Anaesthesia breathing circuits

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During clinical anaesthesia gases pass through a complex conduit interposed between the anaesthesia machine and the patient. This conduit brings gases and vapours to the patient and is an egress for expired substances. New circuits continue to be developed¹⁻⁴ because many factors, including users' priorities, influence design. Attempts at classification of anaesthetic breathing circuits have been numerous and nomenclature is confusing. The three main functions of anaesthesia circuits are (i) delivery of anaesthetic gases and vapours, (ii) oxygenation of the patient, (iii) carbon dioxide elimination from the patient.

In this review a functional classification based on carbon dioxide elimination⁵ is used (Table I). Carbon dioxide is eliminated either by "washout," produced by the fresh gas inflow, or by absorption (soda lime or equivalent). A functional classification is useful because it emphasizes differences in circuit performance based on the manner in which it is used.

Finally, additional important information of secondary consideration is summarized under the headings:

- Breathing circuit resistance, work of breathing and wasted ventilation.
- Breathing circuit malfunction.

TABLE I Classification of anaesthesia breathing circuits

Carbon dioxide washout circuits

- Open (no reservoir bag)
  - Open mask (drop)
  - Insufflation
  - T-piece
- Semi-open (with reservoir bag)
  - Magill circuit
  - Bain system
  - Jackson-Rees system
  - Lack system
  - Mera F system
  - Non-breathing valve systems

Carbon dioxide absorption circuits

- Closed (fresh gas flow = uptake by patient)
- Semi-closed (fresh gas flow > uptake)

No further reference is made to open circuits. They are of historical interest, unless an anaesthetist is faced with the need to construct his own equipment under primitive circumstances. Insufflation techniques may be employed under special circumstances that do not fall within the scope of this review. Consideration of the issues of humidity in breathing circuits, and of transmission of infection is not possible due to space limitations.

Carbon dioxide washout circuits

These comprise those systems not intended to include a carbon dioxide absorption device. As will be examined for each circuit, their performance is influenced by the clinical circumstances under which the circuit is used, particularly whether or not the patient is breathing spontaneously.

Magill circuit (Figure (A))

SPONTANEOUS RESPIRATION

The dynamics of this system are complex. While the fresh gas flow required to avoid rebreathing of carbon dioxide is not influenced by the respiratory waveform, critical factors include the fresh gas flow, setting of the excess gas venting valve, reservoir bag, and volume of the corrugated tubing. Theoretical consideration shows that rebreathing has probably been eliminated if the fresh gas flow is at least equal to the minute volume^{6,7} which is sufficient to maintain normocarbina. In another study a mean fresh gas flow of 82 ml·kg⁻¹·min⁻¹ was required to prevent respiratory stimulation due to rebreathing.⁸ It is difficult to know exactly what gas composition the patient is receiving.

ARTIFICIAL VENTILATION

The variability and unpredictability of the rebreathing of alveolar gas and the venting of fresh gas is

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FIGURE (A) Magill circuit; (B) Bain circuit; (C) Jackson-Rees system; (D) Lack system; (E) Mera F system; (F) Non-breathing valve system; (G) Circle carbon dioxide absorption circuit; (H) To and fro carbon dioxide absorption circuit.

such that Sykes believed artificial ventilation should never be attempted.⁹ Opinions differ, however, and probably normocarbica can be maintained in the adult if the fresh gas flow exceeds $5 \text{ L} \cdot \text{min}^{-1}$ with less emphasis on the tidal volume has been recommended,⁹ but in the light of available information Sykes' conclusion is a wise one in any clinical situation where the anaesthetist must predict accurately the constitution of inspired gases.

