THE MINIMUM RESERVOIR CAPACITY NECESSARY TO AVOID AIR-DILUTION

An Experimental Model of Spontaneous Breathing through a T-piece

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When a T-piece is used in anaesthesia, the fresh gas flow rate ($\dot{V}_F$) required to avoid rebreathing in spontaneously breathing subjects was recommended by Ayre (1956) to be twice total ventilation ($\dot{V}_F = 2\dot{V}_E$). This recommendation has since been reaffirmed by Onchi, Hayashi, and Ueyama (1957) using theoretical analysis, and by Willis, Pender and Mapleson (1975) using both experimental and theoretical investigation. The minimum reservoir volume ($V_{RM}$) necessary to avoid dilution by air of anaesthetic gases was originally recommended by Ayre to be 30% of tidal volume (0.3$\dot{V}_T$), and was subsequently reduced to 0.2$\dot{V}_T$ by Onchi, Hayashi and Ueyama. The latter recommendation was, however, based on an analysis assuming zero deadspace ($V_D$) and an I:E ratio of 1:1. Under conditions of hyperventilation an I:E ratio of 1:1 may be found but, clearly, zero deadspace is untenable.

It was decided to construct an experimental model of spontaneous breathing through an Ayre's T-piece system, using the recommended fresh gas flow rate, to measure $V_{RM}$ and to compare it with that obtained by theoretical analysis.

MATERIALS AND METHODS

The arrangement of the apparatus is shown diagrammatically in figure 1, and consisted of a 10-litre glass bottle containing a 4-litre bag connected to a T-piece system. To mimic spontaneous respiration, air was blown alternately into or extracted from the bottle by means of a modified Cape-Waine multipurpose ventilator. The I:E ratio of the ventilator was fixed, but the frequency of ventilation ($f$) and the tidal volume

SUMMARY

The fresh gas flow rate necessary to prevent rebreathing in T-piece anaesthesia is well established at twice total ventilation. The minimum reservoir volume to avoid air dilution of anaesthetic gases in the alveolus at this flow rate is, however, undecided. A lung model was constructed to represent spontaneous respiration, and the value of minimum reservoir volume as a proportion of tidal volume determined experimentally. The values so obtained were in close accord with those calculated theoretically. Extension of the theoretical analysis leads to a recommendation that a reservoir volume one-third that of tidal volume, as originally suggested by Ayre in 1956, will prevent air-dilution.

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Fig. 1. Schematic diagram of the apparatus used.
(VT) could be set by use of the standard controls. Lengths of 12-mm diameter tubing were used for the reservoir volume (VR) and deadspace; a length of 5.0 endotracheal tubing was placed in the system to simulate the conditions occurring when an endotracheal tube was used clinically.

Three sampling lines were incorporated in the system: site 1 in VD immediately after VT input; site 2 at the junction between VD and the alveolar volume (VA); site 3 deep into the alveolar space.

The fresh gas source, oxygen-free nitrogen, was fed into the system via a universal rotameter (Gap-meter Lab Kits A6), which had been calibrated previously by the use of an Ohio 840 Spirometer. Before conducting the investigations, the entire system was cleared of air and PA set at 3 litre. A period of 10 min ventilation at the set VT was allowed between changes in the system and a check made to ensure that the model was free of oxygen.

Analyses of gases aspirated from the sample sites were performed by a mass spectrometer (Centronic 200 MGA), set to measure percentage of oxygen. The readings were displayed graphically on a Brush 220 (Gould) chart recorder for later analysis.

Tidal volumes of 300 ml and 500 ml were chosen, with respiratory frequencies of 20 and 12 b.p.m., respectively, enabling VT to be unchanged. Deadspace/tidal volume ratios (VD/VT) of both 0.3 and 0.45 were used. Before each experimental run, VT and PE were verified, in use of an electronic Wrights respiration monitor (BOC) placed in the deadspace.

