MEASUREMENT OF ENTRAINMENT RATIO DURING HIGH FREQUENCY JET VENTILATION

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SUMMARY

We have measured tidal (VT), entrained (Ve) and "blowback" (Vbb) volumes during high frequency jet ventilation (HFJV) through a Mallinckrodt Hi-Lo Jet tracheal tube in anaesthetized patients. The above volumes were calculated by digital integration of the appropriate regions of flow curves derived from a pneumotachograph placed between the bias flow tubing and the tracheal tube. At a driving pressure of 1 bar, lung minute ventilation increased with increasing ventilatory frequency, whilst tidal volumes decreased. The contribution of entrainment to tidal volume (Ve/VT) remained constant, although the volumes entrained were relatively small and varied widely from subject to subject. Blowback volumes were considerable, especially at ventilatory frequencies used clinically (1–2 Hz). We conclude that it is not possible to entrain predictable concentrations of volatile agents from the low pressure bias flow during HFJV.

KEY WORDS
Lung: high frequency jet ventilation.

The clinical use of high frequency jet ventilation (HFJV) in anaesthesia is limited by inability to introduce volatile agents into the high pressure system. However, it is known that a significant proportion of lung ventilation arises from entrainment of gas [1]. Ability to quantify the extent of entrainment raises the possibility of anaesthetizing patients predictably by introduction of volatile agents into the low pressure bias flow.

Lung ventilation during HFJV is a complex function and depends on the volume of gas delivered with each jet pulse (Vjet), the volume of gas entrained (Ve) and the volume of gas blown back (Vbb) into the bias flow. Previously, measurement of these gas volumes required complex techniques such as box plethysmography [2] or external spirometry [3], or failed to recognize the existence of blowback [4, 5] (i.e. the escape of a volume of jet gas from the tracheal tube into the bias flow during late inspiration, without entering the lungs). Although these volumes have been measured successfully in vitro using a lung model [6], there are currently no satisfactory published studies in human subjects.

In previous experimental studies from this department, simple differential pressure measurements from within the tracheal tube were used to produce gas flow curves [7]. This system has been modified by the measurement of flow between the bias flow tubing and the tracheal tube, using a pneumotachograph. This enabled the measurement of tidal, entrained and blowback volumes by partial integration of the flow curves. With this system, we have studied the variation of the contribution of entrainment to tidal volume (termed entrainment ratio) in patients with alteration of ventilatory frequency and inspiration:expiration time ratios.

PATIENTS AND METHODS

Patients
We studied 12 patients (age 40–97 yr, ASA II–III) undergoing surgery for fractured neck of femur. The study was approved by the District Ethics Committee and all patients gave informed consent. Anaesthesia was induced with fentanyl 0.1 mg and propofol 1.0 mg kg⁻¹ and, following the administration of vecuronium 0.08 mg kg⁻¹, the trachea was intubated using a Mallinckrodt...
Hi-Lo Jet tube. Anaesthesia was maintained with an i.v. infusion of propofol according to the dose regimen described by Roberts and colleagues [8]. All patients were monitored with continuous ECG and pulse oximetry recordings, and by non-invasive measurement of systemic arterial pressure.

Experimental apparatus (fig. 1)

HFJV was applied using a Penlon Bromsgrove jet ventilator [9] and a bias flow, both supplying an $F_{1O_2}$ of 1.0. The bias flow was delivered from a conventional Bain system, the distal end of which was attached to a Fleisch No. 3 pneumotachograph head (Gould, Bilthoven) connected to a capacitive differential pressure transducer. The linear range of the flow transducer was 0-160 litre min$^{-1}$, and the apparatus had a frequency response flat to 16 Hz (−3 dB at 32 Hz, 95% step response time 0.015 s). The pressure relief valve of the Bain system was opened fully and the bias flow adjusted so that the reservoir bag remained semi-inflated at all times. This ensured that the bias circuit remained at atmospheric pressure. Bias flows were typically 1 litre min$^{-1}$. Rebreathing was not found to be a problem, presumably because most of the respiratory gas was injected directly into the tracheal tube. The attachment of the pneumotachograph head to the tracheal tube was made via a conical rubber adaptor, in order to produce a smooth velocity profile at the pneumotachograph screen. Failure to do this might have resulted in a higher gas velocity (and hence pressure decrease) at the centre of the screen, which would not be detected by the piezometer rings, as these sense pressure changes across the screen at its periphery. Any tendency for this to occur was compensated for by carrying out the calibration procedure (see below) with the tracheal tube connected.

