CARBON DIOXIDE CLEARANCE DURING HIGH FREQUENCY JET VENTILATION

Effect of Deadspace in a Lung Model

A. J. MORTIMER, J.-L. BOURGAIN, J. UPPINGTON AND M. K. SYKES

During high frequency jet ventilation (HFJV) the clearance of carbon dioxide appears to be very variable. This may be the result of differences in the volume of gas delivered to the trachea or of variations in the pattern of gas transport in the conducting airways and alveoli. Since it is difficult to collect true mixed expired gas during HFJV, we have studied the effects of adding deadspaces of different lengths and volumes on the elimination of carbon dioxide from a lung model.

METHODS

The model lung (Manley Lung Ventilator Performance Analyser) consisted of a spring-loaded bellows with a variable orifice to simulate airway resistance. The compliance was adjusted to 50 ml cm H$_2$O$^{-1}$ and the airway resistance to 5 cm H$_2$O litre$^{-1}$ s$^{-1}$. The end-expiratory lung volume was 500 ml. The lung was ventilated with a high frequency jet ventilator set to deliver different tidal volumes at frequencies of 1, 3 and 5 Hz. The clearance of carbon dioxide from the lung was measured by recording the flow rate of carbon dioxide which had to be added to the lung to maintain a mean concentration of 6% at each ventilator setting. Tidal and minute volumes were determined from the variations in pressure within a box plethysmograph which surrounded the lung (fig. 1).

SUMMARY

The effects of the volume and length of deadspace on the clearance of carbon dioxide from a lung model have been investigated during high frequency jet ventilation (HFJV) at 1, 3 and 5 Hz. At 1 Hz, increasing the volume of the deadspace without changing the length caused a reduction in the clearance of carbon dioxide. At 5 Hz, an increase in the length of deadspace decreased carbon dioxide clearance, whilst an increase in volume had no effect. Since the delivered tidal volume was less than the volume of the morphological deadspace at this frequency, the elimination of carbon dioxide must have been accomplished by mechanisms which are not considered important at normal tidal volumes and frequencies. Furthermore, the clearance of carbon dioxide at 5 Hz was very inefficient compared with that at 1 Hz. It is concluded that, during HFJV, carbon dioxide is cleared most efficiently when the frequency is low enough for the delivered tidal volume to be greater than the volume of the morphological deadspace.
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Fig. 1. Experimental arrangement: carbon dioxide is supplied to the interior of the model lung which is placed inside the plethysmograph. HFJV is delivered to the lung through deadspaces of known length and volume from a nozzle fixed in the T-piece. Minute ventilation of the lung is determined from the pressure changes in the plethysmograph whilst the volume delivered from the jet nozzle is collected in the ventilation circuit (hatched area) and measured by the dry gas meter.

cycling frequency and the duty cycle (the proportion of each cycle during which the valve is open). The flow rate was controlled by the number of valves opening simultaneously and by the pressure gradient across the valves.

The pulses of air were delivered to the lung through 1.5 m of non-compliant tubing (4 mm i.d.) to a 1.8-mm brass nozzle incorporated in a T-piece. The T-piece was connected directly to the proximal end of a 9-mm i.d. cuffed Portex tracheal tube so that the jet was directed down the axis of the tube. The cuffed end of the tracheal tube formed an airtight seal with the proximal end of the deadspace under investigation, the distal end of the latter being connected directly to the model lung. The side ports of the T-piece had 22-mm tapers to which 1-m lengths of corrugated rubber tubing were attached. The opposite ends of these tubes were joined by a second T-piece through which gases were led to a calibrated dry gas meter (Parkinson Cowan, CD1). This meter measured the volume of gas entering the circuit through the jet plus the volume of carbon dioxide added to the lung. Thus the minute volume of the jet could be calculated. The circuit contained a large chamber to minimize fluctuations in pressure when the jet entrained gas. A recirculating fan promoted mixing of the air in the circuit with the carbon dioxide-rich expired gas. The volume of

the complete circuit, which included the chamber, both lengths of 22-mm tubing and the T-pieces, was 65.5 litre measured by carbon dioxide dilution. The resistance of the circuit to gas flow was less than 2 cm H$_2$O litre$^{-1}$ s$^{-1}$. Any errors attributable to rebreathing have been ignored since, in a previous investigation using the same circuit and lung model with a non-linear airway resistance, we have found entrainment to be small (up to 20%), and to occur only at 1 Hz and with low I:E ratios (Mortimer and Bourgain, 1983).

