AYRE'S T-PIECE: A REVIEW OF ITS MODIFICATIONS
BY
G. A. HARRISON
Department of Anaesthetics, Welsh National School of Medicine, Cardiff, Wales

SUMMARY
The modifications of Ayre's T-piece system can be divided into three types. In the first there is no expiratory limb, in the second the capacity of the expiratory limb is greater than the tidal volume, and in the third the capacity of the expiratory limb is less than the tidal volume. On the basis of previous mathematical and laboratory investigations by other authors, the three types are discussed with reference to the resistance to respiration and minimum fresh gas flow required to prevent rebreathing and air dilution during both spontaneous and controlled ventilation. The resistance and the fresh gas flow requirements are related to the expiratory flow rates and respiratory flow patterns which occur in children. It is suggested that the most convenient system is a T-piece of 10 mm diameter with an expiratory limb greater than the tidal volume and a bag attached to the expiratory limb. A fresh gas flow of up to 2½–3 times the minute volume is required.

The T-piece system was described originally by Ayre (1937a) for endotracheal anaesthesia of infants and young children undergoing operations for the repair of a harelip or cleft palate. He also used the system successfully for neurosurgical anaesthesia (Ayre, 1937b). The diameter of the T-piece was 10 mm and the expiratory limb was short, so air was often inhaled in addition to fresh gases. Ayre stressed that the major advantage of the arrangement was the low resistance to respiration.

The original system has been modified by many workers. Brooks, Stuart and Gabel (1958) illustrated eighteen variations but their list is by no means complete. Ayre (1956) felt that the essential simplicity of the apparatus was becoming "lost in a tangled web of expiratory valves and corrugated tubing". The many modifications can, however, be classified into three major types. In type 1 the T-piece is used without an expiratory limb (fig. 1a) or the fresh gas flow is directed into the endotracheal tube with a side hole for expiration (fig. 1b). The patient's lungs can be inflated by intermittently occluding the expiratory orifice with a finger. In type 2 the T-piece has an expiratory limb with a capacity greater than the patient's tidal volume so that room air cannot be inspired (fig. 2a). The lungs can be inflated by a variety of methods. The end of the expiratory limb can be intermittently occluded with a finger or a bag can be attached to the expiratory limb and artificial ventilation carried out manually with positive-atmospheric (Rees, 1950) (fig. 2b) or positive-negative (Eger and Hamilton, 1958) (fig. 2c) pressures. An automatic ventilator can be used in the same way (Keuskamp, 1963) (fig. 2d). In type 3 the T-piece has a smaller capacity than the tidal volume, so that in certain circumstances room air is inspired. Artificial ventilation is performed by methods similar to those in type 2. Further minor modifications can be made to each system by altering the angle at which the fresh gas meets the patient's expiratory flow (fig. 4).

The anaesthetist is mainly concerned with the fresh gas flow required to prevent the inspiration
Examples of type 2 modifications of Ayre’s T-piece. The expiratory limb has a capacity greater than the patient’s tidal volume.

(a) For spontaneous ventilation.
(b) With bag for manual positive-atmospheric ventilation.
(c) With injector and bag for manual positive-negative ventilation.
(d) With a ventilator for automatic ventilation.

Examples of type 3 modifications of Ayre’s T-piece. The expiratory limb has a capacity less than the patient’s tidal volume. The purpose of each modification is the same as listed in figure 2.

Modifications of Ayre’s T-piece based on the angle at which the fresh gases meet the patient’s expiratory flow.

FGF = Direction of fresh gas flow.
P = Direction of patient’s expiratory flow.
(a) Right angle. (b) Acute angle. (c) Obtuse angle.

Of expired gases or room air, and the resistance to respiration during both spontaneous and controlled ventilation.

FRESH GAS FLOW REQUIRED TO PREVENT THE INSPIRATION OF EXPIRED GASES OR ROOM AIR

Type 1 (No expiratory limb).

Spontaneous respiration.

