THE EFFECT OF THE RESPIRATORY FLOW PATTERN ON REBREATHING IN A T-PIECE SYSTEM

BY

G. A. HARRISON

Department of Anaesthetics, Welsh National School of Medicine, Cardiff, Wales

SUMMARY

The effect of the respiratory flow pattern on the fresh gas flow required to prevent rebreathing in a T-piece system was investigated using laboratory models. With a sine wave pattern slightly less than \(2\frac{1}{2}\) times the minute volume was necessary. With the flow patterns produced by the ventilators studied, up to 3 times the minute volume was required. It is suggested that during artificial ventilation with certain flow patterns higher fresh gas flows may be required.

The T-piece system (Ayre, 1937) (fig. 1a) is commonly used for children who are breathing spontaneously during anaesthesia. If the capacity of the expiratory limb is large enough to prevent dilution of the inspired gases by air, the fresh gas flow must be high enough to avoid rebreathing of expired gases. The fresh gas flow required is affected by the respiratory flow pattern. In a mathematical analysis Onchi, Hayashi and Ueyama (1957) assumed that the respiratory flow during spontaneous ventilation resembles a sine wave and suggested a fresh gas flow of over \(3\) times the minute volume. Mapleson (1958) assumed a square wave flow and suggested a fresh gas flow of twice the minute volume if the inspiratory/expiratory ratio is \(1:1\), and \(3\) times the minute volume if the inspiratory/expiratory ratio is \(1:2\). Inkster (1956) investigated the T-piece system using a pump to represent the lungs and found that a fresh gas flow of as much as \(2\frac{1}{2}\) times the minute volume may be required to prevent rebreathing. The pattern of respiratory flow produced by the pump was not stated but probably resembled a sine wave.

When the patient is apnoeic the lungs can be inflated by using a bag (Rees, 1950) (fig. 1b) or by an automatic ventilator (Keuskamp, 1963) attached to the end of the expiratory limb (fig. 1c). During spontaneous and controlled respiration the flow pattern of gases through the respiratory tract and the T-piece are different. The effect of this change of respiratory flow pattern on the fresh gas flow required to prevent rebreathing has not been investigated and this paper describes such a study with laboratory models.

![Diagram](https://example.com/diagram.png)

**Fig. 1** Ayre's T-piece and two modifications.

(a) T-piece for spontaneous respiration.
(b) Bag attached to expiratory limb for controlled manual ventilation.
(c) Ventilator attached to expiratory limb for automatic ventilation.

(1) Fresh gas.
(2) Patient.
(3) Expiratory limb.
(4) Bag.
(5) Tap.
(6) Ventilator and spill valve.

METHOD

Two experimental arrangements were used.

**Circuit I** (fig. 2).

This was almost identical with the arrangement described by Voss (1963) for the investigation of the deadspace in some types of apparatus for paediatric anaesthesia. A closely similar experimental procedure was followed.

An Ayre's T-piece of 12 mm internal diameter and 52 mm length was attached by a short length of tubing to a unidirectional circle system. The expiratory limb consisted of a tube of 20 mm internal diameter with a total volume of 250 ml. This was greater than any of the tidal volumes used in
the experiments so that dilution of the system by air did not occur. A piston pump with an independently variable stroke volume and frequency provided the ventilation. At the start of each experiment the size of the total deadspace (stippled area in fig. 2), as measured by the volume of water it could contain, was adjusted until it was one-third of the tidal volume.

At the start and finish of each experiment the ventilation and respiratory flow pattern at the maximum and minimum fresh gas flows were recorded with a pneumotachometer which was placed between the Ayre's T-piece and the circle system.

The total deadspace at each fresh gas flow was calculated from the following formula, which was employed by Voss (1963).

\[ V_D = V_T - \frac{V_{CO_2}}{F_{ACO_2} \times f} \]

where
- \( V_D \) = deadspace
- \( V_T \) = tidal volume
- \( F_{ACO_2} \) = fraction of carbon dioxide in the circle system ("alveolar concentration.")
- \( V_{CO_2} \) = volume of carbon dioxide added per minute.
- \( f \) = frequency of ventilation per minute.

The fresh gas flow necessary to prevent rebreathing was the lowest at which the deadspace was the same as at the highest fresh gas flow.

Circuit II (fig. 3).