Bain Circuit (Figure (B))

SPONTANEOUS RESPIRATION

Use of the Bain Circuit for the spontaneously breath-

ing patient has long been a subject of controversy. Evidence exists that the system can safely be used with a fresh gas flow of $100 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ in suitable patients anaesthetised to retain an adequate carbon dioxide response.¹¹⁻¹³ The concern about the adequacy of such a gas flow is largely based on unpredictable variations in carbon dioxide production ($\dot{V}\text{CO}_2$), minute ventilation, ratio of dead space ventilation to tidal volume ($\dot{V}_D/\dot{V}_T$), and respiratory waveform that occur in the clinical situation. These variations can all influence fresh gas flow requirements.^{14,15} Various formulae to predict fresh gas flow requirements during spontaneous respiration with a Bain circuit have been presented.^{6,13,16-20}

TABLE II Formulae proposed for the calculation of fresh gas flows necessary when a patient is breathing spontaneously through a Bain circuit. Superscripts indicate reference sources.

F.G.F. = $2-3 \times \dot{V}E^6$
= $100 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ¹³
= $3 \times \dot{V}E^{16}$
= $2 \times \dot{V}E^{17}$
= 8 L unless $\dot{V}CO_2$ is more than 250 ml ¹⁸
= Estimated normal ventilation ¹⁹
= $2.5 \times 6 \times \text{kg body weight} \times f(15 \times \text{kg} \times f)^{20}$

(Table II). The anaesthetist who customarily uses a calculation giving a relatively low fresh gas flow relative to alternative calculations should take into account the prevailing clinical circumstances. The critical issue is whether rebreathing of a character that will have an important effect on that patient's PaCO₂ is occurring. If specific blood gas values are essential for that patient's welfare these should be measured, because clinical signs of hypercarbia are not always obvious.

ARTIFICIAL VENTILATION

When the Bain circuit is used in this fashion two relationships are important. When the fresh gas flow is very high the PaCO₂ is ventilation limited, i.e., by virtue of flow the patient does not rebreathe exhaled gases. However, when the minute volume

substantially exceeds the fresh gas flow, the fresh gas flow becomes the controlling factor for carbon dioxide elimination, i.e., rebreathing occurs. Thus different combinations of fresh gas flow and minute volume can be selected to produce a desired PaCO₂, the choice being based on the clinical circumstances. Many formulae have been devised relating fresh gas flow to a normal carbon dioxide tension or to the prevention of rebreathing (Table III). A commonly used figure is $100 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ with appropriate attention to the patient's ventilation.

Jackson-Rees system (Figure (C))

This is a T-piece arrangement with a reservoir bag that incorporates a relief mechanism for gases to be vented. When the patient exhales, exhaled gases pass down the expiratory limb, mixing with fresh gases entering via the fresh gas inlet. During the expiratory pause fresh gases continue to flush exhaled gases away from the T-piece and down the expiratory limb. During inspiration the gases inhaled come from the fresh gas flow and the expiratory limb which includes the reservoir bag. If the expired gas cannot readily escape from the reservoir bag reinhalation of mixed gas may occur.²⁰

SPONTANEOUS RESPIRATION

The fresh gas flows necessary to prevent rebreathing are similar to those used for the Bain system. However, if a positive end-expiratory pressure exists an increase in end-tidal carbon dioxide is likely to develop unless the fresh gas flow is at least three times the minute volume.²¹

ARTIFICIAL VENTILATION

The fresh gas flows required are similar to those described for the Bain system. However, the manner in which the ventilation and venting is managed during ventilation will have varying effects on rebreathing and in some clinical circumstances other circuits can be employed more easily.

Lack system (Figure (D))

This is a coaxial system, but in contrast to the Bain circuit the fresh gas flow passes up the outer tube and expiration passes through the central conduit. This circuit has not been subjected to the same intensive study that alternative systems have

TABLE III Formulae proposed for the calculation of fresh gas flows when a patient is being artificially ventilated with a Bain circuit. Superscripts indicate reference sources.