Data were collected from the flow transducer using a Gould 1604 digital storage oscilloscope. Gas volumes were obtained by partial digital integration of the flow signal (Gould waveform processor 160).

The pneumotachograph was calibrated directly for volume by injecting air from a gas syringe (Hans Rudolph Super 1.5 litre) and capturing the flow waveform using the digital oscilloscope. Volumes of 50–800 ml were injected manually in both directions through the tracheal tube and pneumotachograph assembly, and the flow waveform was integrated. The integrated volume, expressed in mV·s, was plotted against injected volume to yield a linear regression line ($r = 0.99$, $P < 0.0001$). The volumes injected varied between 162 ml and 1400 ml. Three of these samples were injected at the highest rate obtainable with the gas syringe, the remainder being injected over a 2-s period. When all the points were analysed, the standard deviation of the residuals from the regression line was 27.32 ml. With the three high flow points removed, the standard deviation of the residuals was 2.02 ml.

Experimental procedure

Each patient's lungs were ventilated at 0.8, 1.0, 1.2, 1.5, 2.0 and 2.5 Hz, and $I:T$ ratios (ratio of inspiratory:total time) of 0.1, 0.3 and 0.5, in random order (a total of 18 measurements in each patient). The driving pressure of the jet gas was maintained at 1 bar (100 kPa). Each set of jet
parameters was maintained only long enough to obtain the physical measurements required, the ventilator then being re-set to a frequency and I:T ratio setting found to maintain good gas exchange ($f = 1.5$ Hz, $I:T = 0.3$). Pulse oximetry was observed at all times, and no clinically significant desaturations were noted.

For each frequency and I:T setting, the digital oscilloscope was set to capture eight or 16 cycles, depending on the degree of cardiac impulse artefact present, and an averaged waveform produced. This eliminated the superimposed flow waveform produced by cardiac impulses. The averaged waveform was divided digitally into three regions, which were integrated separately, as described below.

**Measurement of gas volumes**

Typical flow and airway pressure traces recorded by the oscilloscope are shown in figure 2. When the jet pulse begins, some of the gas passing through the bias flow tubing is entrained into the tracheal tube by momentum exchange. The inward flow of gas recorded by the pneumotachograph has been defined as a positive deflection. As airway pressure increases, further entrainment is opposed, and flow through the pneumotachograph ceases. The integral of the flow signal between the start of inspiration and the crossing of the zero flow line provides a measure of the gas entrained ($V_e$).

During the remainder of inspiration, some of the jet gas is blown back directly into the bias flow without entering the lungs. Area $V_{bb}$ represents the integral of the measured flow from the point where entrainment ceases to the end of the jet pulse, indicated by the peak in airway pressure and a rapid change in the slope of the flow curve. Finally, area $V_T$ is the outward passive flow during expiration, corresponding to tidal volume. The volume delivered by the jet may be calculated as follows:

$$V_{jet} = V_T + V_{bb} - V_e$$

**RESULTS**

**Lung minute ventilation**

Increases in the ventilation frequency from 0.8 to 2.5 Hz at constant I:T ratio induced an increase in minute ventilation, although this effect was smaller at small I:T ratios (fig. 3). Because the mean flow from the jet ventilator is the product of inspiratory flow and the I:T ratio, irrespective of frequency (Manufacturer's test data), this increase in minute ventilation must have resulted from either an increase in entrainment volume or a decrease in blowback volume.

Increasing the I:T ratio caused an increase in minute ventilation at any given frequency (fig. 3), although the volumes measured were less than predicted. For example, a change in I:T ratio from 0.1 to 0.3 represented an increase of 300% in inspiratory time fraction, whilst, at 2.5 Hz,
recorded mean minute ventilation increased by only 197 (SEM 2.4) %.

Calculated tidal volumes at different ventilatory frequencies and I:T ratios are shown in table I. As expected, tidal volume decreased with increasing frequency and increased with increasing I:T ratio.

**Entrainment volume**

The entrained minute ventilation increased with frequency at I:T ratios of 0.3 and 0.1 (fig. 4). However, a prolongation of fractional inspiratory time, by increasing I:T from 0.3 to 0.5 allowed "auto-PEEP" to develop, and restricted considerably the amount of gas entrained.

The calculated entrained volumes per insufflation (table II) were small and decreased with increasing I:T and ventilation frequency.