The artificial deadspaces were constructed from rigid plastic tubing. Two were short in length (17 cm), one of these being small in volume (16 ml) and the other large in volume (40 ml). The third deadspace was both long (35 cm) and large (40 ml). All three deadspaces had the same resistance to continuous flow (1 cm H$_2$O at 50 litre min$^{-1}$). The total calculated volumes of morphological deadspace (which included the tracheal tube, the artificial deadspace and the tubing leading into the model lung) were 73 ml (short, small volume deadspace), 97 ml (short, large volume deadspace) and 102 ml (long, large volume deadspace).

Mean alveolar pressures were recorded from the inside of the bellows and mean airway pressures from the distal end of the deadspace tubing using air-filled catheters (1.5 mm i.d.) and
transducers. Alveolar pressure was sensed with an optical defocusing pressure transducer (Mercury Electronics, UK) incorporating a 0–30 cm H\textsubscript{2}O pressure cell. Airway pressure was sensed with a Druck PDCR 75 transducer. The signals from both transducers were displayed on a heated stylus recorder (Devices M19), and mean values were obtained by electronic damping.

**Measurement of tidal and minute volumes**

The box plethysmograph had an internal volume of 125 litre. Changes in pressure were detected with an air filled pressure transducer (EMT 33, Elema Schönannder, Sweden) connected to the box by a short (2-cm) piece of rigid plastic tubing (3 mm i.d.). The pressure signals were displayed on an ink-jet recorder (EMT 34, Elema Schönannder, Sweden). The frequency response of the transducer alone was within ±5% up to 50 Hz. The frequency response of the box plethysmograph and pressure recording system was tested by oscillating the air inside the box with a rolling diaphragm piston pump and was found to be flat up to 15 Hz. At higher frequencies, vibration from the piston pump interfered with the recordings.

During each investigation the plethysmograph was calibrated (with a 1-litre syringe) by the rapid injection of 500 ml of air either as a single bolus or in 100-ml increments. The increase in pressure in the plethysmograph decayed over 50–75 s, the initial pressures (adiabatic compression) being greater than the final pressures (isothermal compression) by 26% ± 2 SD at volumes up to 500 ml. All volumes were measured at ambient temperature and pressure dry (ATPD).

The validity of the calibration procedure was confirmed by comparing the box pressures recorded when increments of air were added to the test lung inside the box, and when the same volumes of air were added directly to the box but with the lung sealed off inside. The results for each procedure were identical.

**Measurement of carbon dioxide clearance**

Carbon dioxide was supplied to the interior of the bellows from one of three parallel mounted rotameters. The first regulated flow up to 100 ml min\textsuperscript{-1}, the second, flow up to 1 litre min\textsuperscript{-1}, and the third, flow up 5 litre min\textsuperscript{-1}.

The concentration of carbon dioxide inside the bellows was measured by passing a 150–200-ml min\textsuperscript{-1} sample through an infra-red analyser (Gould MK III) calibrated from 0 to 10% carbon dioxide in air and returning this to the bellows. At each ventilator setting the flow rate of carbon dioxide into the lung was increased progressively until a mean concentration of 6% was recorded. The flow rates were recorded at ATPD. Equilibrium was reached quickly at 1 Hz but, at 5 Hz, 15–20 min was required to achieve a steady state.

**Experimental design**

Two complementary studies were performed. First: the three deadspaces were randomly interchanged and the elimination of carbon dioxide determined at 1, 3 and 5 Hz. The pressure gradient across the solenoid valves was held constant at 300 kPa. At each frequency nine different tidal volumes were obtained by the use of one, two or four solenoid valves at inspiratory: expiratory (time) ratios of 1:1, 1:2 and 1:4.

