RESISTANCE TO AIRFLOW IN ANAESTHETIC BREATHING SYSTEMS

D. G. MARTIN, K. L. KONG AND G. T. R. LEWIS

The resistance to airflow of the components of breathing systems have been examined previously. Tracheal tubes and their connectors have been studied by a number of authors [1,2] and expiratory valves by others [3,4]. Smith [5] examined the resistance of the Magill system for both separate and assembled components. Shandro [6] studied the Ayre's T-piece, Bain and several circle systems.

Several new breathing systems have been developed in recent years, and changes have been introduced, into both the design of their components and the materials used. These changes may have affected the resistance to gas flow.

The aim of this study was to investigate the resistance to airflow in some of the commonly used anaesthetic breathing systems under standardized conditions.

METHODS

The apparatus used to measure resistance to airflow was described by Gaensler and colleagues [7] and is shown in figure 1.

Air was supplied from a cylinder through a variable pressure regulator (Murex Saffire BS 5741). The airflow rate was controlled by a needle valve and measured by a flowmeter (Platon Gap Meter type GTLK laboratory flow meter). The air was passed into a 10-litre glass bottle, which was used to avoid any Venturi effect [8]. The outlet of this bottle was fitted with a standard 22-mm male connector, to which apparatus under investigation was connected either directly or via a 22-mm female–female adaptor. The inside of the glass bottle was connected by a tube to one limb of a U-tube manometer, the other limb of which was open to the atmosphere. Thus this manometer measured the changes in pressure produced by air.

SUMMARY

We have examined, under reproducible conditions, the resistance to airflow of complete anaesthetic breathing systems (Magill, Coaxial Lack, Parallel Lack and Bain systems) and components of these systems. All systems had resistances within the recommended ranges at all flows likely to be experienced in normal clinical practice. The Magill system had the lowest resistance under all conditions. It is concluded that comparisons should be made only between complete breathing systems.
AIRFLOW RESISTANCE

flowing through the apparatus under test. The U-tube manometer used was accurate to ±10 Pa. In the case of the corrugated and smooth-bore breathing tubes, angle piece and catheter mount, an inclined angle manometer accurate to ±5 Pa was used.

All the tests were conducted at 20 (SD 3) °C after the apparatus had been equilibrated at that temperature for at least 1 h. Flow rates of 10–100 litre min⁻¹ in ascending and then descending steps of 10 litre min⁻¹ were used. Each reading was taken after allowing the pressure in the apparatus to stabilize for at least 30 s. The reading at each flow step was repeated three times and the average of the sets of readings obtained was taken.

The tests were carried out with the breathing system laid out straight and unstretched on a bench and repeated with the system coiled once through 360° around a 5-cm diameter mandrel.

The specifications of the breathing apparatus examined are shown in table I. The direction of gas flow through the systems during inspiration and expiration is demonstrated in figure 2.

**RESULTS**

It was found that a breathing system composed of the same set of components produced consistent results on different days with barometric pressures of 750–780 mg Hg. However, there was a variable increase in the pressure changes during

<p>| Table I: Dimensions of breathing systems studied. Lack 1 = Coaxial Lack system (MIE Ltd); Lack 2 = Parallel Lack system (Tricomed Ltd); Bain manufactured by Blease Medical Ltd. *Allowing for the cross-sectional area of the inner tube (outer diameter of inner tube = 19 mm in Lack 1 system and 10 mm in Bain system) |</p>
<table>
<thead>
<tr>
<th>Minimum internal diameter (mm)</th>
<th>Minimum cross-sectional area (mm²)</th>
<th>Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magill</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Lack 1</td>
<td>28</td>
<td>15</td>
</tr>
<tr>
<td>Lack 2</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Bain</td>
<td>22</td>
<td>22</td>
</tr>
</tbody>
</table>

Fig. 2. Direction of airflow through the breathing systems in inspiratory and expiratory modes.
air flow in sets of a breathing system with different degrees of use. Therefore, unused breathing systems were used throughout this study.

The pressure changes produced by air flowing through the corrugated and smooth-bore tubes are shown in figure 3.

The pressure changes in the Magill, Lack 1 (Coaxial) and 2 (Parallel) and Bain systems produced by air flow in the inspiratory and expiratory directions are shown in figures 4-7. The results presented were obtained with the adjustable pressure limiting (APL) valve closed in the inspiratory mode and open in the expiratory mode. It was found that, in the inspiratory mode, there was no difference in the values obtained with the APL valve open and closed, except at very high flows in systems including the catheter mount when high pressures were generated.

The pressure changes obtained with the breathing systems at air flows of 10, 30 and 60 litre min⁻¹ are summarized in table II.

The gradients of the relationship between log pressure and log flow are shown in table III. These were obtained by calculating the regression equation of the line. The gradients of log pressure difference against log flow can be used to determine whether flow is laminar, transitional or turbulent (see Appendix).