The piston pump was replaced by a polyethylene bag in a glass bottle. Provided that the bag did not become distended or collapsed, this arrangement produced a compliance of 8 ml/cm H_2O, equivalent to that of a 1-year-old child (Mushin, Mapleson and Lunn, 1962). Alteration in the size
of the bag was avoided by the occasional intro-
duction of air into the bottle through a three-way
tap. The bag was joined to the same T-piece and
circle arrangement as in system I by a 4-mm endo-
tracheal tube. Ventilation was provided by an
automatic ventilator on the end of the expiratory
limb. Aga, Bird, Cyclator and Jefferson ventila-
tors were used to provide various respiratory
flow patterns, if necessary with a "controlled
leak" to reduce the inspiratory flow (Mushin,

In each case at the start of the experiment the
total deadspace (stippled area in fig. 3) was made
equal to one-third of the tidal volume. When the
minute volume was less than 2 l./min the fresh
gas flow was reduced in steps of 0.5 l./min every
10 minutes. The rest of the experiment was con-
ducted as with circuit I.

RESULTS

The piston pump produced a respiratory flow
pattern which resembled a sine wave with no
pause between expiration and inspiration (fig. 4a).
Over a wide range of tidal volumes, respiratory
rates and minute volumes, the fresh gas flow
required to prevent an increase in deadspace was
from 2 to 2.3 times the minute volume (table I).
When the pump was adjusted so that pauses
existed at the end of expiration and inspiration
(fig. 4b) the fresh gas requirements fell slightly
below twice the minute volume.

The Aga, Bird and Cyclator acted during ins-
piration as constant flow generators (Mapleson,
1962). During expiration the flow was initially
rapid but became slower before the next inspira-
tion began (fig. 4c). With rapid respiratory rates
there was no pause towards the end of expiration
and the fresh gas flow required to prevent an in-
crease in deadspace was as high as 2.8 times the
minute volume. At slower respiratory rates there
was a period towards the end of expiration when
no respiratory flow occurred (expiratory pause).
The longer the expiratory pause (fig. 4d) the lower
was the fresh gas flow/minute volume ratio re-
quired (table I). In some experiments as the fresh
gas flow diminished the minute volume also de-
creased slightly, as a result of the interaction of
flows from the fresh gas source and the ventilator.

<table>
<thead>
<tr>
<th>Tidal volume (ml)</th>
<th>Respiratory rate</th>
<th>Minute volume (l)</th>
<th>Method of ventilation</th>
<th>Expiratory pause (sec)</th>
<th>FGF/MV to prevent rebreathing</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>70</td>
<td>5.2</td>
<td>Piston pump</td>
<td>None</td>
<td>2.3</td>
</tr>
<tr>
<td>66</td>
<td>60</td>
<td>3.9</td>
<td>Piston pump</td>
<td>None</td>
<td>2.1</td>
</tr>
<tr>
<td>58</td>
<td>48</td>
<td>2.8</td>
<td>Piston pump</td>
<td>None</td>
<td>2.2</td>
</tr>
<tr>
<td>75</td>
<td>44</td>
<td>3.3</td>
<td>Piston pump</td>
<td>None</td>
<td>2.1</td>
</tr>
<tr>
<td>103</td>
<td>39</td>
<td>4.0</td>
<td>Piston pump</td>
<td>None</td>
<td>2.0</td>
</tr>
<tr>
<td>44</td>
<td>67</td>
<td>2.9</td>
<td>Piston pump</td>
<td>0.2</td>
<td>1.9</td>
</tr>
<tr>
<td>60</td>
<td>50</td>
<td>3.0</td>
<td>Piston pump</td>
<td>0.2</td>
<td>2.0</td>
</tr>
<tr>
<td>40</td>
<td>75</td>
<td>3.0</td>
<td>Cyclator</td>
<td>None</td>
<td>2.6</td>
</tr>
<tr>
<td>66</td>
<td>53</td>
<td>3.5</td>
<td>Cyclator</td>
<td>None</td>
<td>2.6</td>
</tr>
<tr>
<td>52</td>
<td>34</td>
<td>1.8</td>
<td>Cyclator</td>
<td>None</td>
<td>2.5</td>
</tr>
<tr>
<td>36</td>
<td>47</td>
<td>1.7</td>
<td>Cyclator</td>
<td>None</td>
<td>2.4</td>
</tr>
<tr>
<td>52</td>
<td>34</td>
<td>1.8</td>
<td>Cyclator</td>
<td>0.2</td>
<td>2.3</td>
</tr>
<tr>
<td>53</td>
<td>40</td>
<td>2.1</td>
<td>Cyclator</td>
<td>0.5</td>
<td>1.9</td>
</tr>
<tr>
<td>80</td>
<td>25</td>
<td>2.0</td>
<td>Cyclator</td>
<td>0.7</td>
<td>1.7</td>
</tr>
<tr>
<td>65</td>
<td>60</td>
<td>3.9</td>
<td>Aga</td>
<td>None</td>
<td>2.8</td>
</tr>
<tr>
<td>75</td>
<td>45</td>
<td>3.4</td>
<td>Aga</td>
<td>None</td>
<td>2.6</td>
</tr>
<tr>
<td>75</td>
<td>25</td>
<td>1.9</td>
<td>Aga</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>62</td>
<td>62</td>
<td>3.8</td>
<td>Bird</td>
<td>None</td>
<td>2.6</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
<td>2.4</td>
<td>Bird</td>
<td>None</td>
<td>2.5</td>
</tr>
<tr>
<td>105</td>
<td>21</td>
<td>2.2</td>
<td>Jefferson</td>
<td>None</td>
<td>2.8</td>
</tr>
<tr>
<td>110</td>
<td>19</td>
<td>2.1</td>
<td>Jefferson</td>
<td>None</td>
<td>2.9</td>
</tr>
<tr>
<td>65</td>
<td>25</td>
<td>1.5</td>
<td>Jefferson</td>
<td>None</td>
<td>3.0</td>
</tr>
</tbody>
</table>
EFFECT OF RESPIRATORY FLOW PATTERN ON REBREATHING