To obtain experimental values for VRM, VR was decreased gradually until entrained air led to a peak concentration of 1.0% oxygen being found in gas sampled from site 2 (VA–VD junction).

**RESULTS**

Figure 2 illustrates the respiratory waveform of the model in operation, as recorded via a pneumotachograph placed in VD. It displays a sine-wave respiratory pattern with 1:1 ratio of 1:1. Figure 3 illustrates the tidal carbon dioxide waveform recorded from site 1 when carbon dioxide was fed into the working model via site 3. Both tracings authenticate the lung model as a system that may be compared closely to a spontaneously breathing subject.

Figure 4 shows the tracing recorded when gas samples were aspirated for analysis from the sampling lines in rotation when a peak of 1.0% oxygen was registered from site 2.

<table>
<thead>
<tr>
<th>Tidal volume (ml)</th>
<th>VR/VT</th>
<th>Reservoir volume (ml)</th>
<th>Experimental VR/VT</th>
<th>Theoretical VRM/VT</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.300</td>
<td>54</td>
<td>0.180</td>
<td>0.174</td>
</tr>
<tr>
<td>300</td>
<td>0.450</td>
<td>38</td>
<td>0.126</td>
<td>0.123</td>
</tr>
<tr>
<td>500</td>
<td>0.300</td>
<td>92</td>
<td>0.184</td>
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</tr>
<tr>
<td>500</td>
<td>0.450</td>
<td>68</td>
<td>0.136</td>
<td>0.123</td>
</tr>
</tbody>
</table>
The reservoir volumes recorded at this point are listed in table I, as are the values $\frac{V_R}{V_T}$ and the theoretical values $\frac{V_{RM}}{V_T}$. The method of theoretical analysis is listed in the appendix.

**DISCUSSION**

The theoretical analysis of the system is similar to that used by Onchi, Hayashi and Ueyama (1957) and by Willis, Pender and Mapleson (1975). It makes the same assumptions that respiratory pattern is sine-wave in form, and that no longitudinal mixing of gases occurs in the anatomical or apparatus deadspace. During inspissation, gas from $V_R$ is drawn towards $V_A$ only when the inspiratory flow ($V_I$) is greater than $V_F$, and that a proportion of this volume will be retained in $V_D$ and not enter $V_A$. It is further assumed that, for a given $V_E$, the ratio $V_D/V_T$ does not alter with changes in $f$. In practice, some mixing does occur which experimentally led to a gradual increase in detected oxygen as $V_R$ was reduced. It was necessary, therefore, to set a reproducible end-point at which alveolar air dilution started, enabling $V_{RM}$ to be measured. When a peak of 1% oxygen was recorded from site 2, approximately 0.3% was recorded in the alveolar space (fig. 4). This value could be equated to a dilution of alveolar gas by between 1 and 2% air. The experimental $V_R$ recorded at this point can thus be read as $V_{RM}$, and experimental $V_R/V_T = V_{RM}/V_T$ (table I).

The values for $V_{RM}/V_T$ predicted by theoretical analysis are supported by the experimental findings, and follow the expected pattern that, for a fixed $V_T$, as $V_D/V_T$ increases so $V_{RM}/V_T$ decreases (entrained gas being more easily contained in a greater $V_D$ and so not reaching $V_A$). Alterations in $i:E$ ratio also affect $V_{RM}/V_T$, the value increasing as the inspiratory phase of the respiratory cycle shortens (the proportionally increased $V_I$ being greater than $V_F$ during more of the phase, so leading to increased demand for gas from $V_R$). If the values for $V_D/V_T$ and $i:E$ ratio least favourable to $V_{RM}$ are used in the theoretical analysis, a value for $V_{RM}/V_T$ can be calculated that would prevent air entrainment under all circumstances.

