CARBON DIOXIDE CLEARANCE AND DEADSPACE DURING HIGH FREQUENCY JET VENTILATION

Investigations in the Dog

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At normal respiratory frequencies the elimination of carbon dioxide is governed by the alveolar ventilation which, in turn, is dependent on the tidal volume and the volume of the anatomical deadspace. As frequency is increased and tidal volume is decreased, a smaller proportion of each tidal volume reaches the alveoli, so that progressively greater minute volumes are required to maintain physiological values of arterial $P_{CO_2}$ (Chakrabarti and Sykes, 1980; Fletcher and Epstein, 1982). However, at high frequencies (above 5 Hz), adequate elimination of carbon dioxide may be sustained with tidal volumes which are less than the anatomical deadspace (Slutsky et al., 1980). This suggests that other mechanisms are responsible for the elimination of carbon dioxide at high frequencies (Chang, 1984).

Furthermore, we have observed a frequency-dependent effect of deadspace on carbon dioxide clearance when a lung model was ventilated at frequencies up to 5 Hz (Mortimer et al., 1986).

To examine this problem in more detail, we have studied the effects of different deadspaces on the elimination of carbon dioxide from canine lungs.

SUMMARY

The effects of frequency, tidal volume and added deadspace on carbon dioxide clearance were measured during high frequency jet ventilation at 1, 3 and 5 Hz in dogs. With a short, small volume deadspace, carbon dioxide clearance increased with minute volume at each frequency, but for a given minute volume the clearance decreased with increase in frequency. At 5 Hz, carbon dioxide clearance was less than carbon dioxide production. At 1 Hz, an increase in the volume of added deadspace decreased carbon dioxide clearance, but changes in the length of the deadspace, without change in volume, had no effect. At 5 Hz, an increased volume of added deadspace had little effect on carbon dioxide clearance, but increased length, without change in volume, decreased clearance. Carbon dioxide clearance was increased by placing the jet at the lung end of the tracheostomy tube. It is concluded that at 1 Hz, carbon dioxide elimination is governed by bulk flow, but at 5 Hz other mechanisms are important.

MATERIALS AND METHODS

Seven healthy mongrel dogs of either sex (body weight 10.4—15.0 kg) were studied in the supine position after premedication with morphine 1.4 mg kg$^{-1}$ i.m. Anaesthesia was induced with thiopentone 15 mg kg$^{-1}$ and pentobarbitone 30 mg kg$^{-1}$ i.v. After tracheal intubation with a cuffed tube (9 mm i.d.) mechanical ventilation was instituted with a Cape–Waine ventilator delivering air. A tracheotomy was performed and the distal end of a rigid Perspex tube (25 cm long, 9 mm i.d.) was tied in the trachea with several strong ligatures. This ensured a leakproof airway in the animal without any significant change in the total deadspace since the volume of the tube (16 ml) was considered to be similar in volume to the upper airway deadspace. Mechanical ventilation was continued through the tracheostomy tube and the tidal volume adjusted to produce an end-tidal
concentration of carbon dioxide of $4.2 \pm 0.2\%$ at a frequency of 10 b.p.m. Anaesthesia was maintained with regular increments of pentobarbitone 30–60 mg and apnoea maintained during the periods of measurement by intermittent injections of pancuronium 2 mg. The total duration of each investigation was 10–12 h.

One carotid artery was cannulated to permit measurement of systemic arterial pressure and sampling of arterial blood. The external jugular veins were cannulated to permit the measurement of central venous pressure and the infusion of drugs and fluids. Sodium bicarbonate 8.4% was infused at a rate of 0.5 ml kg$^{-1}$ h$^{-1}$ to maintain a normal non-respiratory acid–base state and lactated Ringer’s solution was infused at a rate of 5–10 ml kg$^{-1}$ h$^{-1}$. Body temperature was monitored by a thermistor placed in either the oesophagus or external auditory meatus. Vascular pressures were measured with Druck PDCR75 transducers and displayed on a Devices M19 heated stylus recorder. Airway pressure was measured at the distal end of the tracheostomy tube with an air-filled tube (i.d. 1.5 mm) connected to an optical defocusing pressure transducer (Mercury Electronics U.K.) with a measuring cell sensitive in the range 0–30 cm H$_2$O. Mean airway and vascular pressures were obtained by electronic damping. Arterial pH, $P_{CO_2}$ and $P_{O_2}$ were measured by a Radiometer ABL2 blood-gas analyser which had been previously calibrated with tonometered blood samples. All values were corrected for body temperature.

