High frequency jet ventilation and gas trapping

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We have compared three types of high frequency jet ventilation (HFJV) with conventional positive pressure ventilation in patients recovering from elective coronary artery bypass surgery. Twelve patients were allocated randomly to receive HFJV at ventilatory frequencies of 60, 100, 150 and 200 bpm from a standard jet ventilator at either the proximal or distal airway (HFJV.p and HFJV.d), or from a valveless high frequency jet ventilator acting as a pneumatic piston (VPP). Trapped gas volume ($V_{tr}$), cardiac index (CI) and right ventricular ejection fraction (RVEF) were measured. $V_{tr}$ was related to the type of HFJV used ($P<0.05$) and ventilatory frequency ($P<0.05$). CI decreased with increasing rate of HFJV ($P<0.05$) and there were significant differences between the three types of HFJV ($P<0.05$). RVEF showed a linear relationship with ventilatory frequency ($P<0.05$) decreasing most with the VPP. The decrease in RVEF was associated with an increase in right ventricular end-systolic volume ($P<0.05$) suggesting that an increase in right ventricular afterload was the cause. The same three types of HFJV were compared using a lung model with variable values of compliance and resistance, to assess the impact of lung mechanics on gas trapping ($V_{tr}$, ml). Lung model compliance ($C$) was set at 50 or 25 ml cm H2O$^{-1}$ and resistance ($R$) at 5 or 20 cm H2O litre$^{-1}$ s, where values of 50 and 5, respectively, are normal. $V_{tr}$ increased with ventilatory frequency for all types of jet ventilation ($P<0.05$), varying with the type of jet ventilation used ($P<0.05$).

Keywords: ventilation, intermittent positive pressure; ventilation, high frequency jet; lung, gas trapping

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Ventilation of the lungs using high pressure gas driven through a small cannula with consequent entrainment of air by the Venturi effect was first described by Sanders in 1967. In 1971, Jonzon and colleagues introduced the concept of high frequency positive pressure ventilation using tidal volumes just greater than deadspace and in 1977, Klain and Smith described ventilation of the lungs using high frequency percutaneous transtracheal jet injection.

High frequency jet ventilation (HFJV) is a method of ventilatory support which, despite considerable interest, has failed to gain broad acceptance. In the management of respiratory failure, despite theoretical advantages over conventional ventilation by minimizing cyclical variations in airway pressure while maintaining mean lung volumes, it is little used. Increased lung volume should improve oxygenation in acute respiratory failure by recruitment of closed alveoli. However, this may also cause excessive intrathoracic pressure and more ‘gas trapping’ or ‘auto-PEEP’.

Gas trapping can impair ventricular function by increasing right ventricular afterload or by compression of the heart, preventing right ventricular filling. A balance is necessary between improvement in gas exchange by maintenance of functional residual capacity (FRC) and depression of cardiac function caused by increased mean lung volumes. Jet ventilation can impair cardiac output at high ventilatory frequencies, high mean airway pressures and greater I:E ratios.

We first measured how changes in resistance and compliance in a lung model affected gas trapping using the three types of jet ventilation described, and then conducted a clinical study comparing these types of HFJV ventilation with conventional positive pressure ventilation in patients recovering from elective uncomplicated coronary artery bypass surgery. The effects of varying the position of the jet within the airway, and the ventilator, were examined using ventilatory frequencies of 60–200 bpm. The effects
on mean and peak airway pressure, gas trapping, cardiac index and right ventricular ejection fraction were measured.