Intubated patients breathing spontaneously under halothane anaesthesia have an average $V_D/V_T$ of 0.458 (Kain, Panday and Nunn, 1969). The lower limit is unlikely to be as low as 0.30 when including equipment deadspace. The $i:E$ ratio under similar circumstances depends on several factors, including surgical stimulus, depth of anaesthesia and the use of opiates. A value of 1:2 could be taken as an upper limit under normal anaesthetic conditions. If these values are substituted in the analysis when $V_F = 2V_E$, a value of $V_{RM}/V_T$ of 0.325 is obtained. This figure is in almost exact agreement with that first suggested by Ayre in 1956. In theory, one other factor may make air dilution less likely at $V_{RM}$. $V_F$ is usually measured at atmospheric temperature, pressure dry (ATPS) and $V_E$ at approximately body temperature pressure saturated (BTSS). This may, in effect, alter $V_F$ to equal between 2.0 and 2.256 $V_E$, so making entrainment less likely.

**APPENDIX**

The respiratory waveform and associated volume, flow and time variables are shown in figure 5.

The ratio $V_D/V_T$ has been considered to remain constant regardless of changes in $V_I$ and $V_E$. In each respiratory cycle inspiration lasts for $t_i$ min (fig. 5A) and expiration for $t_e$ min. If the $i:E$ ratio, $R$, is defined as $t_i/t_e$ and $f$ is the respiratory frequency, then

$$\frac{t_i}{f(1+R)}$$

and

$$\frac{R}{f(1+R)}$$

Inspiratory flow $V_I$ is assumed to vary sinusoidally with time $t$. Thus, at time $t$ during inspiration, respiratory flow $\dot{V}_I(t)$ is given by

$$\dot{V}_I(t) = V_{max} \sin \frac{\pi \cdot t}{t_i}$$

$V_{max}$ is peak inspiratory flow, and it can be shown that

$$\dot{V}_{max} = \frac{\pi V_T}{2t_i} = \frac{\pi V_E}{2f \cdot t_i}$$

The line marked $\dot{V}_F$ in figure 5A represents fresh gas flow. Time $t_0$ in figure 5A separates the initial alveolar and later deadspace fractions of $V_T$. These two components are denoted by areas $A$ and $D$ in the same figure.

As

$$V_T \left(1 - \frac{V_D}{V_T}\right) = \int_0^{t_i} V_I \cdot dt = \frac{V_T}{2} \left(1 - \cos \frac{\pi \cdot t_0}{t_i}\right)$$

then

$$t_0 = \frac{t_i}{\pi} \cos^{-1} \left(\frac{2V_D}{V_T} - 1\right)$$

In figure 5C time $t_x$ denotes the time early in inspiration when $\dot{V}_F = \dot{V}_I$. Equating $\dot{V}_I(t)$ to $\dot{V}_F$ and $t$ to $t_x$ in equation (1) and solving for $t_x$ gives

$$t_x = \frac{t_i}{\pi} \sin^{-1} \left(\frac{2V_F \cdot f \cdot t_i}{\pi V_E}\right)$$

The volume of gas inspired up to time $t_x$, $V_x$, is given by

$$V_x = \frac{V_T}{2} \left(1 - \cos \frac{\pi \cdot t_x}{t_i}\right)$$
FIG. 5. A: Displays the respiratory waveform and defines some of the respiratory parameters. B: Definition of time $t_a$, which separates the initial alveolar and later deadspace fractions of tidal gas. C: Definition of $t_x$ as the time in early inspiration when fresh gas flow equals the inspiratory flow. D: Definition of $V_{RM}$, which represents the volume of gas entering the alveolar space whilst inspiratory flow exceeds fresh gas flow.

In figure 5D the area marked $V_{RM}$ represents the volume of gas entering the alveolar space from the reservoir limb whilst $\dot{V}_T > \dot{V}_F$. To prevent atmospheric air entering the alveolar space, the reservoir must have a capacity equal to or greater than the volume represented by $V_{RM}$. Thus $V_{RM}$—the minimum reservoir volume—is given by:

$$V_{RM} = V_T \left( 1 - \frac{V_D}{V_T} \right) - V_x - \dot{V}_F(t_a - t_x) \quad (5)$$

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REFERENCES