Pneumotachographic tracings of the respiratory wave forms investigated for their effect on the fresh gas flow required to prevent rebreathing in a T-piece system.

(a) Piston pump.
(b) Piston pump. Pauses between inspiration and expiration.
(c) Aga, Bird and Cyclator ventilators. No expiratory pause.
(d) Cyclator ventilator. Expiratory pause 0.5 sec.
(e) Aga ventilator. Expiratory pause 1 sec.
(f) Jefferson ventilator.

With the Jefferson ventilator it was possible to produce an inspiratory flow pattern which was triangular in shape. The expiratory flow was slow and continued throughout the phase (fig. 4f). In three experiments the fresh gas flow required to prevent rebreathing was up to three times the minute volume (table I).

DISCUSSION

The flow of fresh gas required to prevent rebreathing in a T-piece system is related to the respiratory flow pattern (fig. 5). This relationship exists during both spontaneous and intermittent positive pressure ventilation.

If the respiratory flow during the early part of inspiration is low, the gases passing into the respiratory tract come from fresh gas flow. In addition, some of the fresh gases pass down the expiratory limb of the T-piece (fig. 5a). At the height of inspiration, if the peak inspiratory flow is not greater than the fresh gas flow $FG_1$, all the inspired gases come from the fresh gas flow (fig. 5b), and no rebreathing of expired gases occurs. Rebreathing of expired gases can always be avoided by using a fresh gas flow at least equal to the peak inspiratory flow. There is, however, no fixed relationship between the peak flow and the minute volume as it is determined by the tidal volume, respiratory rate, inspiratory/expiratory ratio, and the shape of the inspiratory flow pattern (fig. 6). With some patterns of ventilation

<table>
<thead>
<tr>
<th>I:E Ratio</th>
<th>1:1</th>
<th>3:1:1</th>
<th>4:1</th>
<th>2:1</th>
<th>3:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:2</td>
<td>47:1</td>
<td>6:1</td>
<td>3:1</td>
<td>4:1</td>
<td></td>
</tr>
</tbody>
</table>

FIG. 6

The ratio of peak inspiratory flow to minute volume ventilation with various inspiratory flow wave forms at inspiratory/expiratory ratios of 1:1 and 1:2.
it requires an extravagantly high fresh gas flow to equal the peak inspiratory flow. If the fresh gas flow $F_G$ is less than the peak inspiratory flow, some volume (hatched area in fig. 5) is inspired from the expiratory limb (fig. 5c). During expiration both fresh gases and expired gases pass down the expiratory limb (fig. 5d). When there is no respiratory flow during expiration (expiratory pause) fresh gases continue to flow down the expiratory limb, driving expired gases before them (fig. 5e), thus creating a reservoir of fresh gases in the expiratory limb.

When some of the inspired gases will come from the expiratory limb, the composition of these gases depends on the pattern of flow during expiration and inspiration.

**Expiratory flow pattern.**

If the expiratory flow is initially rapid but comparatively slow towards the end of expiration, the gases at the T-piece end of the expiratory limb at the start of inspiration consist mainly of fresh gases. When there is a period of no respiratory flow at the end of expiration there is even less likelihood of expired gases being inspired. Conversely, if the expiratory flow is relatively constant throughout expiration with no pause before inspiration, the gases in the patient's end of the T-piece at the start of inspiration are likely to consist of expired gases as well as fresh gases.

**Inspiratory flow pattern.**

With a slow flow of gases into the respiratory tract at the start of inspiration the fresh gas flow continues to drive expired gases down the expiratory limb so that when the inspiratory flow becomes greater than the fresh gas flow the gases in the patient end of the T-piece are predominantly fresh gases. Conversely, with a rapid early inspiratory flow there is an increased risk of expired gases entering the respiratory tract.

Table II is a summary of the factors which influence the fresh gas flow required to prevent rebreathing.