**Patients and methods**

**In vitro model**

A bench investigation using a previously described lung model\(^1\) was first performed to establish the likely effects of HFJV on airway pressures and gas trapping in lungs with different compliance and resistance values, to simulate normal and abnormal lung mechanics. Using a method described by Chakrabarti, Loh and Gilchrist,\(^2\) carbon dioxide was delivered into the model at a rate of 200 ml min\(^{-1}\). The resting volume of the reservoir bag was set at 2.5 litre by aspiration of surrounding gas so as to approximate the FRC of a normal adult. The driving pressure of the jet was increased in a stepwise manner until normocapnia (\(P_{CO_2} 4.5–5.5\) kPa) was achieved. Gas flow and volume measurements were made using a pneumotachograph with a Lilly-type head (Mercury VP5 Pneumotachograph; GM Instruments, Kilwinning, Scotland). This device automatically integrates the gas flow vs time signal using an electronic analogue integrator, which is triggered whenever gas flow exceeds zero (>2.5% from baseline), thus allowing measurement of gas volumes with negligible cumulative drift. Flow signal zero estimation is performed by interruption of gas flow input to the transducer with a solenoid valve, with an electronic feedback loop to ensure accurate zero flow measurement. This process is repeated automatically during use to ensure minimal baseline drift. The pressure changes within the model lung were measured by a strain gauge pressure transducer and amplifier (Baxter ‘TruWave’, model series PX) connected to the model by a saline filled manometer tube. Dynamic response and calibration of the pressure record was checked with a Hewlett Packard anaesthetic monitor, and the waveforms of pressure and volume were recorded using a heated stylus recorder.

Trapped gas volume was measured by stopping ventilation at end-expiration, as indicated by a trough in the pressure waveform recording, disconnection from the ventilation, and then allowing passive exhalation to the residual volume of the lung model through the pneumotachograph. We measured the effects of changing lung mechanics on gas trapping for a variety of jet ventilation methods to estimate the likely values of gas trapping *in vivo*. Three types of jet ventilation were investigated at ventilatory frequencies of 60–200 bpm. These were: jet ventilation at the proximal and distal inlets of the lung model with a conventional jet ventilator (HFJV.p and HFJV.d) and ventilation with the valveless jet ventilator of Chakrabarti and Whitwam\(^3\) (valveless pneumatic piston or ‘VPP’) (Fig. 1). The VPP type of HFJV uses a conventional breathing system between the machine and the patient; in this case a Mapleson ‘D’ system of 180 cm was used.

Lung model compliance (C) was set at 50 or 25 ml cm H\(_2\)O\(^{-1}\) (SI units 510 or 255 ml kPa\(^{-1}\)) and resistance (R) at 5 or 20 cm H\(_2\)O litre\(^{-1}\) s (SI units 51 or 204 kPa litre\(^{-1}\) s) (Fig. 2). Values of 50 ml cm H\(_2\)O\(^{-1}\) and 5 cm H\(_2\)O ml\(^{-1}\) min, respectively, are relatively normal.

**In vivo study**

After obtaining approval from the Local Ethics Committee and written consent, we studied 12 patients immediately after uncomplicated, elective, coronary artery bypass surgery. All patients were NYHA class 2 or 3, with left ventricular ejection fraction >30% and normal preoperative respiratory function tests.

All patients received standard premedication, with morphine and hyoscine i.m. Anaesthesia was induced with a benzodiazepine and fentanyl. Intubation of the trachea was facilitated with pancuronium and a jet ventilation tracheal tube (Mallinckrodt ‘Hi-Lo’ tube) was placed in the trachea. This can be used for ventilation at either its proximal or distal apertures, in addition to conventional ventilation, and allows continuous measurement of airway pressure via a dedicated channel to the distal end. A pulmonary artery flotation catheter (Baxter, RVEF model) was inserted after induction of anaesthesia to measure cardiac index (CI) and estimate right ventricular ejection fraction (RVEF), right ventricular end-diastolic volume (RVEDV) and right ventricular end-systolic volume (RVESV). This device also estimates end-
diastolic temperature in the thermodilution curve and calculates the volume of blood remaining in the right ventricle at the end of systole. Ejection fraction is calculated and then RVEDV, RVESV and stroke volume are derived using concurrent values for cardiac output and heart rate.

Patients were transferred to the intensive care unit after operation, and after at least 1 h of cardiac and respiratory stability, baseline measurements of cardiac and respiratory function were made. These included arterial blood-gas analysis, arterial pressure (AP), right atrial pressure (RAP), pulmonary artery pressures (PAP) and pulmonary artery occlusion pressure (PAOP), in addition to cardiac index (CI) and right ventricular ejection fraction (RVEF). Peak and mean airway pressure (Paw) were measured by a strain gauge pressure transducer and amplifier (Baxter ‘TruWave’, model series PX), connected to the distal port of the Hi-Lo tracheal tube by a saline filled manometer tube. Conventional positive pressure ventilation was provided by a Siemens Servo ‘C’ ventilator, which was used as the control ventilator throughout the study.