**High frequency jet ventilator**

The ventilator was similar to that described by Carlon and colleagues (1981). Compressed medical air at 400 kPa was connected to a variable pressure regulator which decreased the driving pressure to 300 kPa. Air flow was regulated by four electronically controlled solenoid valves which were mounted in parallel. The inspiratory:expiratory time ratio was set at 1:2 and different flow rates, and therefore tidal volumes, were obtained by varying the number of solenoid valves opened during inspiration. The pulses of air were delivered to the animal through non-compliant tubing, 1.5 m long, 4 mm i.d., with a terminal brass nozzle (2 cm long, 1.8 mm i.d.) fixed in the centre of a T-piece which was connected directly to the tracheostomy tube. The side ports of the T-piece had 22-mm tapers to which standard corrugated anaesthetic tubing was connected. The experimental arrangement is illustrated in figure 1.

**Measurement of tidal volume**

Since no satisfactory method has been devised for the direct measurement of tidal volume at high ventilatory frequencies (Mortimer and Sykes, 1983), tidal volume was measured indirectly with a plethysmographic technique. Minute volume was calculated by multiplying the measured tidal volume by the frequency of ventilation. The animal was placed in a constant volume, 125-litre box with rigid walls and the change in thoracic volume was detected by sensing the change in pressure in the box with a pressure transducer (EMT33 Elema Schonander, Sweden), which was inserted directly to the lid of the box. This transducer had been shown to have a flat frequency response ($\pm 5\%$) up to 50 Hz. The signal was recorded on an ink–jet recorder (EM34 Elema Schonander, Sweden) and the frequency response of the complete system was tested by connecting the interior of the box to a sinusoidal pump and shown to be flat up to 15 Hz.

The plethysmograph was calibrated at the end of each experiment with the animal still inside. The tracheostomy tube was sealed with a rubber bung and a total of 500 ml of air was rapidly injected to the box in increments of 100 ml. The increase in pressure inside the box was accompanied by an increase in temperature which decayed over 50–75 s. Since the lowest frequency used during the investigation was 1 Hz, gas compression in the plethysmograph was considered to be adiabatic (Bargeton and Barres, 1969).

To determine whether gas compression in the airways contributed any error in the estimation of tidal volume, identical volumes of air were rapidly injected directly to the box and to a Manley lung ventilator performance analyser placed within the box. This lung analogue consisted of a spring-loaded bellows which had a volume of approximately 500 ml. It was adjusted to have a compliance comparable to that of the dog (20 ml cm H$_2$O$^{-1}$), and airway resistance of 5 cm H$_2$O litre$^{-1}$ s$^{-1}$. The plethysmograph was calibrated adiabatically as in the animal study, with the model lung sealed off inside the box. The results of the investigation revealed that, under adiabatic conditions, the same pressures were recorded for identical added volumes up to 500 ml, regardless of whether the air was added to the lung inside the box or directly.
into the box itself. Consequently, no error was attributable to gas compression.

The ambient temperature in the laboratory was maintained constant throughout each experiment and the plethysmograph opened to air, except during the period of measurement, to minimize thermal drift. Because the plethysmographic technique infers tidal volume from the displacement of the thorax, the tidal volumes measured are expressed in ml at body temperature and pressure saturated (BTPS).