Rebreathing of expired gases cannot occur with this system, but room air may be inspired. To prevent dilution of the anaesthetic mixture the fresh gas flow must be at least equal to the peak inspiratory flow. In babies during anaesthesia the respiratory flow pattern at very high respiratory rates resembles a sine wave with an inspiratory: expiratory (I:E) ratio of 1:1 (Harrison, 1964). The peak flow of this wave form is 3.1 times the minute volume, so that in babies with respiratory rates of over 70 per minute a fresh gas flow of at least 3 times the minute volume is necessary to prevent air dilution. At slower respiratory rates in babies and children expiration becomes longer relative to inspiration. With an I:E ratio of 1:2 and an inspiratory flow pattern resembling a half-cycle of a sine wave the peak inspiratory flow is 4.7 times the minute volume. In clinical practice a fresh gas flow of 4 to 5 times the minute volume is probably necessary to prevent air dilution in the system when used for children. Lewis and Spoerel (1961) investigated a type 1 system using a Starling pump to represent the lungs. They found that a fresh gas flow of as much as 5 times the minute volume was required to avoid air dilution. With a fresh gas flow of 2.5 times the minute volume approximately 25 per cent of the inspired mixture was air.

Controlled respiration.

The lungs can be inflated by intermittently occluding the expiratory opening. Neither rebreathing of expired gases nor air dilution can occur at any fresh gas flow. The system behaves as a constant flow generator (Mapleson, 1962) and the tidal volume is determined by the fresh gas flow and the time for which the expiratory opening is occluded.

Type 2 (Expiratory limb capacity greater than tidal volume).

Spontaneous respiration.

Air dilution of the anaesthetic mixture cannot
The fresh gas flow required to prevent rebreathing has been estimated by Mapleson (1958) and Onchi, Hayashi and Ueyama (1957) and investigated with laboratory models by Woolmer and Lind (1954), Inkster (1956) and Harrison (1964). The results suggest that a fresh gas flow of as much as 2–3 times the minute volume is necessary with the respiratory flow patterns which occur in babies and young children. It is not necessary for the fresh gas flow to equal the peak inspiratory flow, as the expiratory limb forms a reservoir in which fresh gases collect during the early part of inspiration and during any expiratory pause during expiration. If the fresh gas flow is decreased steadily while the minute volume remains constant, when rebreathing starts the inspired carbon dioxide concentrations rise slowly at first then very rapidly (Mapleson, 1958). However, the use of a T-piece with a capacity greater than the tidal volume or the attachment of a bag to it cannot further increase the amount of rebreathing in the system at any fresh gas flow, as none of the inspired gases are derived from the distal end of the expiratory limb. The fresh gas flow requirements have been estimated for an expiratory limb in which there is little longitudinal mixing of gases. It is possible that the use of a very wide expiratory limb requires higher fresh gas flows than discussed above.

**Controlled respiration.**

If the lungs are inflated by intermittently occluding the end of the expiratory limb the system behaves in the same way as type 1 and rebreathing does not occur. The fresh gas flow required with the other methods shown in figure 2 depends on the respiratory flow pattern but up to 3 times the minute volume is probably sufficient unless the inspiratory flow pattern is “peaky” and the expiratory pattern prolonged with no expiratory pause in flow (Harrison, 1964).

**Type 3 (Expiratory limb capacity less than tidal volume).**

**Spontaneous ventilation.**

Many of the features of types 1 and 3 are present in this system. If the fresh gas flow is as great as the peak inspiratory flow neither rebreathing of expired gases nor room air occurs. If the fresh gas flow is less than peak inspiratory flow some volume of gases is inspired from the expiratory limb. If this volume is less than the capacity of the expiratory limb, air cannot be inspired but rebreathing may occur. If the volume is greater than the capacity of the expiratory limb, air dilution occurs and rebreathing may take place. There are some differences in the results of the studies on this system depending on the apparatus used and the respiratory wave form assumed. Inkster (1956) used a pump to represent the lungs. His graphs suggest that with a fresh gas flow of 1.5 times the minute volume and an expiratory limb of a capacity one-third the tidal volume, slight rebreathing occurs, and 35 per cent of the inspired mixture is air. Onchi, Hayashi and Ueyama (1957) suggested that under the same conditions there is no air dilution but 13 per cent of the expired air is rebreathed. The graphs of Mapleson (1958) also show very little air dilution but significant rebreathing at a similar fresh gas flow and T-piece capacity. It seems that a fresh gas flow of at least 2.5 times the minute volume is the most satisfactory if rebreathing and air dilution are to be avoided (Inkster, 1956). The system then behaves in the same way as type 2.