Patients were allocated randomly, using sealed envelopes, to receive two of the three types of jet ventilation outlined in the bench top study at ventilatory frequencies of 60, 100, 150 and 200 bpm in random order. Restricted randomization was made by block allocation to HFJV types to ensure equal numbers in each group, and then allocation of ventilatory frequencies with the use of random number tables.

During jet ventilation, blood-gas analysis was repeated at 5-min intervals and the driving pressure of the jet was adjusted to achieve normocapnia (Paco2, 4.5–5.5 kPa). The I:E ratio was maintained at 1:2 throughout. Cardiac and ventilatory variables were then measured. Trapped gas volume was measured by closing the airway at endexpiration, disconnection from the ventilation and then at the end of systole. Ejection fraction is calculated and mean airway pressure (Paw) was related linearly to I:E ratio while HFJV.d showed the lowest observed effects. Paw was converted to a log scale, adding a constant (23.5) to remove skew and allow for zero values. Paw was converted by taking simple logs. Distributions of other outcomes were close to normal without conversion.

Analysis of the data was by repeated measures analysis of variance (RM-ANOVA). Patient differences and observation number (equivalent to time of observation) were included as possible confounds. For jet rate and observation number, further ANOVA models were fitted with separate terms for linear and non-linear effects. Possible interactions between machine and rate (regarded as continuous) were also investigated. Tests were made for linear and non-linear effects of jet rate and observation number, and for interactions between machine and rate. For all main outcomes, values are shown of means by ventilatory method and rate, with 95% error bars. Results for the Siemens Servo ‘C’ ventilator are also shown. Correlation between the four main outcomes was calculated, adjusting by the Bonferroni method for multiple comparisons. An imbalance in the randomization of applied types of jet ventilation was observed which was corrected for in the analysis, as far as possible.

Cardiac function also increased progressively with time, as might be expected in patients immediately after operation. Because of the imbalance in randomization, we cannot be certain that including observation number in the statistical model or the time the observation was made is able to remove this confounding effect. However, the estimated effects are not large and bias is likely to be small.

Results
In vitro trapped gas volumes
Vtr increased with ventilatory frequency for all types of jet ventilation (P<0.05 for linear trend in each data set) and the rate of increase in Vtr varied according to the type of jet ventilation used (P<0.05) (Fig. 3). The raw data were converted to values for the slopes of each of the data sets to examine the effects of changing compliance and resistance on gas trapping, and the interactions these had with the type of ventilation and rate dependant changes. There was a consistent relationship between the slope of the data set and compliance (P<0.05), although no general relationship with resistance was observed. An independent effect of type of jet ventilation on this relationship was also observed (P<0.05).

In vivo trapped gas volumes
Vtr showed a linear relationship with ventilatory frequency for all three types of jet ventilation (P<0.05) and a clear interaction between Vtr and type of jet ventilation used was also observed (P<0.05) (Fig. 4). VPP ventilation showed the greatest values for Vtr while HFJV.d showed the lowest values. The rate dependant increase was, however, most marked with the HFJV.p type. The magnitude of these observed effects can be seen in Table 1 where, because log values were used in analysis, multiplying effects are given. For example, the volume of trapped gas with the conventional jet ventilator at the proximal airway (HFJV.p) was, on average, 0.48 (48)% of the value measured with the valveless jet ventilator (VPP) (95% CI 0.38–0.6).

Airway pressures
Peak airway pressure (Paw max) was related linearly to ventilatory frequency for all three types of jet ventilation
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Fig 3 In vitro values of trapped gas volume (Vtr) for the HFJV.p, HFJV.d and VPP.

Fig 4 Trapped gas volumes (Vtr) for the HFJV.p, HFJV.d and VPP in vitro.