### Table II. Pressure differences (Pa) in the breathing systems (straight)

<table>
<thead>
<tr>
<th>System</th>
<th>Inspiratory flow</th>
<th>Expiratory flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magill</td>
<td>Lack 1</td>
</tr>
<tr>
<td>Inspiratory flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>30</td>
<td>13</td>
<td>33</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
<td>113</td>
</tr>
</tbody>
</table>

FIG. 3. Pressure differences produced by airflow through corrugated tubes (internal diameter 22 mm): straight ▲—▲ or coiled ▲—▲; and smooth bore Rusch tubes (internal diameter 15 mm): straight ○—○ or coiled ○—○.
DISCUSSION

Breathing systems should be studied as a whole when considering their resistance to breathing. When a number of resistors are joined to form a breathing system they interact in a complex manner. Adjacent components may have unpredictable effects on the resistance to air flow in each other [9]. Thus the total resistance of a breathing system is not the simple sum of the resistances of its component parts. This complex interaction is demonstrated clearly by the effects of adding a catheter mount or angle piece to the system.

It may be seen from the gradients of the log–log plots (table III) that the flow in anaesthetic breathing systems was almost exclusively turbulent in the direction of inspiratory flow (see Appendix). The pressure changes in anaesthetic breathing systems depend, therefore, on the density of the gas rather than its viscosity, in addition to the diameter and length of the tubes. However, the flow in the expiratory direction appears to be less turbulent. This is because the expiratory valve opens progressively as flow increases, tending to produce a constant pressure difference, thus reducing the gradient of the log

<table>
<thead>
<tr>
<th>System</th>
<th>Inspiration</th>
<th>Expiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magill</td>
<td>2.17 (0.069)</td>
<td>0.807 (0.005)</td>
</tr>
<tr>
<td>Lack 1</td>
<td>1.52 (0.054)</td>
<td>1.19 (0.036)</td>
</tr>
<tr>
<td>Lack 2</td>
<td>2.05 (0.035)</td>
<td>1.37 (0.019)</td>
</tr>
<tr>
<td>Bain</td>
<td>1.78 (0.018)</td>
<td>1.37 (0.022)</td>
</tr>
</tbody>
</table>
pressure–log flow relationship of the system. The effect of the expiratory valve alone is demonstrated clearly in the Magill system in expiration, resulting in a gradient of less than 1. It was noted that the log pressure–log flow plots showed no sudden change in gradient, suggesting that the expiratory valves are not open fully at flow rates of up to 100 litre min⁻¹. Our results (table II) showed that the expiratory valves in the systems studied have remarkably low opening pressures of less than 80 Pa and resistances of only 125–150 Pa at flows of 30 litre min⁻¹. These results are similar to those described by Nott and Norman [4].

The increased work of breathing produced by anaesthetic breathing systems has been regarded as a more relevant measure of their suitability [5,10]. However, the work of breathing is a function of the pressure difference across the resistance [11] and there is little difference in the clinical value of data obtained from the work of breathing and that from the resistance to air flow [5]. As it is difficult to produce a standardized sinusoidal gas flow [5], the pressure changes produced by the resistance of a system to continuous air flow is the most practical measure when comparing breathing systems under standardized conditions.

Nunn [12] has suggested that pressures greater than 3 cm H₂O (294 Pa) at flows of 30 litre min⁻¹.
and 6 cm H₂O (588 Pa) at flows of 60 litre min⁻¹ represent excessively high resistances, likely to produce physiological disturbances. This study shows that only relatively small changes in pressure occur at gas flows within the physiological range in all the systems investigated. However, it must be remembered that, in the typical anaesthetized patient, the total resistance to breathing may be much higher because of the extra resistance of tracheal tubes and that of the patient’s bronchial tree.

APPENDIX

Reynolds [13] postulated a general law for all types of flow in a system:

\[
\left( \frac{k_1 P r^3}{\nu^2} \right) = \left( \frac{k_2 \bar{u}^n}{\rho} \right)
\]

where \( k_1 \) and \( k_2 \) are constants; \( \nu \) = kinematic viscosity (\( \eta/\rho \)); \( \bar{u} \) = mean velocity; \( \rho \) = pressure needed to maintain a constant flow; \( r \) = radius of the tube; \( n \) = a variable exponent which has the value 1.0 for laminar flow and 2.0 for turbulent flow.

The above equations are stated in terms of \( \bar{u} \), the linear velocity. They can be restated in terms of flow rate by volume \( \dot{V} \), where \( \dot{V} \) = \( \pi r^2 \bar{u} \) units per unit of time:

\[
\left( \frac{k_1 P r^3}{\nu^2} \right) = \left( \frac{k_2 \dot{V}}{\pi \nu r \bar{u}} \right)^n
\]

thus

\[
P_{\text{Fl}} \dot{V}^n
\]

thus

\[
\log P_{\text{Fl}} = n \log \dot{V}
\]

therefore, if \( \log P \) is plotted against \( \log \dot{V} \), the gradient of the line through these points is \( n \). If \( n = 1.0 \), flow is laminar; if \( n = 2.0 \), flow is turbulent.

REFERENCES

13. Reynolds O. An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. *Philosophical Transactions* 1883; 174: 935-982.