An advantage of type 3 with a very short expiratory limb is that rebreathing is limited. If the minute volume increases while the fresh gas flow remains constant more room air is inspired while the inspired carbon dioxide concentration rises only a little. Under the same circumstance the inspired carbon dioxide concentration with a type 2 system is higher (Mapleson, 1958).

This advantage of a type 3 system disappears if a bag is attached to the end of the expiratory limb.

**Controlled respiration.**

If the expiratory limb is occluded intermittently the system becomes identical to types 1 and 2. The effect on the fresh gas requirements when artificial ventilation is carried out with a bag or ventilator has not been investigated, but it is likely that the fresh gas flow must be at least as great as with type 2. Air dilution may occur if a ventilator which delivers air is used.

Table 1 is a summary of the fresh gas flow requirements for each type of system.
TABLE I
Summary of the fresh gas flow/minute volume ratios required to prevent rebreathing or air dilution in T-piece systems during spontaneous, manual and automatic ventilation. Rebreathing or air dilution does not occur.

<table>
<thead>
<tr>
<th></th>
<th>To prevent rebreathing</th>
<th>To prevent air dilution</th>
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<tbody>
<tr>
<td></td>
<td>Spontaneous Manual Automatic</td>
<td>Spontaneous Manual Automatic</td>
</tr>
<tr>
<td>No expiratory limb</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Expiratory limb &gt; tidal volume</td>
<td>2.5–3</td>
<td>2.5–3</td>
</tr>
<tr>
<td>Expiratory limb &lt; tidal volume</td>
<td>2.5–3</td>
<td>2.5–3</td>
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TABLE II
The approximate total peak flow (fresh gas flow + patient's peak expiratory flow) in the expiratory limb of a T-piece system for children of 1, 3 and 5 years. The peak expiratory flows are based on measurements by the author and the minute volumes are assumed.

<table>
<thead>
<tr>
<th>Age in years</th>
<th>Peak expiratory flow (l./min)</th>
<th>Minute volume (litre)</th>
<th>Fresh gas flow</th>
<th>Peak flow in expiratory limb (l./min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FGF MV =2.5</td>
<td>FGF MV =5</td>
<td></td>
<td>FGF MV =2.5</td>
</tr>
<tr>
<td>1</td>
<td>3.7</td>
<td>7.5</td>
<td>10.3</td>
<td>14.1</td>
</tr>
<tr>
<td>3</td>
<td>5.0</td>
<td>10.0</td>
<td>13.0</td>
<td>18.0</td>
</tr>
<tr>
<td>5</td>
<td>7.5</td>
<td>15.0</td>
<td>16.7</td>
<td>24.2</td>
</tr>
</tbody>
</table>

THE RESISTANCE TO RESPIRATION
The most important manifestation of the resistance to expiration in each type is the pressure difference across the expiratory opening at the flow rate of gases met in clinical practice. The highest flow rate of gases through this orifice is given by the sum of the patient's peak expiratory flow rate and the fresh gas flow. Table II shows the average maximum expiratory flow rates for a 1-, 3- and 5-year-old child measured by the author with a pneumotachometer in 70 children during halothane and oxygen anaesthesia. The table also shows the total flow of gases which passes through the expiratory opening at minute volumes which might occur in each age group with the maximum fresh gas flows required to prevent air dilution and rebreathing. The pressure drop which these flows produce across the expiratory opening should be compared with the normal pressure drop on a child's airway during expiration. The pressure drop in the airway is not known but is probably about 2 cm H₂O as judged by the peak expiratory flows and calculated airway resistance for each age group (Mushin, Mapleson and Lunn, 1962).

Type I (No expiratory limb).
Lewis and Spoerel (1961) investigated the resistance to flow in the system shown in figure 1b. When the expiratory opening had a diameter of 12 mm they found a pressure drop of 1 cm H₂O at 25 l./min and 0.5 cm H₂O at 15 l./min. With an opening of 10 mm diameter the pressure drop was 3 cm H₂O at 25 l./min and 1 cm H₂O at 15 l./min. If an increase of 1 cm H₂O in the pressure drop is accepted as a reasonable addition to the normal pressure drop across the airway, the system offers only slight resistance to expiration in children under 3 years when the expiratory opening is 10 mm diameter and the fresh gas flow is sufficient to prevent air dilution. For older children a fresh gas flow less than 5 times the minute volume or an opening greater...
than 10 mm diameter is necessary to restrict the pressure drop to 1 cm H₂O.