Second: the T-piece, tracheal tube and artificial deadspace were replaced with a Perspex tube 35 cm long and 9 mm i.d. The proximal end of this tube was connected to a modified T-piece which permitted the jet to be advanced down the axis of the tube to the distal end, the axial position of the jet being maintained with guidewires. The difference in volume of the morphological deadspace between the proximal and distal positions of the jet nozzle was 20 ml. The clearance of carbon dioxide was determined at 1, 3 and 5 Hz at each nozzle position using the same nine ventilator settings as were used in the first study.

**Statistical analysis**

The data obtained from both investigations were analysed by least squares linear regression analysis. From the first experiment, the regression lines relating the clearance of carbon dioxide and tidal volume for each deadspace at 1, 3 and 5 Hz were tested for homogeneity of variance with Bartlett's test (Snedecor and Cochrane, 1980). The slopes were then compared by analysis of variance. Since three sets of data were compared at each frequency, statistical significance was accepted when $P < 0.01$.

**RESULTS**

**First study**

The tidal volumes recorded by the box plethysmograph were similar for each deadspace
and decreased as the frequency of ventilation increased.

There was a strong positive linear relationship at each frequency between the clearance of carbon dioxide and minute ventilation ($P < 0.001$), the increase in carbon dioxide clearance for a given increase in minute volume being greatest at 1 Hz, least at 5 Hz and intermediate at 3 Hz (fig. 2). However, the relationship between the carbon dioxide cleared and tidal volume at each frequency varied with the dimensions of the deadspace (figs 3, 4 and 5).

At 1 Hz (fig. 3) the slopes of the regression lines of carbon dioxide cleared on tidal volume were not significantly different. However, the magnitude of carbon dioxide cleared, judged from the elevation of the regression lines, was significantly greater ($P < 0.001$) with the short, small volume deadspace compared with the two large volume deadspaces. There was no significant difference between the latter (table I). At this frequency, the tidal volume ($V_t$) exceeded the total morphological deadspace volume ($V_d$) by a factor which ranged from 1.3 to 5.2 and the length of each deadspace had no effect on carbon dioxide elimination.

At 3 Hz (fig. 4), $V_t$ was always smaller than at 1 Hz and ranged from 0.4 to 1.6 times $V_d$ (table I). With the short, small volume deadspace in position, $V_t$ exceeded $V_d$ in five measurements. When these readings were included in the calculation of the regression line (fig. 4), the slope of carbon dioxide clearance was significantly greater from this deadspace ($P < 0.001$) compared with the two large volume deadspaces (table I), there being no significant difference between the latter. However, when these figures were eliminated so that all comparisons were made with $V_t$ less than $V_d$, there were no significant differences between the slopes of all three regression lines.

The tidal volumes at 5 Hz (fig. 5) were smaller than at 3 Hz and ranged from 0.2 to 0.6 times $V_d$ (table I). The slopes of the regression lines of carbon dioxide cleared were identical for the two deadspaces which were short in length. At the higher tidal volumes, the clearance of carbon dioxide from these was greater than from the long deadspace (table I). At 5 Hz, therefore, the length of the deadspace was more important than the volume in influencing carbon dioxide elimination.