Adults	
F.G.F.	
= $70 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ at ventilation of $150 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ^{6,16}	
F.G.F.	
= $100 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ at ventilation of $120 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ¹⁷	
Children¹⁸	
<i>(Body weight 10-30 kg)</i>	
To produce a PaCO ₂ of 4.9 kPa (37 torr)	FGF = $1000 + 100 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$
To produce a PaCO ₂ of 4.0 kPa (30 torr)	FGF = $1600 + 100 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$
<i>(Body weight 30-70 kg)</i>	
To produce a PaCO ₂ of 4.9 kPa (37 torr)	FGF = $2000 + 50 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$
To produce a PaCO ₂ of 4.0 kPa (30 torr)	FGF = $3200 + 50 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$

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enjoyed. Available information is summarized as follows:

SPONTANEOUS RESPIRATION

A fresh gas flow of the order of expired minute volume is likely to avoid rebreathing,²² but it may be wiser to use a greater flow.²³ A flow of $58 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ has been proposed.²⁴

ARTIFICIAL VENTILATION

The same flow considerations apply as for the Magill circuit. More recently, in an endeavour to reduce the fresh gas flows necessary to prevent rebreathing, a Lack circuit with an injector device has been used successfully.²⁵ This was achieved by introducing the oxygen through a Venturi device (Wolf Injectomat – Richard Wolf (U.K.) Ltd) positioned between the Lack circuit and the patient.

MERA F system (Figure (E))

This multipurpose breathing system^{3,16} is designed to be used either as a coaxial circle attached to the inspiratory and expiratory valves of conventional circle anaesthesia delivery systems (Figure (G)) or as a modified type of T-piece circuit.

SPONTANEOUS RESPIRATION

Rebreathing is avoided with a fresh gas flow of $100 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ and it has been used at flows as low as $50 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ in some patients, without demonstrable rebreathing.⁶

ARTIFICIAL VENTILATION

The function and fresh gas flow requirements are likely to be similar to those described later for a closed circuit or a "closed circuit with a leak."

Non-rebreathing valve systems (Figure (F))

A variety of non-rebreathing valves have been incorporated with a conduit and reservoir bag to form a breathing circuit (Figure (F)). There is no mixing of inhaled and exhaled gases proximal to the mask or endotracheal tube connector. The apparatus deadspace is confined to the deadspace of the valve. Fresh gas comes from the reservoir bag and the valve directs exhalations into the atmosphere or a scavenging device. Assuming the system is not defective and is used correctly during artificial ventilation the fresh gas flow should equal the patient's minute volume. During spontaneous

ventilation the fresh gas flow is adjusted to keep the reservoir bag about three quarters full at the beginning of inspiration. Distension of the bag should be avoided and too low a gas inflow is equally hazardous. In the opinion of many anaesthetists, the difficulties and potential hazards associated with non-rebreathing valve systems outweigh their usefulness for clinical anaesthesia except for emergency resuscitation or during the transport of patients.

Carbon dioxide absorption circuits

Closed systems (Figures (G) and (H))

In a completely closed system, the fresh gases and vapours provide the metabolic and anaesthetic needs of the patient and venting of excess gases should be unnecessary. Gases may follow a repetitive circular pathway (Figure (G)) or pass to and fro through an absorber (Figure (H)). The relative placement of the items comprising the circle system do influence its function and the Figure illustrates a commonly used arrangement.

Semi-closed carbon dioxide absorption circuits

The breathing circuits just referred to can also be used in a semi-closed manner by opening the venting port. The to and fro system (Figure (H)) is little used though it is useful for anaesthetists who do not have a circle carbon dioxide absorption system available. However, circle systems are frequently used with a fresh gas flow greater than the patient's requirements, thus requiring venting of excess gases. This is commonly referred to as "a closed circuit with a leak." Employed in this fashion the fresh gas flow can exercise partial control of arterial carbon dioxide tension and can be used to regulate it.