Types 2 and 3 (Expiratory limb capacities greater and less than tidal volume).

The resistance in these two systems is similar, as, within reasonable limits, the length of the expiratory limb produces only a small increase in the pressure drop (Onchi, Hayashi and Ueyama, 1957). Brooks, Stuart and Gabel (1958) investigated the resistance experimentally and clinically. With a constant fresh gas flow of 8 l./min and a T-piece of 10 mm diameter the pressure drop was less than 0.5 cm H₂O with flows through the T-piece of up to 30 l./min. The marked difference of these results as compared with those of Lewis and Spoerel may be due in part to the methods of measurement (Lewis and Spoerel, 1961). There was less pressure drop when the fresh gas flow met the expiratory flow at an acute angle (fig. 4b) and more when the angle was obtuse (fig. 4c). These differences were only marked at flows of 40 l./min with a Y-piece of 6 mm diameter, a combination unlikely to occur in clinical practice. With a bag attached to the expiratory limb the resistance is similar provided that the bag does not become distended during expiration. With an automatic ventilator attached to the expiratory limb the resistance depends on the type of expiratory or spill valve in the ventilator.

CONCLUSION

Each type of modification of the Ayre T-piece can be used successfully for clinical anaesthesia. Provided that the diameter for expiration is at least 10 mm, as recommended by Ayre, each type has a low resistance; although systems in which the fresh gases flow against the expiratory stream are associated with the highest resistance. Type 1 has the advantage that rebreathing cannot occur but air dilution may be inconvenient if conservation of the fresh gases is desired. In addition, there is some danger that the expiratory opening may become occluded by the surgical drapes with a sudden and excessive rise in intra-alveolar pressure. Types 2 and 3 offer the advantage that lower fresh gas flows may be used with type 1 without air dilution, but rebreathing may occur. At low fresh gas flows rebreathing is greatest with type 2, as air dilution in type 3 limits the inhaled carbon dioxide concentration. However, as the tidal volume of a child varies considerably during anaesthesia (Harrison and Wilson, in preparation) it is difficult with a type 3 system to use an expiratory limb the capacity of which is a constant fraction of the tidal volume. With an increase in the patient’s tidal volume there is a greater chance of air dilution; but with a decrease in the tidal volume, there is an increased chance of rebreathing. With a fresh gas flow of 2½–3 times the minute volume neither air dilution nor rebreathing occurs in either type and type 2 offers the convenience of maintaining the expiratory opening remote from the surgical fields or drapes. A bag can be attached to the expiratory limb and artificial ventilation carried out without a change in the fresh gas flow/minute volume ratio and without the necessity of disturbing the surgical field in operations on the head and neck.

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REFERENCES


**LA PIÈCE EN T DITE D'AYRE ET SES MODIFICATIONS**

**SOMMAIRE**

On peut repartir les modifications possibles des systèmes utilisant la pièce T d'Ayre en trois types ou catégories. Dans la première il n'y a pas de partie assurant l'expiration, dans la seconde la capacité de cette partie est plus grande que nécessaire pour l'air d'expiration normal et dans la troisième sa capacité est moindre. — Se basant sur les recherches antérieures (calculs mathématiques et études de laboratoire) faites par d'autres auteurs, l'auteur discute la résistance à la respiration et l'influx minimum d'air frais requis pour empêcher la ré-aspiration et la dilution d'air frais pendant la ventilation spontanée et "contrôlée" (surveillée). Résistance et besoin de gaz frais sont fonction de la vitesse du flux d'expiration et des types d'expiration existant chez les enfants. L'auteur considère comme le meilleur système celui comportant une pièce en T de 10 mm de diamètre avec une branche d'expiration plus ample ne nécessiterait le volume d'air d'expiration courant. A cette branche serait attaché un sac. En principe un flux de gaz frais de 2 fois 1/2 à 3 fois le volume/minute est nécessaire.

**DAS AYRE T-STÜCK, EINE ÜBERSICHT ÜBER DIE MODIFIKATIONEN**

**ZUSAMMENFASSUNG**


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