**Measurement of carbon dioxide clearance**

The animal was ventilated with a Cape-Waine ventilator between each test and the end-tidal \( P_{CO_2} \) maintained at 4.2 ± 0.2 kPa for 10–15 min before each measurement. The jet breathing system (which had previously been flushed with air) was then connected for a 2-min period and carbon dioxide clearance measured using the circuit shown in figure 1. The tracheostomy tube was connected by a T-piece and corrugated tubing to
a mixing chamber and a fan which circulated the gas in the circuit at 60 litre min⁻¹. The injected gas and carbon dioxide from the lungs left the circuit through a second T-piece which was connected to a previously calibrated dry-gas meter. The volume of the circuit measured by carbon dioxide dilution was 65.5 litre and the transit time from the jet to the outlet was 3 s.

Clearance of carbon dioxide was considered to be the sum of the carbon dioxide accumulating in the circle and the carbon dioxide eliminated through the gas meter during the first 1 min after the connection of the jet. Carbon dioxide concentrations at ambient temperature and pressure saturated (ATPS) were measured simultaneously in the mixing chamber and at the outlet of the circuit by two infra-red analysers (Gould Mk III and Hartmann Braun URAS 4) which conformed to the characteristics reported by Cormack and Powell (1972). The analysers were calibrated by serial dilution to read in the range 0.0–0.5% carbon dioxide and the outputs were displayed on a two-channel heated stylus recorder (fig. 2). Sample flow rates were 150–200 ml min⁻¹ and the gas sampled from the mixing chamber was returned to the circuit. Carbon dioxide clearance during the first 1 min after connection of the jet ventilator was calculated from the formula:

\[ V_{\text{CO}_2} = (F_e \times V_o) + (F_o \times V_o) \]

where \( V_{\text{CO}_2} \) is the volume of carbon dioxide eliminated in 1 min, \( F_e \) is the measured concentration of the gas in the circuit at the end of 1 min, \( V_c \) is the volume of the circuit (65.5 litre), \( F_o \) is the measured mean concentration of carbon dioxide in gas leaving the circuit during the first 1 min and \( V_o \) is the volume of gas leaving the circuit during this period.

Jet ventilation was continued for 2 min and a blood sample drawn at the end of this period to ascertain the direction and magnitude of change in arterial \( P_{\text{CO}_2} \) and to aid in the rapid restoration of control conditions before the next measurement.

**Plan of investigation**

**Group A.** The influence of three additional deadspaces on carbon dioxide clearance was examined in five dogs. Two of the deadspaces had the same length (24 cm), but different volumes (25 ml and 60 ml). The third had a length of 50 cm and a volume of 60 ml. The resistances of the three deadspaces were identical up to a flow of 100 litre min⁻¹. The deadspaces were inserted in random sequence and carbon dioxide clearance measured at frequencies of 1, 3 and 5 Hz using three different tidal volumes at each frequency. The different tidal volumes were obtained by switching into operation one, two or three solenoids at 1 Hz and two, three or four solenoids at 3 Hz and 5 Hz. Directly comparable ventilator settings were not used at each frequency because pilot studies had demonstrated that the animal developed an unstable circulation at certain combinations of frequency and number of solenoid valves used. At 1 Hz the use of four valves opening simultaneously caused profound hyperventilation, cooling and bradycardia, whilst at 3 Hz and 5 Hz using only one valve, minimal elimination of carbon dioxide occurred and severe hypertension and tachycardia developed. The inspiratory:expiratory time ratio was maintained constant at 1:2.
Group B. In two dogs the gas was injected through a 35 cm long, 1.8 mm i.d. tube, the tip of which was maintained in the centre of a large Perspex tracheostomy tube by means of guide wires. The position of the tip of the injection tube was changed from the distal to the proximal end of the tracheostomy tube, the distance between the two positions being 32 cm and the volume of the intervening tube being 20 ml. Measurements were made at three different tidal volumes and at frequencies of 1, 3 and 5 Hz, using inspiratory: expiratory time ratios of 1:2 and 1:4.

