $paCO_2$ levels (table 1).

The delivered volume correlated significantly with disease severity, as indicated by an inverse relation with both the OI and $AaDO_2$. The infants with severe lung disease would be expected to have the stiffest lungs, limiting volume delivery.

Despite using two oscillator types, infants were usually oscillated at a delivered volume of 2 to 3 ml/kg. We studied infants under clinical conditions and their oscillatory settings were adjusted to maintain their blood gases in a predetermined range. It is, therefore, not surprising that the delivered volume was relatively similar between infants. Certain oscillators

incorporate a digital output of volume delivery. Our results provide guidance as to what settings are likely to achieve acceptable $paCO_2$ concentrations and would probably do this more reliably than simply basing such decisions on visual assessment of the degree of “chest wall bouncing.”

It has been argued that one mechanism by which HFO reduces the incidence of CLD is by avoiding large volume changes within the conducting airways.¹⁶ Thus volumes of 2 ml/kg, approaching 50% of that used during conventional ventilation,¹⁷ might put the infants at risk of lung damage. In the clinical situation, however, ventilator settings are manipulated to keep $paCO_2$ concentrations within predetermined ranges. During HFO, carbon dioxide concentrations are controlled by the oscillatory amplitude, and to a much lesser extent, frequency.¹¹ We used the minimum oscillatory amplitude associated with an acceptable $paCO_2$ and therefore our results represent those of routine clinical practice. Under such circumstances we conclude that the delivered volume is usually greater than 50% and, in certain infants, larger than 100% of the anatomical dead space.

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