The contribution of entrainment to tidal volume was small, with a peak of approximately 20% at low I:T, and it decreased to negligible amounts...
as 1:1 and frequency increased (fig. 5). These conditions would be expected to increase airway pressure and so reduce the volume entrained.

**Blowback volume**

The volume of the jet pulse blown back into the bias flow decreased as ventilation frequency increased and was always minimal at low 1:1 ratios (table III). Measured as a proportion of the volume delivered by the jet pulse (Vbb/Vjet), the loss was large (30–40%) at low frequencies with relatively long inspiratory times (fig. 6).
Generally, values for $V_e$, $V_{bb}$ and $V_T$ varied widely from subject to subject.

**DISCUSSION**

The method described here enables the gas volumes involved in HFJV to be measured in a clinical setting without the use of complex apparatus. This technique is similar to, but has some technical advantages over, the method developed independently by Young and Sykes, which has been applied in a lung model [6] and dogs [10]. In the present method, none of the background bias flow passes through the pneumotachograph, and so the only sources of error in the flow signal zero are amplifier and transducer drift. The method of Young and Sykes allows the whole of the bias flow to pass through the pneumotachograph, and so the “zero” output is susceptible to changes in the residual bias flow. As the separate ventilatory volumes are obtained by integration, it is important that zero values are maintained accurately.

In this paper the term “blowback” has been used in place of the word “spill” used by Young and Sykes, as it is felt that the former emphasizes the fact that this is an active phenomenon, occurring during the jet pulse.

Before examining the results obtained with this technique, it is necessary to examine the accuracy of the measurements. This study requires the pneumotachograph to operate at frequencies greater than the normal ventilatory frequency. The Fleisch head and pressure transducer combination used had a frequency response flat to 16 Hz. As the maximum ventilation frequency used was 2.5 Hz, and examination of the Fourier power spectra of jet drive pressure signals reveals negligible power at frequencies above the fourth harmonic [unpublished observations], the degree of error induced by the frequency response characteristics of the pneumotachograph should be minimal. The peak gas flows obtained in this technique (during passive expiration) were less than during normal tidal breathing, for which the transducer was designed, and so the measurements may be expected to fall within the linear range (0–160 litre min$^{-1}$).

We found that minute ventilation increased with frequency, despite a constant delivered volume from the ventilator. Consequently, the jet minute volume is not a useful guide in assessing the minute ventilation of the patient, as this does not take into account entrained and blowback volumes.

Entrainment is considered usually to be an important component of tidal volume. However, our results indicate that entrainment is quantitatively less important than has been suggested, at least with the commonly used insufflation system described. Entrainment ratio was optimal at an $I:T$ of 0.1, any increase in percentage inspiratory time allowing a degree of “auto-PEEP” to develop and reducing the entrained volume to insignificant amounts.

The fraction of the inspired volume provided by entrainment remained relatively constant with frequency. Because the entrainment ratio was always low (usually 0.2 or less), and showed a wide inter-subject variation, it does not seem feasible to introduce volatile agents into the bias flow and produce predictable inspired concentrations. Minor changes in pulmonary mechanics (e.g. reduction in compliance, increase in airway resistance) may reduce or eliminate any contribution of entrainment. Similar conclusions were reached by Young and Sykes in studies using a model lung [6].

Blowback is a phenomenon occurring during the late part of the inspiratory period and is related to the interaction of the airway pressure and insufflation pressure of the body of gas accelerated by the entry of the jet. When the airway pressure exceeds the insufflation pressure, blowback occurs. Our study indicated that the loss of jet volume was substantial (30–40 %) and influenced the tidal and minute volumes during HFJV. As the blowback volume was relatively large at lower frequencies, especially with increased $I:T$, this may be important in clinical practice, where the frequencies used most often are 1–2 Hz. The study by Tamsma and Spoelstra [11], using a canine model, supports this suggestion.

There was a wide variation in tidal, entrainment and blowback volumes between subjects under any given conditions, suggesting that the partitioning of the volume of gas delivered with each jet pulse ($V_{jet}$) into blowback volume ($V_{bb}$) and tidal volume ($V_T$) must be dependent on individual variations in airway and thoracic mechanics. It would be expected that subjects with a low thoracic compliance would reach the critical airway pressure, above which blowback occurs, at lower lung volumes than those achieved in normal subjects, thereby reducing tidal volume and
increasing blowback volume. Thus the high frequency jet ventilator may act in a manner analogous to a pressure-cycled conventional ventilator under the conditions described.

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REFERENCES