(P<0.05) (Fig. 5). There was an interaction between type of jet ventilation and Paw max (P<0.05). All methods of jet ventilation decreased Paw max significantly up to ventilatory frequencies of 100 bpm. At greater ventilatory frequencies, VPP and HFJV.p showed values close to control (conventional IPPV) while HFJV.d showed persistently smaller Paw max values throughout the test range.

Mean airway pressure (mean Paw) values followed those of Paw max, although the reduction in pressure was less and tended towards control values in all three types of jet ventilation with increasing ventilatory frequency (Fig. 6). Mean Paw exceeded control values with ventilatory frequenc-
Previous work has shown that a shorter expiratory time and greater time constant of the lung led to more significant gas trapping. Greater ventilatory frequencies shorten the expiratory time and we found a rate-dependent increase in gas trapping for all types of jet ventilation. The time constant of a lung unit is a product of its compliance and resistance, and we have shown the effect of changing this variable in our bench study, with a relationship between lung model compliance and trapped gas volumes. The in vitro data showed that the change in $V_{tr}$ with greater lung model time constant was not uniform. The HFJV.p and HFJV.d types of ventilation appeared to show a steady increase in $V_{tr}$ with increasing time constant at all ventilatory frequencies. However, the VPP type showed a decrease in $V_{tr}$ when the time constant increased from 0.25 to 0.5 s. This change represents a decrease in compliance and an increase in resistance whereas the increases in time constant from 0.125 to 0.25 s and from 0.5 to 1.0 s represent changes in compliance only. The VPP type of ventilation is predominantly affected by compliance, which may account for the overall correlation between $V_{tr}$ and compliance found on statistical analysis of all types of HFJV.

The rate-dependent changes in $V_{tr}$ varied with the type of jet ventilation used. Overall, VPP showed greater values for gas trapping than the conventional jet ventilator at all ventilatory frequencies and a more proximal point of jet injection showed greater values than distal injection. This may be explained, at least in part, by the gas flow characteristics within the breathing system caused by changes in type of HFJV. Turbulent conditions exist primarily within the conducting or ‘central’ airways during HFJV while the terminal airways and alveoli gas flow show a predominantly laminar pattern. Turbulent gas flow generated within the central airways is conducted for a variable distance downstream, thus a point of jet injection or HFJV distant from the patient generates a greater column of turbulent gas flow than a more ‘proximal’ ventilatory type. This may cause increased expiratory resistance and therefore a greater tendency to gas trapping. In both our bench and in vivo results, HFJV.p had greater $V_{tr}$ values than the same ventilator jetting at the carina (HFJV.d), for all ventilatory frequency and lung model settings. VPP ventilation is...
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separated from the patient by a 180-cm Mapleson ‘D’ system and is thus a more ‘proximal’ type of HFJV than either HFJV.d or HFJV.p. It also differs in that the jet injection and subsequent gas entrainment seen with HFJV.p and HFJV.d types is replaced by simple pneumatic compression of a column of gas. It may be that this results in a more sustained column of turbulent gas flow, causing the observed increase in Vtr compared with conventional jet ventilation. Mean and peak airway pressure values broadly paralleled the variations in gas trapping observed both in vivo and in our bench top study. However, prediction of Vtr from measurement of airway pressure is unreliable.

The effects that changes in ventilator mechanics may have on clinical performance has been blamed, in part, for the difficulty in comparing previous studies of HFJV, and the wide array of jet ventilators available may account for widely varying clinical results.

HFJV reduces cyclical variations in airway pressure, and it is this reduction in peak airway pressure, together with maintenance of adequate mean pressure, that accounts for much of the interest in HFJV. However, airway pressure values during HFJV depend on the point of measurement within the airway. The pivotal study by Carlon and colleagues, where HFJV was evaluated prospectively in the management of acute lung injury, showed no clear benefit of HFJV over conventional types of respiratory support. This study aimed to reduce all airway pressures so that cardiovascular stability was enhanced and barotrauma reduced. Therefore, it overlooked the important ability of HFJV to maintain mean Pav; and thus mean lung volumes, while reducing shear stress on the small airways and alveoli. As has been suggested recently, the increase in lung volume while minimizing Pav variations may preserve lung integrity in acute lung injury.