If the carbon dioxide absorber is switched out of the circuit rebreathing of expired gases will not occur until the fresh gas flow is less than alveolar ventilation. If the configuration is as in (Figure (G)) the fresh gas flow should equal the minute ventilation predicted necessary to produce the desired arterial carbon dioxide value.²⁶ Such a technique is unusual and customarily the carbon dioxide absorber is switched into the circuit and the fresh gas flow is deliberately less than the minute ventilation.

It is particularly important to realise that the

smaller the fresh gas flow of nitrous oxide and oxygen the greater the difference between the fresh gas flow oxygen concentration and the inspired oxygen concentration. Inspired oxygen concentration should always be measured when an anaesthetic is being administered, but it is useful to know the circumstances under which it may be fairly successfully predicted. If the fresh gas flow is $1.0 \text{ L} \cdot \text{min}^{-1}$ or less, the inspired oxygen concentration may be at least 20 per cent less than that in the fresh gases.²⁷ It has been shown that inspired oxygen concentration can be predicted after twenty minutes steady state with a fresh gas flow of $1\text{--}5 \text{ L} \cdot \text{min}^{-1}$.²⁸ In respect of inspired oxygen concentration, perhaps a useful compromise between a totally closed system and a "closed carbon dioxide absorption system with a leak" is the finding that in normal patients a fresh gas flow of nitrous oxide $1200 \text{ ml} \cdot \text{min}^{-1}$ oxygen $800 \text{ ml} \cdot \text{min}^{-1}$ ensures an inspired oxygen concentration of 30 per cent or more.²⁷

Mechanical factors

Breathing circuit resistance, work of breathing and wasted ventilation

Reported differences between breathing circuits are small and for adults the circle absorber system with a standard 22 mm diameter is likely to have the least resistance during spontaneous breathing.²⁹ The magnitude of this resistance is important because of the potentially wasted ventilation and the increased work of breathing. Any increase in volume of a breathing circuit produced during the inspiratory phase of positive pressure ventilation is likely to result in clinically important variations in delivered ventilation, so the pressure within the system and the material it is made of are very important. Highly compliant adult circuits can result in a compression volume loss that exceeds the tidal volume setting of the ventilator.³⁰ The situation is even more complicated if small infants are ventilated at high rates. Gas flow in the infant airway lags that generated by the ventilator and at the beginning of a breath ventilation may be wasted.³¹

The total work of breathing through a system is important as is the rate at which work is imposed and the fraction done during expiration. Laboratory studies³² show that the Lack and Bain circuits are more acceptable than the Magill and circle systems.

In general the higher the fresh gas flow the greater the work imposed on the patient. Mechanical ventilation, manual ventilation, or alternatively the contractility of a distended reservoir bag, could reduce the work of inspiration but under some circumstances this work could be transferred to the expiratory muscles. However, regardless of the breathing system used, the major factor governing resistance to a patient's respiration is the endotracheal tube.

Breathing system malfunction

Many and varied problems have been publicized. Some are due to errors in design or manufacturer, others occur in transit or the hospital. It is because of these problems and their serious consequences for all concerned that a pre-use check of an anaesthesia delivery system including the breathing circuit, should always be done prior to starting a case. A detailed account of the manoeuvres that should be performed is inappropriate here but specific directions³³ are summarized as follows:

Circle systems

- 1 *Pressure gauge*: make certain it reads zero.
- 2 *Carbon dioxide absorber*: ensure it is active and switched into or out of the circuit as desired.
- 3 *Unidirectional valves and circuit patency*: ensure valves are present and working correctly. Testing the patency of inspiratory and expiratory limbs as well as the absorber itself. A method for detecting incompetent unidirectional drive valves in a circle carbon dioxide absorption system is as follows³⁴:
  - (a) *Preparation*: remove breathing tubes from the circle, turn off all gas flows, and close relief valve.
  - (b) *Checking inhalation valve*: connect a reservoir bag at the usual bag connector site and one limb of the corrugated tube on the inhalation outlet of the absorber; while the exhalation inlet is covered with the palm of a hand, apply positive pressure (approximately 5–10 cm H_2O) to the corrugated tube with "gently slow blow" (see (d) for interpretation).
  - (c) *Checking exhalation valve*: connect a reservoir bag to the exhalation inlet and a corrugated tube on the bag connector site; while the inhalation outlet is covered with the palm of hand, apply gentle positive pressure

to the corrugated tube as described above (see (d) for interpretation).