**Second study**

There were no significant differences between the mean airway and mean alveolar pressures.
TABLE I. VT:VD ratios and regression equations for carbon dioxide clearance (y) on tidal volume (x) for each deadspace at 1, 3 and 5 Hz. Statistical comparison of the slopes is included together with comparison of the elevation of each line when the slopes are not significantly different.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Deadspace length</th>
<th>Type of volume</th>
<th>Tidal volume: deadspace ratio (VT:VD) (range)</th>
<th>n</th>
<th>Slope</th>
<th>Intercept</th>
<th>r</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a Short</td>
<td>Small</td>
<td>1.9-5.2</td>
<td>8</td>
<td>4.73x</td>
<td>-529.35</td>
<td>0.99</td>
<td>&lt; 0.001</td>
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<tr>
<td></td>
<td>b Short</td>
<td>Large</td>
<td>1.4-3.9</td>
<td>9</td>
<td>3.62x</td>
<td>-431.05</td>
<td>0.98</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>c Long</td>
<td>Large</td>
<td>1.3-3.8</td>
<td>9</td>
<td>3.93x</td>
<td>-482.17</td>
<td>0.99</td>
<td>&lt; 0.001</td>
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<tr>
<td>3</td>
<td>a Short</td>
<td>Small</td>
<td>0.6-1.6</td>
<td>9</td>
<td>5.07x</td>
<td>220.28</td>
<td>0.97</td>
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<tr>
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<td>0.4-1.1</td>
<td>9</td>
<td>1.90x</td>
<td>34.35</td>
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<td>0.4-1.1</td>
<td>9</td>
<td>2.27x</td>
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</tr>
<tr>
<td>5</td>
<td>a Short</td>
<td>Small</td>
<td>0.3-0.6</td>
<td>9</td>
<td>3.98x</td>
<td>-61.03</td>
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<td>&lt; 0.001</td>
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<tr>
<td></td>
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<td>0.2-0.5</td>
<td>9</td>
<td>3.99x</td>
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<tr>
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<td>c Long</td>
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<td>0.2-0.5</td>
<td>9</td>
<td>1.35x</td>
<td>-14.26</td>
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</table>

\( \text{VT:VD} \) ratios and regression equations for carbon dioxide clearance (y) on tidal volume (x) for each deadspace at 1, 3 and 5 Hz. Statistical comparison of the slopes is included together with comparison of the elevation of each line when the slopes are not significantly different.

**Fig. 4.** Relationship between carbon dioxide cleared and tidal volume at 3 Hz for the short, small volume (○), short, large volume (□) and long, large volume (■) deadspaces. The encircled symbols (◎) indicate the measurements of carbon dioxide clearance from the short, small deadspace when VT is greater than 1.2 times VD. The regression line when these points are omitted from the analysis is represented by the dotted line. The regression lines suggest that when VT exceeds VD, carbon dioxide elimination is much more efficient compared with when VT is smaller than VD.

**Fig. 5.** Relationship between carbon dioxide cleared and tidal volume at 5 Hz for the short, small volume (○), short, large volume (□) and long, large volume (■) deadspaces. For each measurement, VT is smaller than VD. The regression lines suggest that carbon dioxide clearance is affected more by a change in the length of the deadspace than by a change in the volume.
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Whether the jet was situated proximally or distally. The clearance of carbon dioxide at any minute volume was greatest at 1 Hz and least at 5 Hz (fig. 6). However, for a given minute volume at each frequency, distal placement of the nozzle resulted in the greatest carbon dioxide clearance. The increase in minute volume required to produce a normal carbon dioxide clearance (200 ml min⁻¹) with the jet in a proximal position was approximately 1.5 litre min⁻¹ at 1 Hz, 5 litre min⁻¹ at 3 Hz and 11 litre min⁻¹ at 5 Hz.

DISCUSSION

Several features of relevance to the elimination of carbon dioxide during HFJV are illustrated by these results. In both studies a good correlation was observed at each frequency between the clearance of carbon dioxide and the minute and tidal ventilation. Since the different volumes at each frequency were obtained by changing both the number of solenoid valves opening and the duration of air flow, it appears that the clearance of carbon dioxide is related primarily to \( V_T \) and not to the inspiratory : expiratory time ratio. These results agree with those reported by Rossing and co-workers (1981) during high frequency oscillation (HFO) in patients. They found that, at frequencies between 30 and 200–300 cycles min⁻¹, carbon dioxide clearance was linearly related to both \( V_T \) and the product of \( V_T \) and frequency. At frequencies greater than 3 Hz, the elimination of carbon dioxide was influenced more by the delivered volume than by the frequency. In a separate study in dogs (Bourgain, Mortimer and Sykes, 1986) in which carbon dioxide clearance during HFJV was determined by a completely different method, we have observed similar linear relationships between the elimination of carbon dioxide and both minute and tidal ventilation at frequencies up to 5 Hz.

