INFLUENCE OF END-EXPIRATORY LUNG VOLUME ON CARBON DIOXIDE ELIMINATION DURING HIGH FREQUENCY VENTILATION IN DOGS

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Oxygen transfer during conventional mechanical ventilation depends on the lung surface area. Varying mean airway pressure by the application of PEEP or by increasing the I:E ratio has been shown to improve oxygenation in animal experiments [1, 2] and in patients [3].

Reports on the influence of lung volume on elimination of carbon dioxide during HFV are contradictory. Results derived from mathematical models of gas transport during high frequency oscillation (HFO) suggest that the efficiency of ventilation should be independent of lung volume [4]. Slutzky and colleagues [5] found no effect of lung volume in dogs during HFO, but other investigators using a tracer gas technique observed a significant change in the decay of xenon-133 when lung volume was altered during HFO [6].

In patients with acute lung failure undergoing ventilation with a different type of HFV termed “forced diffusion ventilation” (FDV) we always observed an increase in $P_aCO_2$, when mean airway pressure was increased at a given minute ventilation. This clinical impression has been verified in dog experiments, using the FDV type of high frequency ventilation.

METHODS

High frequency circuit

Two jets of gas enter the airway at the carina level through a specially designed tracheal tube, with two pressure lines inside its walls (fig. 1) [7]. The gas jets exiting from the tip of the tracheal tube remain coherent until they reach the inner edge of the carina. From this point, gas layers travel down into the lungs without significant mixing. At the same time, a retrograde flow of exhaled gases is established across the remaining bronchial cross section, ultimately leaving the lungs through the tracheal tube [8]. Thus gas transport is dependent on a continuous washout process during forced diffusion ventilation (FDV). With this type of HFV, no entrainment takes place ($V_E$ is always positive) and alveolar pressure amplitude and mean pressure are low.

Experimental model

Ten anaesthetised and paralysed mongrel dogs (mean weight 32 kg) underwent ventilation with FDV at different frequencies. To obviate interference with the FDV, the dogs were placed in
heat exchanger was included in the blower system to prevent an increase in temperature in the dog. The specially prepared tracheal FDV tube, arterial and central venous catheters were led through the front panel of the body box. Expired minute volume ($\dot{V}E$) was measured by a wet spirometer connected to the proximal end of the tracheal tube. The spirometer also acted as a gas mixing chamber so that mean expired carbon dioxide and carbon dioxide elimination ($\dot{V}E$. $FE_{CO_2}$) could also be determined.

**Experiment**

After the dog had been placed in the body box, conventional ventilation was initiated with an Engström Ventilator (ER 300) at a frequency of 12 b.p.m., minute volume approximately 4 litre and $FIO_2$ 0.5. Three lung volume conditions were maintained for periods of at least 20 min: normal end-expiratory resting position of the lungs (atmospheric box pressure); increased end-expiratory lung volume (subatmospheric box pressure of —1 kPa); reduced end-expiratory lung volume (positive box pressure +0.5 kPa).

The positive box pressure was limited to +0.5 kPa to avoid airway closure at low lung volumes. Arterial blood-gas tensions were measured at the end of each period. Carbon dioxide elimination was determined 2 min after transition to a new lung volume. After baseline measure-
CO₂ ELIMINATION DURING HFV

12 b.p.m. IPPV
6Hz FDV
50Hz FDV
Cont. FDV

FIG. 3. Mean (SEM) \(P_{a_{\text{CO}_2}}\) at low (\(\square = \) box pressure + 0.5 kPa), normal (\(\square = \) ambient pressure) and high (\(\blacksquare = \) box pressure — 1 kPa) lung volumes for the different settings of ventilation. For high lung volumes, \(P_{a_{\text{CO}_2}}\) is significantly higher, particularly at higher frequencies. \(n = 10\) dogs.

ments with conventional mechanical ventilation, the previously described sequence of lung volumes was repeated for FDV at frequencies of 6 Hz and 50 Hz and with a continuous flow FDV similar to the so-called “continuous flow apnoeic ventilation” [9]. Expired minute volume was kept constant at 10.5 ± 0.2 litre min⁻¹ for all HFV modes by adjusting the driving pressure.

RESULTS

The high lung volume condition always resulted in an increased arterial \(P_{\text{CO}_2}\) compared with the resting position of the lungs (box pressure = 0) (fig. 3). This effect could be observed during IPPV (0.42 kPa), but it was more pronounced during high frequency ventilation, particularly at 50 Hz (1.06 kPa) and continuous flow ventilation (1.52 kPa). For these two conditions \(P_{a_{\text{CO}_2}}\) was also significantly lower (−0.47 kPa at 50 Hz, −0.74 kPa at continuous flow) with positive box pressures (reduced lung volume) compared with normal expiratory resting position of the lungs (box pressure = 0).