Cardiovascular stability can be achieved with HFJV while maintaining adequate gas exchange. An early review showing minimal cardiovascular depression with HFJV was followed by evidence to suggest HFJV improved cardiac output and regional blood flow compared with conventional IPPV, even where hypovolaemia or right ventricular dys-function co-existed. As with the study of Carlon and colleagues, these concentrated on reducing all airway pressures and did not examine the effects of changes in lung mechanics, ventilator mechanics or ventilator strategies on cardiac function during HFJV. Excessive gas trapping is not an inevitable consequence of jet ventilation. Small values of Vtr and minimal change in cardiac index occur with ventilatory frequencies of 150 bpm with HFJV.p ventilation.

In contrast, other studies have emphasized cardiac compromise with HFJV, with a decrease in cardiac output during HFJV with increasing I:E ratios, where increased mean airway pressure and increased right ventricular afterload occur, probably because of increased gas trapping. In our study, shortening the expiratory period caused a decrease in cardiac index and right ventricular ejection fraction, as ventilatory frequency increased, for all types of HFJV. This contradiction shows how the clinical performance of HFJV can change with ventilator strategy, which may also include variation from small changes in ventilator mechanics.

The rate-related decrease in cardiac index and RVEF varied, showing how varying the injection point, in addition to varying ventilator mechanics, could alter trapping, as changes in cardiac function paralleled the observed variations in gas trapping and were associated with an increased RVESV. An increased right ventricular afterload probably accounts for the changes we observed in right ventricular function, by compression of the pulmonary vasculature as a result of increased intrathoracic volume. A poorly compliant vasculature may protect against this effect, suggested by a previous study where cardiac function was preserved during HFJV even when PEEP was deliberately added.

Cardiac output is preserved during HFJV where lung compliance is small. Reports of HFJV in patients with bullous lung disease, where a large lung compliance might suggest large trapped gas volumes, found adequate ventilation with no apparent cardiovascular compromise, even at ventilatory frequencies of 250 bpm.

As several variables interact with regard to gas trapping during jet ventilation, and this may affect cardiac function, the choice of a method that allows repeated measurement of gas trapping would be appropriate. Improved understanding of factors affecting gas trapping may be useful in the application of jet ventilation in acute lung injury where alveolar recruitment may be important, but the effect on cardiac output may also be important.

In summary, shortened expiratory time and altered lung mechanics affected gas trapping during HFJV in our experimental study with both rate- and resistance-dependant changes. These effects varied with the type of HFJV used. More gas trapping occurred with VPP and HFJV.p types of ventilation, associated with a decrease in cardiac output and an increased right ventricular afterload. In contrast, HFJV.d showed consistently small values of gas trapping and small changes in cardiac performance.

References

5 Lachmann B, Danzmann E, Heandley B, Jonson B. Ventilator settings and gas exchange in respiratory distress syndrome.

7 Normandale J, Patrick M, Sherry KM, Feneck RO. Comparison of conventional intermittent positive pressure ventilation with high frequency jet ventilation. *Anaesthesia* 1987; 42: 824–34


10 Chakrabarti MK, Sykes MK. Cardiorespiratory effects of high frequency intermittent positive pressure ventilation in the dog. *Br J Anaesth* 1980; 52: 475–82


17 Simone AF, Ultman JS. Longitudinal mixing of oxygen with air during steady flow through the larynx. *Eur Physiopathol Respir* 1982; 18: 389–93


20 Lachmann B. Open up the lung and keep the lung open. *Intensive Care Med* 1992; 18: 319–21

21 Sjostrand U. High frequency positive pressure ventilation: a review. *Crit Care Med* 1980; 8: 345–64


24 Fusiardi J, Rouby JJ, Benhamou D, Viars P. Haemodynamic consequences of increasing mean airway pressure during high frequency jet ventilation. *Chest* 1984; 86: 30–4

25 Sherry KM, Windsor JPW, Feneck RO. Comparison of the haemodynamic effects of intermittent positive pressure ventilation with high frequency jet ventilation. *Anaesthesia* 1987; 42: 1276–83