The elimination of carbon dioxide was most efficient when the frequency was 1 Hz and \( V_T \) exceeded \( V_D \) (fig. 2). At the higher frequencies, when \( V_T \) was smaller than \( V_D \), carbon dioxide elimination was less than the normal production of 200 ml min⁻¹ despite the use of large minute volumes. Similar observations have been recorded in dogs (Chakrabarti and Sykes, 1980; Colgan, Teneyck and Sawa, 1983; Weinmann, Mitzner and Permutt, 1984) and in rabbits (Fletcher and Epstein, 1982).

The use of a single airway–alveolus lung model with non-linear resistance and compliance characteristics (Chakrabarti and Sykes, 1976) may be criticized on the grounds that it is a gross simplification of the normal anatomy. However, the compliance was linear over the range of volumes studied (20–400 ml) and the use of such a model permits greater control of variables and increases the range of measurements which can be made.

The results in the first series of experiments suggest that, at 1 Hz, the elimination of carbon dioxide was decreased by an increase in the volume of the deadspace, but that its length had no effect whereas, at 5 Hz, carbon dioxide elimination was decreased by an increase in length but was not affected by an increase in volume. At 3 Hz, when \( V_T \) was less than \( V_D \), length also appeared to be more important than volume. These observations suggest that, at 1 Hz, \( V_T \) was sufficiently large to flush out \( V_D \) and that ventilation was primarily the result of convective transport. If this was the case, then the mean alveolar concentration of carbon dioxide (\( F_{A\text{CO}_2} \)) calculated from the measured carbon dioxide clearance (\( V_{\text{CO}_2} \)) and alveolar ventilation (\( V_A—$
derived from the minute volume and the morphological deadspace volume), should be the same as the $F_{A_{CO}}$ used in the experiment (0.06). To verify the results at 1 Hz, $F_{A_{CO}}$ was calculated at each ventilator setting for the two extremes of deadspace (short length, small volume and long length, large volume) from the relationship:

$$F_{A_{CO}} = \frac{V_{CO} \text{ ml min}^{-1}}{V_{A} \text{ ml min}^{-1}} \quad (1)$$

The calculated value of $0.058 \pm 0.008$ SD ($n = 17$) was very close to the set value which was (0.06), thus confirming that gas exchange could be explained by conventional physiological principles.

At 3 Hz, the clearance of carbon dioxide was greatest from the deadspace which was short in length and small in volume (fig. 4). The tidal volume exceeded $V_D$ in 10 measurements out of the total of 27, but in only five of these was the calculated $F_{A_{CO}}$ ($0.059 \pm 0.007$ SD) close to the set level of 0.06. The latter values were associated with the short length, small volume deadspace (fig. 4), when $V_T$ exceeded $V_D$ by a factor which ranged from 1.2 to 1.6. This suggests that, under these circumstances, gas transport was primarily as observed at 1 Hz. However, the calculated $F_{A_{CO}}$ for the other five measurements ($0.12 \pm 0.053$ SD) when $V_T$ was between 1.0 and 1.2 times $V_D$, was twice that used in the study. This indicates that the effective alveolar ventilation was greater than that calculated from equation (1), and implies that the effective deadspace volume was smaller than the volume of the total morphological deadspace.

At 5 Hz, $V_T$ was always smaller than $V_D$. The length of $V_D$, as opposed to the volume, became dominant in influencing the clearance of carbon dioxide. Elimination of carbon dioxide always exceeded the basal loss from the lung ($5-10 \text{ ml min}^{-1}$) which occurred when the bellows concentration was 6% in the absence of ventilation, but was markedly lower than normal carbon dioxide production.