**Table II**

<table>
<thead>
<tr>
<th>Factors decreasing ratio</th>
<th>Factors increasing ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Square&quot; wave pattern of inspiratory flow</td>
<td>&quot;Peaked&quot; wave pattern of inspiratory flow</td>
</tr>
<tr>
<td>High I:E ratio</td>
<td>Low I:E ratio</td>
</tr>
<tr>
<td>Slow rise in inspiratory flow rate</td>
<td>Rapid rise in inspiratory flow rate</td>
</tr>
<tr>
<td>Low respiratory flow rate late in expiration</td>
<td>High respiratory flow rate late in expiration</td>
</tr>
<tr>
<td>Expiratory pause</td>
<td>No expiratory pause</td>
</tr>
</tbody>
</table>

**CONCLUSION**

**Spontaneous ventilation.**

In older children the respiratory flow pattern is similar to that found in adults. Inspiration resembles a half-cycle of a sine wave and during expiration the flow is at first rapid but then quickly decreases (fig. 7a). An expiratory pause may be present. The younger the child the higher the respiratory rate during anaesthesia. In babies the rate may rise to 100 per minute (Harrison and Wilson, in preparation) and the respiratory flow pattern has a different character from that in the adult.

![Fig. 7](image)

Pneumotachographic tracings of two children during halothane and oxygen anaesthesia.

(a) 20-month-old child. Respiratory rate 30/min.

(b) 1-week-old child. Respiratory rate 100/min.

Inspiration and expiration together resemble a continuous sine wave, the inspiratory/expiratory ratio is approximately 1:1, and there is no respiratory pause (fig. 7b). A sine wave pattern gives an adequate representation of the air flow through the respiratory tract of a young child. The peak inspiratory flow of this wave form is 3.14 times the minute volume but as the initial
inspiratory flow is not rapid it is unlikely that the fresh gas flow need be as high as 3 times the minute volume. The results in this study confirm those of Inkster (1956) that 2½ times the minute volume is a sufficiently high flow to prevent rebreathing.

Artificial ventilation.

The flow patterns produced by automatic ventilators are often complex. Both constant flow and constant pressure generators may produce a rapid increase of flow into the lungs during inspiration (Mapleson, 1962) but wave forms with a slower rate of rise of inspiratory flow may also be achieved. Some ventilators must be modified before they can be used for children (Mushin, Mapleson and Lunn, 1962). The expiratory flow may be slow and continued throughout the phase due to the resistance of valves. In this study, when the initial inspiratory flow was rapid and most of the expiratory flow occurred early in the phase the highest fresh gas flow required was 2.8 times the minute volume. When the expiratory flow was slow and continued throughout expiration up to 3 times the minute volume was required although the initial inspiratory flow was not rapid. In clinical practice higher fresh gas flows will be necessary with the combination of a rapid early inspiratory flow and a slow, continuous expiratory flow with no expiratory pause.

The respiratory rate during artificial ventilation is usually slower than that which occurs during spontaneous ventilation. This slower rate is commonly achieved by increasing the expiratory period so that an expiratory pause exists before inspiration. Under these conditions the fresh gas flow required will be less than three times the minute volume. If the slower rate is achieved by increasing the inspiratory time with the same inspiratory/expiratory ratio the fresh gas flow required will be unaltered.

ACKNOWLEDGMENTS

My thanks are due to Professor W. W. Mushin, Professor of Anaesthetics, Welsh National School of Medicine, for his encouragement during this study. Dr. W. W. Mapleson helped greatly during many discussions on the preparation and interpretation of the experiments. My thanks are also due to Mr. E. K. Hillard, Senior Technician of this Department, for his technical assistance and preparation of the illustrations.

REFERENCES


L’EFFET DU TYPE DE CIRCULATION RESPIRATOIRE SUR LA RÉ-ASPIRATION EVENTUELLE DES GAZ EXPIRES DANS UN APPAREIL À PIÈCE EN T

SOMMAIRE

L’effet de la circulation des gaz exhalés sur le courant de gaz nouveau et sa puissance nécessaire pour empêcher la réabsorption dans un appareil comportant une pièce en T a été examiné avec des méthodes de laboratoire. — Pour empêcher cette ré-absorption dans un appareil "non-alternant" (sine wave), il fallait un peu moins de deux fois et demi de vol./min. normal. Pour les appareils à circulation (flow pattern) produite par les types de ventilateurs étudiés, il fallait jusqu’à trois fois le vol./min. normal. — L’auteur propose de surveiller ce détail: Dans certains systèmes de respiration artificielle "à circulation" (flow pattern) il peut être nécessaire de fournir un influx plus élevé de gaz frais que d’habitude.

DIE AUSWIRKUNG DER RESPIRATORISCHEN STRÖMUNGSVERHÄLTNISSE AUF DIE RÜCKATMUNG IN EINEM T-STÜCK-SYSTEM

ZUSAMMENFASSUNG