Least squares linear regression analysis was used to determine the relationship between carbon dioxide eliminated and the volume of ventilation delivered for each deadspace. At each of the three frequencies of ventilation studied, the data for each regression line were then tested for homogeneity of variance using Bartlett's test (Snedecor and Cochrane, 1980). The slopes and elevations of the lines were then compared by analysis of variance (Snedecor and Cochrane, 1980). The carbon dioxide clearance data at 5 Hz were also compared with paired t tests. As three groups have been compared throughout the statistical analysis (carbon dioxide cleared against volume of ventilation for each of three deadspaces) the level of statistical significance has been taken as $P < 0.01$ (Glantz, 1981).

RESULTS

**Group A**

Mean airway pressure increased with the number of solenoid valves opened (i.e. with inspiratory flow rate), but was unaffected by changes of deadspace (table I) or operating frequency (table II).

There was a positive linear correlation between the minute volume and the carbon dioxide clearance when the short, small volume deadspace was in place (fig. 3). However, the slope varied with frequency (table III).

The effects of altering deadspace on carbon dioxide clearance depended on frequency. At 1 Hz, the two large volume deadspaces produced a significant decrease in carbon dioxide clearance when compared with the small volume deadspace.
TABLE IV. Comparison by analysis of variance of the slope and elevation of the regression lines for each deadspace at 1 Hz

<table>
<thead>
<tr>
<th>Deadspace type</th>
<th>Slope</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short small v. short large</td>
<td>ns</td>
<td>P &lt; 0.01</td>
</tr>
<tr>
<td>Short small v. long large</td>
<td>ns</td>
<td>P &lt; 0.01</td>
</tr>
<tr>
<td>Short large v. long large</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

(fig. 4, table IV). At 3 Hz, clearance was greatest with the short, small volume deadspace and least with the long, large volume deadspace, the clearance with the short, large volume deadspace being intermediate between these two (fig. 5). At 5 Hz, carbon dioxide elimination was significantly higher with the two short deadspaces (table V, fig. 6), the difference in volume having no effect on carbon dioxide elimination, whilst clearance was least with the long, large volume deadspace (figs 6, 7). The individual regression equations for carbon dioxide cleared on tidal volume for each deadspace at each frequency are given in table VI.

Carbon dioxide production was measured in each of the dogs during the control periods of ventilation. The values ranged from 40 to 70 ml min⁻¹ (3.5 to 5.0 ml kg⁻¹ min⁻¹) under the conditions of the study.

TABLE V. Comparison by analysis of variance of the slope and elevation of the regression lines for each deadspace at 5 Hz

<table>
<thead>
<tr>
<th>Deadspace type</th>
<th>Slope</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short small v. short large</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Short small v. long large</td>
<td>ns</td>
<td>P &lt; 0.001</td>
</tr>
<tr>
<td>Short large v. long large</td>
<td>ns</td>
<td>P &lt; 0.001</td>
</tr>
</tbody>
</table>

Group B

In the two dogs in group B, there were no significant differences in the relationship between carbon dioxide clearance and tidal volume when the inspiration:expiration ratio was varied and the values were, therefore, pooled. As may be seen in figure 8, carbon dioxide clearance was greater when the catheter tip was placed at the distal end of the tracheostomy tube, the difference in clearance between the two positions being greatest at 3 Hz and 5 Hz.

Fig. 6. Carbon dioxide clearance in five dogs at various tidal volumes at 5 Hz. The equations for the regression lines are given in table VI. Deadspace type: short, small ○; short, large ∅; long, large □.

Fig. 5. Carbon dioxide clearance in five dogs at various tidal volumes at 3 Hz. The equations for the regression lines are given in table VI. Deadspace type: short, small ●; short, large ○; long, large □.

DISCUSSION

These investigations indicated that, at 1 Hz, the elimination of carbon dioxide depends on the volume of added deadspace, whilst at 5 Hz, elimination is independent of volume, but dependent on the length of the deadspace. These results
were confirmed by the significant increase in elimination of carbon dioxide which resulted from distal as opposed to proximal placement of the jet nozzle.