In the second series of experiments distal placement of the jet decreased both the length and volume of the deadspace. The difference in volume (20 ml) was similar to the difference in volume between the other deadspaces, but the difference in length (35 cm) was twice as great. At both 3 Hz and 5 Hz, distal injection more than doubled carbon dioxide clearance. At 1 Hz the difference in clearance was much smaller, the increase in $V_T$ required to achieve the same clearance being closely related to the added volume of the deadspace (fig. 6).

The mechanisms which may account for adequate elimination of carbon dioxide during small volume, high frequency ventilation have been reviewed recently (Chang, 1984; Drazen, Kamm and Slutsky, 1984). The consensus of opinion is that, whilst delivery of carbon dioxide from pulmonary blood to the alveoli occurs by molecular diffusion, four mechanisms acting in concert can account for the transport of carbon dioxide from the alveoli to the mouth. First, direct ventilation of the most proximal and centrally situated alveoli, since their deadspace is small relative to the peripheral alveoli; second, mixing within the airways as a result of transfer of gas between alveoli with different time constants (Pendelluft); third, convective streaming which results from differences between the inspiratory and expiratory velocity profiles; and fourth, augmented dispersion in which gas mixing occurs longitudinally by radial diffusion from an axial velocity profile which is non-uniform (Taylorian dispersion).

In our first experiment at 1 Hz and 3 Hz, the clearance of carbon dioxide was greatest when $V_T$ exceeded 1.2 times $V_D$ and behaved in accordance with the conventional concept of alveolar ventilation (equation (1)). At 3 Hz and 5 Hz, however, when $V_T$ was less than 1.2 times $V_D$, appreciable quantities of carbon dioxide were still removed from the lung. The higher level of effective alveolar ventilation ($V_{A*}$) therefore, must have been achieved by a reduction in the effective deadspace volume ($V_D*$). This was calculated by rearranging equation (1) as follows:

$$V_{A*} = \frac{V_{CO} \text{ ml min}^{-1}}{F_{A_{CO}} \text{ ml min}^{-1}} \quad (2)$$

where the value for $F_{A_{CO}}$ was 0.06 as used in the study. The resultant value of $V_{A*}$ was then used to derive $V_D*$ from the measured minute ventilation.

In figure 7 the calculated $V_{A*}$ is compared with the $V_A$ derived from $V_A = f (V_T - V_D^{\text{morph}})$ at 1, 3 and 5 Hz. The regression line for $V_A$ greater than 5 litre min$^{-1}$ shows there is a good correlation between $V_A$ and $V_{A*}$. At lower values of $V_A$ this correlation no longer holds, $V_{A*}$ remaining positive down to $V_A$ values of minus 25 litre min$^{-1}$. This suggests that, within this range, $V_D*$ becomes smaller than $V_D$. Figure 8 illustrates the
Fig. 7. Relationship between the effective alveolar ventilation ($\dot{V}_A^*$—derived from equation (2)) and the alveolar ventilation ($\dot{V}_A$—derived from equation (1)). All measurements at each frequency are included. The solid circles (●) represent the results when $V_T$ is greater than 1.2 times $V_D$ whilst the open circles (○) represent the results when $V_T$ is smaller than 1.2 times $V_D$.

The relationship between $\dot{V}_A^*$ and $V_T$ at 3 Hz with the short length, small volume deadspace. The data are presented as two separate regression lines, one which includes the results where $V_T$ is greater than $V_D$ and the other where $V_T$ is smaller than $V_D$. This shows that a reduction in $V_T$ produces a smaller reduction in $\dot{V}_A^*$ when $V_T$ is less than $V_D$, than when it is greater than $V_D$. It also demonstrates that there is a transitional zone where ventilation by bulk flow gives way to other mechanisms discussed previously. The $x$-axis intercept of the regression line where $V_T$ exceeds $V_D$ gives a reasonable approximation to the true morphological deadspace volume (73 ml), thus confirming that bulk flow is dominant under these circumstances.