- (d) *Interpretation of test*: if the valve being tested is competent, the reservoir bag will not fill; filling of the reservoir bag indicates incompetency of the valve tested; if the incompetency is not corrected after replacement of the suspected valve, look for an irregularity on the annular seat.

4 *System integrity*: ensure hoses and reservoir bag are attached in their correct positions. Check for leaks within the system by generating a positive pressure of 30 cm H₂O within it and making sure the pressure does not fall more than 5 cm H₂O during the ensuing 30 seconds.

5 *Relief valves*: ensure the low pressure relief valve – located between the wall outlet or gas cylinder and the flow meters and the high pressure relief valve – located between the flow meters and the breathing circuit, are functioning adequately. These respectively protect the patient against a dangerous decrease or increase in breathing circuit pressure. Once system integrity has been checked the pressure should be released by slowly opening the relief valve. There should be a gradual loss of pressure from the system. The low pressure relief valve is checked by first closing the high pressure relief valve and occluding the patient port. The reservoir bag is partially filled via the oxygen flush. A 4 L·min⁻¹ flow is set on the oxygen flow meter. After one minute the bag should be filled but not distended and the pressure in the breathing system should not increase. The bag is then given a quick squeeze. The relief valve should close and the pressure in the system increase. Releasing the bag should cause the valve to open and the pressure to fall.

Carbon dioxide washout circuits

The aspects of function to be tested are similar to those listed for circle systems. Among potential problems with the Bain circuit is disconnection of the inner tube or a leak from it. Several safety checks have been reviewed.³⁵ The most widely used consists of flushing the circuit with oxygen flush valve and watching the reservoir bag. Collapse of the bag secondary to the Venturi effect in the outer tube shows the circuit is intact.³⁶

The conscientious use of appropriate checks

should bring to light existing problems but will not indicate problems that develop during the conduct of a case. These are almost invariably manifested early by clinical signs³⁷ so vigilant monitoring is the only protection for patient and anaesthetist. Once a problem has been detected the anaesthetist may immediately identify the cause in the breathing system and correct it or postpone elucidation of the cause until later and take active steps to protect the patient.

Certain axioms for the user are obvious but bear repetition. A breathing system should be used only for the purpose for which it was designed. The configuration of the system should not be altered unless the user is fully conversant with the principles under which the old and new version function. The breathing system should only be used in the recommended manner, bearing in mind that a device may be in use for some time before problems become evident, particularly when a combination of devices is employed. For example, it has been shown that positioning and temperature are critical factors when certain filters and humidifiers are in use.³⁸

Conclusion

Traditional breathing systems used for anaesthesia purposes perform well if they are cared for properly and the user understands the principles that underlie their function. The circuit selected will depend on the task to be performed and the professional environment. Much valuable information omitted in this review is available in specialized books dealing with anaesthesia equipment and should be easily accessible in any department of anaesthesia. Continuing changes include the adoption of materials that absorb inhalational agents less than does conductive rubber and design changes to combine as many desirable qualities as possible in one breathing system. Whether greater safety lies in having available two or three separate near perfect systems for different clinical situations or in developing a single circuit that will function in different modes according to a selector setting remains to be seen. However, a sound knowledge of the potential problems in breathing circuits is essential for the safe practice of anaesthesia and can effectively be derived from the Canadian Standards Association publication Standard Z 188.9, Breathing Systems for Use in Anaesthesia.

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