The measurement system utilized in these experiments enabled us to measure the tidal volume delivered to the animals' lungs and to calculate the minute volume. Furthermore, the volume of air delivered from the jet was measured, thus enabling us to calculate the degree of entrainment at each ventilator setting. However, the measurement of the effective ventilation proved to be more difficult. The most satisfactory method of assessing the efficiency of high frequency ventilation is to measure the arterial $P_{\text{CO}_2}$. However, any change in elimination of carbon dioxide inevitably alters carbon dioxide stores in the body, so that a new equilibrium is seldom achieved in less than 45 min. Since this delay would have greatly limited the number of results obtained from each investigation, it was decided to utilize the volume of carbon dioxide cleared from the lungs during the first 1 min after connection of the jet ventilator as an index of the efficiency of ventilation. Since there are major dynamic changes during this period, it is necessary to analyse the process of carbon dioxide excretion in some detail.

**Table VI. Regression equations for carbon dioxide clearance v. tidal volume in five dogs ($n = 15$ for each equation)**

<table>
<thead>
<tr>
<th>Deadspace type</th>
<th>Frequency</th>
<th>Length</th>
<th>Volume</th>
<th>$y$</th>
<th>$r$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Hz</td>
<td>Short</td>
<td>Small</td>
<td>$-25.12 + 0.70x$</td>
<td>0.94</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Short</td>
<td>Large</td>
<td>$-38.37 + 0.68x$</td>
<td>0.98</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Long</td>
<td>Large</td>
<td>$-53.71 + 0.76x$</td>
<td>0.96</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td></td>
<td>3 Hz</td>
<td>Short</td>
<td>Small</td>
<td>$-84.27 + 1.49x$</td>
<td>0.82</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Short</td>
<td>Large</td>
<td>$-26.90 + 0.75x$</td>
<td>0.89</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Long</td>
<td>Large</td>
<td>$-15.68 + 0.53x$</td>
<td>0.79</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td></td>
<td>5 Hz</td>
<td>Short</td>
<td>Small</td>
<td>$-11.30 + 0.70x$</td>
<td>0.85</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Short</td>
<td>Large</td>
<td>$-1.73 + 0.55x$</td>
<td>0.76</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Long</td>
<td>Large</td>
<td>$-6.73 + 0.40x$</td>
<td>0.80</td>
<td>$&lt; 0.001$</td>
</tr>
</tbody>
</table>
FIG. 9. Effect of a step increase or decrease in alveolar ventilation \( (\dot{V}_A) \) on volume of carbon dioxide \( (\dot{V}_{CO_2}) \) entering (in) or leaving the lung (out) and on alveolar \( P_{CO_2} \) \( (P_{A_{CO_2}}) \).

In a steady state the volume of carbon dioxide cleared by the alveolar ventilation equals the volume of carbon dioxide entering the lungs. However, if there is a step change in alveolar ventilation there is a temporary imbalance between the volumes entering and leaving the alveoli. This is illustrated in simplified form in figure 9. The discrepancy between input and output is maximal immediately after the step change and then declines in an approximately exponential fashion until input and output are once again equal. Two points should be noted. First, the change is not a true exponential because the change in alveolar \( P_{CO_2} \) is modified by changes in the input of carbon dioxide as a result of readjustment of body stores. Second, the time constant of this exponential depends on the ratio of the volume of gas in the alveoli to alveolar ventilation, so that the difference between input and output will tend to be larger and to last for a shorter time when the step increase in ventilation is large than when it is small. It is this early period of washout or retention of carbon dioxide which is being measured by the present technique, the time constants of the lung washout (lung volume/minute volume) varying from 12 to 1.5 assuming the lung volume to be approximately 1 litre, and the minute ventilation ranging from 5 to 25 litre min\(^{-1}\) (fig. 3). Thus, most of the change in alveolar \( P_{CO_2} \) would have occurred within the collection period (1 min), and there would have been little change in mixed venous \( P_{CO_2} \) as a result of alteration of body stores. This is confirmed by the measurements of arterial \( P_{CO_2} \) (fig. 10) which show that the change at 2 min was 85% of the change observed at 10 min. Furthermore, there is a strong correlation between the carbon dioxide cleared and change in arterial \( P_{CO_2} \) during this interval (fig. 11).