The generally increased \(P_{a_{\text{CO}_2}}\) values at 50 Hz and continuous flow are common findings with FDV when \(\dot{V}_E\) was kept constant. An increase in \(\dot{V}_E\) of approximately 30% would be necessary to maintain normocapnia under these conditions.

Arterial oxygen always ranged between 22.6 kPa and 29.2 kPa with an \(F_{\text{IO}_2}\) of 0.5 and did not correlate with lung volume. Carbon dioxide elimination rates 2 min after a change in lung volume are given in figure 4. The smaller the lung volume, the more carbon dioxide was washed out with a given setting. This could also be demonstrated during IPPV, but again was more pronounced at 50 Hz and continuous flow where changes of ±27% in elimination of carbon dioxide were seen. Similar changes were seen with negative and positive box pressures. It should be noted that carbon dioxide elimination was measured almost immediately after a change in lung volume and not under steady state conditions. It is obvious that carbon dioxide elimination returns to its initial value after a new steady condition is reached at a higher or lower value of \(P_{a_{\text{CO}_2}}\).

DISCUSSION

Our results indicate that end-expiratory lung volume influenced the efficiency of ventilation during FDV. Similar but smaller changes were observed during IPPV. Other authors [10] have demonstrated that PEEP can increase \(V_D/V_T\) in dogs during conventional ventilation. One of the mechanisms involved is the increase in anatomical deadspace as a result of longitudinal and radial stretching of the conductive airways. It seems to be likely that changes in the geometry of the airways could be of greater importance with lower tidal volumes. In addition, some of the mechanisms thought to be responsible for gas transport in the airways during HFV may respond differently to changes in geometry.

Figure 5 shows the influence of lung volume on
the geometry of the first 14 generations of the bronchial tree. The calculations are based on the morphometric data of Weibel which were gathered originally from lungs fixed at a very high level of inflation (75% of total lung capacity (TLC)). The data were transformed to a lower FRC (50% of TLC) according to the mathematical treatment described by Soong and colleagues [11]. The upper panel of figure 5 gives the total airway cross section as a function of the distance from the carina for a high FRC (solid line) and a normal FRC (broken line). The vertical marks on the curves correspond to the generation number. The steep increase in cross sectional area occurred approximately 1.5 cm closer to carina with the lower lung volume.

In the lower panel of figure 5, total airway volume (anatomical deadspace) is plotted as a function of the distance from carina for both lung volumes. The airway volume from carina to the end of the 14th generation is calculated to be approximately 60 ml at the lower FRC, compared with 95 ml at the high inflation stage.

A physical model to measure concentration gradients for carbon dioxide from the site of its production to the central airways may contribute to understanding of the gas transport mechanisms during FDV [12] (fig. 6). It consists of a rubber cast of the first few generations of the bronchial tree inserted into a rigid container of approximately 30 litre capacity. At the bottom of the container a diffusive plate delivers a stable, adjustable flow of carbon dioxide at rates of 100-300 ml min. A T-bar with multiple sampling ports at its horizontal limb may be positioned at variable distances from the diffusive plate. The model is filled with cotton to separate the gas streams discharging from the 21 distal endings of the bronchial tree cast. The distance between carina and carbon dioxide input is matched to the dimensions of the human adult lung. Carbon dioxide is measured by an infra-red absorption analyser connected to the T-bar. To prevent local convective currents, sampling rate is kept low. For the same reason, carbon dioxide must be delivered through a wide surface. By a stepwise positioning of the T-bar, steady state concentration gradients can be scanned along the distance from the carbon dioxide input to the central airways.

Based on the results of this model, gas transport during FDV does not depend so much on gas mixing in the central and small airways as other modes of HFV do, in particular HFO. It seems that FDV carries unmixed fresh gas down to a point where there is a large cross-sectional area of the airways, where a high concentration gradient is built up. Figure 7 shows the results for different settings of FDV. The interface between the “alveolar” concentration (immediately adjacent to the diffusive plate through which carbon dioxide enters the model) and the airway concentration extends only over the first 10 mm or so from the diffusion plate, as indicated by the steep decrease in concentration; even so, fresh gas enters the model some 150 mm upstream. Frequency in this rigid model has no influence on the position of this interface provided $\dot{V}e$ is kept constant. If $\dot{V}e$ increases, the interface is shifted towards the carbon dioxide input, indicating more effective ventilation.
Changes in airway geometry at different lung volumes may alter the ventilatory efficiency of FDV by varying the distance between the gas interface in the conductive airways and the respiratory zone. However, if gas exchange is determined mainly by mixing in the conductive airways, as is probably the case during HFO, lung volume would be of less importance.
REFERENCES