The relationships between $V_T$ and $V_D^*$ at 3 and 5 Hz are shown for the short length, small volume deadspace in figure 9. The progressive linear reduction in $V_D^*$ with decrease in $V_T$ which occurs when $V_T$ is less than $V_D$, appears to be independent of frequency since the slopes of the regression lines are the same. The results for the other deadspaces when $V_T$ was smaller than $V_D$ were similar.
These observations suggest that the magnitude of alveolar ventilation at any frequency is governed by the relationship between $\nu_T$ and $V_D$. The reduction in $V_D$ with decreasing $\nu_T$ was first described 71 years ago by Henderson, Chillingworth and Whitney (1915). From studies on axial gas flow through a tube, and measurement of the carbon dioxide content of successive fractions of expired air from man, they concluded that considerable elimination of carbon dioxide occurred even when $\nu_T$ was smaller than $V_D$. This provided an explanation for the ability of a dog to maintain adequate gas exchange when $\nu_T$ was smaller than $V_D$, as occurs during panting. These findings were confirmed by Briscoe, Forster and Comroe (1954), who found that, when subjects inspired volumes which were smaller than the Fowler deadspace volume, $V_D$ decreased. They postulated that the inspired air passed through the airways as an elongated cone, leaving static layers of air close to the walls of the trachea and bronchi, thereby reducing the effective volume of the airways.

Other, more recent, observations support our findings. Isabey, Harf and Chang (1984), have introduced the concept of core deadspace to describe the reduction in effective deadspace which they observed in a lung model ventilated between 5 and 40 Hz. They found that, when $\nu_T$ exceeded 1.2 times $V_D$, the clearance of carbon dioxide could be attributed to bulk transport of gas. However, when $\nu_T$ ranged from 0.8 to 1.2 times $V_D$, the effective tidal volume was greater than the measured $\nu_T$. They concluded that the volume of the effective deadspace was smaller than the volume of the morphological deadspace, and that direct alveolar ventilation through the core of the deadspace made a significant contribution to the elimination of carbon dioxide. In another study, in dogs at constant arterial $PCO_2$ ventilated at frequencies between 0.2 and 8 Hz, Weinmann, Mitzner and Permutt (1984) found a marked and progressive decrease in physiological $V_D$ which had been measured during low frequency, large volume ventilation.

The implications of our studies on the clearance of carbon dioxide from a lung model can be summarized as follows. First, when $\nu_T$ exceeds $V_D$ by a factor of 1.2 or more, the elimination of carbon dioxide occurs predominantly by bulk flow. This mechanism appears to be independent of frequency between 1 and 3 Hz. The elimination of carbon dioxide is impaired by an increase in the volume of $V_D$, but is unaffected by a change in the length. Second, when $\nu_T$ is less than 1.2 times $V_D$, bulk transport of carbon dioxide is reduced and other mechanisms assume importance. Under these circumstances the efficiency of carbon dioxide removal is greatly affected by the length of the path between the jet and the lung. Elimination of carbon dioxide is much less efficient and may be inadequate to remove a normal level of carbon dioxide production.

Several reports have confirmed the importance of delivering the fresh gas close to the carina. Davey, Lay and Leigh (1982) found that the efficiency of ventilation was enhanced in a patient when the fresh gas was delivered through a distal jet compared with a proximal jet. Smith, Sjöstrand and Babinski (1983) ventilated dogs at normocapnia with tidal volumes which were approximately 20% smaller when the jet was delivered near the distal end of the tracheal tube compared with the proximal end. During HFO at frequencies up to 12 Hz, Rossing and co-workers (1984) observed an improvement of up to 50% in the elimination of carbon dioxide from patients, when the fresh gas bias flow was changed from the proximal to the distal end of the tracheal tube.

The evidence, together with our own observations, confirm that, during high frequency jet ventilation, the elimination of carbon dioxide is most efficient when $\nu_T$ exceeds $V_D$ by a factor of 1.2 or more. This can be achieved in two ways: first, by an absolute reduction in $V_D$ through delivering the fresh gas as distal as possible in the trachea and, second, by ventilating at a frequency which is sufficiently low to ensure that $V_D$ is exceeded by the delivered $\nu_T$.

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REFERENCES


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