In order to measure the clearance of carbon dioxide, it is necessary to provide a closed system for its collection. This could have been accomplished by directing a large bias flow of fresh gas across the jet T-piece and collecting the expired gas in a Douglas bag. However, since this would have resulted in extremely low carbon dioxide concentrations in the expired gas the recirculating system was devised. Unfortunately, this added further complications. After connection of the jet the carbon dioxide was transferred to a large, well mixed volume (65.5 litre) with an outflow. If carbon dioxide-rich gas were to flow into this system at a constant rate after connection of the jet, it would wash the air out of the system so that there would be an increase in carbon dioxide concentration within the circuit to values which eventually equalled the concentration in the gas leaving the lungs. In a well-mixed system, the pattern of...
change would be exponential. However, if the input of carbon dioxide varied as shown in figure 9, the pattern of change would be modified accordingly.

The types of change observed when the jet ventilator produced hyper-, normo- or hypoventilation are illustrated in figure 12. Under ideal conditions, the time constant of gas mixing within the circuit (circuit volume/minute volume of the ventilator) should be constant in order to make comparisons between the carbon dioxide cleared and the different conditions of deadspace. Whilst the data presented were obtained when the time constant of the circuit ranged from 1.5 to 13 min, they are considered to be valid for several reasons. First, the inclusion of the circulating fan in the circuit (60 litre min$^{-1}$) minimized any errors attributable to the different circuit time constants, since the time difference between detection of carbon dioxide entering and leaving the circuit was always 3–5 s. Second, the carbon dioxide clearance data at 5 Hz are presented at three different levels of minute ventilation and, therefore, with three different time constants (fig. 7). For each time constant, clearance was significantly decreased when the long deadspace was in position. Third, the results confirm the findings of a similar investigation in which carbon dioxide clearance from a lung analogue was determined by an entirely different technique (Mortimer et al., 1986) and, finally, our observations lend support to the work of others (see below).

There is one other problem associated with the use of the recirculating system: namely, that entrainment of gas from the circuit may cause rebreathing of carbon dioxide. However, previous studies using a jet ventilator on a model lung had indicated that entrainment was only significant when the frequency was less than 3 Hz and the inspiratory/expiratory time ratio was small (Mortimer and Bourgain, 1983). These results were confirmed by connecting the ventilation system used in the present experiments to a model lung. When the jet was driven by compressed air and 5% carbon dioxide in air was circulated round the T-piece system, the mean lung concentration of carbon dioxide in the model lung was 0.2% at 1 Hz, and less than 0.1% at higher frequencies. Since the circuit concentration of carbon dioxide never exceeded 0.5% during the 1-min collection period in the present studies, the error resulting from rebreathing was ignored.

Jet ventilation differs from high frequency...
oscillation in that tidal volume inevitably decreases as frequency increases when inspiratory flow rate is unchanged. At 1 Hz the tidal volumes delivered ranged from 50 ml to 350 ml and the volumes of added deadspace from 25 ml to 60 ml. The volume of the anatomical deadspace in the dog plus the volume of the tracheostomy tube is not known. However, if a figure for anatomical deadspace of 4 ml kg\(^{-1}\) is assumed (Severinghaus and Stupfel, 1955), and if it is assumed that a tracheostomy halves the anatomical deadspace by eliminating the upper airway deadspace, the anatomical deadspace should have been about 20 ml in these dogs. The deadspace of the tracheostomy tube was 16 ml, so that the total deadspace must have been approximately 36 ml. To this was added the short, small volume deadspace of 25 ml, making a total deadspace of 61 ml. At 1 Hz the addition of either the short or long, large volume deadspace decreased elimination of carbon dioxide. As may be seen from figure 4, an increase in tidal volume equal to the difference in volume between the large and small deadspaces (35 ml) compensated for the increased deadspace throughout the range of tidal volumes studied. The system thus behaved as predicted by conventional respiratory physiology.

At 3 Hz the range of tidal volumes studied was smaller (80-150 ml) and a different pattern of carbon dioxide clearance emerged; it was least with the long, large volume deadspace, greatest with the short, small volume deadspace, and intermediate with the short, large volume deadspace. An increase in tidal volume from 80 to 140 ml with the short, small volume deadspace produced approximately the same increase in carbon dioxide clearance that had been observed with this deadspace at 1 Hz, but with the other two deadspaces the increase in tidal volume produced a smaller increase in carbon dioxide clearance (fig. 5).

At 5 Hz a very different pattern of carbon dioxide clearance emerged. Tidal volumes were in the range 45–75 ml (less than the combined conducting airway, tracheostomy tube, and large volume deadspace of 96 ml) and carbon dioxide clearance was greatly reduced. Under these conditions, there were no significant differences between the carbon dioxide clearances with the two short deadspaces, whereas the addition of the long deadspace almost halved clearance (figs 6 and 7). Thus at 5 Hz, the volume of deadspace appeared to be unimportant, whilst an increase in length decreased carbon dioxide clearance.

The importance of the distance between the alveoli and tip of the jet is emphasized by the results of the study in which carbon dioxide clearance was measured with the jet at the proximal and distal ends of the tracheostomy tube (fig. 8). At 1, 3 and 5 Hz, clearance was always highest with the jet placed at the distal end of the tracheostomy tube. The volume of the tracheostomy tube was 20 ml, and at 1 Hz an added minute volume of 60 x 16 ml = 960 ml, resulted in the same carbon dioxide clearance as when the jet was placed at the proximal end of the tube. At any given minute volume, an increase in frequency to 3 or 5 Hz resulted in a marked decrease in clearance, that at 5 Hz being less than carbon dioxide production. Furthermore, at 3 Hz and 5 Hz, marked increases in minute volume were required when the jet was placed proximally to secure the same carbon dioxide clearance as had been obtained with the jet placed distally.

These experiments indicate that clearance of carbon dioxide is most effective when frequency is low. Thus, at 1 Hz with the jet placed proximally, a tidal volume of 166 ml (minute volume = 10 litre) clears approximately 110 ml of carbon dioxide in the first 1 min (fig. 8). To clear a similar volume of carbon dioxide at 3 Hz requires a tidal volume of 122 ml, that is a minute volume of 22 litre and at 5 Hz such a minute volume only clears approximately 40 ml of carbon dioxide per minute.

These experiments suggest that, at frequencies in the range 3–5 Hz when tidal volume is similar to, or less than, the volume of the conducting airways, elimination of carbon dioxide no longer takes place by conventional mechanisms. The mechanisms governing gas exchange at high frequencies have not yet been clarified. Using high frequency oscillation and a physical model, Isabey, Harf and Chang (1984) have measured carbon dioxide elimination with different deadspaces and tidal volumes. They found that an increase in length of the deadspace impaired elimination and that, for small tidal volumes, the computed deadspace was smaller than the true deadspace. Therefore, they concluded that, when tidal volume was close to the volume of the deadspace, convective bulk flow through the core was important. These results are comparable to our data. Another possibility is that augmented diffusion may occur (Fredberg, 1980). In this model, the rate of carbon dioxide elimination should depend only on the product of tidal volume
and frequency, and not on tidal volume or frequency individually. In our study, tidal volume had more influence than frequency on the efficiency of elimination of carbon dioxide. For example, doubling \( V_t \) increased carbon dioxide clearance by 2.3, but multiplying frequency by 3 increased the clearance less than twice. Thus, it is clear that this theory cannot be the sole explanation of gas exchange at low tidal volumes.

It is concluded that, at low frequencies and when tidal volumes exceed the deadspace, elimination of carbon dioxide is predictable in terms of conventional respiratory physiology. However, at higher frequencies and smaller tidal volumes, new concepts must be applied to explain gas exchange.

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