THE "D CIRCLE": CLOSED-CIRCUIT OPERATION OF THE BAIN CIRCUIT

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THE MAPLESON D BREATHING CIRCUIT, particularly in the Bain coaxial configuration, offers convenience and versatility.¹⁻³ To avoid re-breathing of exhaled carbon dioxide requires a fresh gas flow equal to 2.5 to 3 multiples of the minute ventilation ($\dot{V}_E$).^{4,5} In adult patients, therefore, 15–20 l/min flow is required, representing a significant wastage and posing an increased scavenging problem. Trimming the fresh gas flow to 100 ml $\cdot$ kg⁻¹ min⁻¹ allows some economy of fresh gas, but at this flow rate the patient's safety depends on the respiratory reserve,⁷ which cannot be guaranteed under anaesthesia or in diseased patients.

In an attempt to overcome these problems we closed such a circuit by recirculating the effluent gas through a gas pump and carbon dioxide absorber, and we tested the arrangement with a simple model of a spontaneously breathing patient (Figure 1). A study of the performance of the circuit and carbon dioxide absorber supports further investigation and development directed towards introduction into clinical practice.

METHOD

Circuit Modification

Air from the to-and-fro limb of a standard Bain circuit was recirculated to the fresh gas port through an upright 7 $\times$ 14 cm Waters canister filled with 600 g soda-lime. The recirculating flow ($\dot{V}_R$) was controlled by a gate clip and measured with a Wright respirometer and stopwatch. The flow was generated by a Gast model 1050-A rotary-vane vacuum pump. Maximum pump flow in this system measured 35 l/min.

Patient model

The cylinder and diaphragm valves of a phase-controlled Harvard model 622 large animal

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FIGURE 1 Schematic diagram of experimental circuit and patient model. The components are: 1, reservoir bag; 2, Wright respirometer; 3, Waters canister; 4, gate clip; 5, recirculating pump; 6, fresh gas input (clamped); 7, Bain circuit; 8, dead space; 9, carbon dioxide input; 10 and 11, one-way valves; 12, ventilator piston; 13, carbon dioxide analyzer. Arrows indicate direction of flow.

ventilator were used as a model of a spontaneously breathing adult. Tidal volume was set at 800 ml, rate at 8/min and inspiratory/expiratory ratio at 1:2 as measured with a stopwatch. This resulted in calculated values of 6.4 l/min for $\dot{V}_E$ and 30 l/min for peak inspiratory flow rate. An "anatomical dead space" of 150 ml was added before connection to the circuit, resulting in a physiological deadspace fraction ($\dot{V}_D/\dot{V}_R$) of 0.19. A British Oxygen Company cyclopropane rotameter metered carbon dioxide into a 200 ml reservoir in the inspiratory limb of the model.

Mensuration techniques

Airway carbon dioxide concentration was measured with a Beckman LB-2 infrared analyser drawing 300 ml/min from the circuit-model junction. This gas was returned to the circuit through the reservoir bag. The output from the analyser, as well as signals from the ventilator indicating the phases of breathing and from an airway pressure transducer, were recorded on a Hewlett-Packard polygraph for later analysis.

The carbon dioxide production ($\dot{V}_{CO_2}$) of the model was calculated by the formula

$$\dot{V}_{CO_2} = (F_{A_{CO_2}} - F_{I_{CO_2}}) \cdot \dot{V}_E \cdot (1 - V_D/V_T),$$

where $F_{A_{CO_2}}$ and $F_{I_{CO_2}}$ are the alveolar and inspired carbon dioxide concentrations respectively. Examination of the tidal waveform of carbon dioxide concentration suggested that the carbon dioxide mixed well with the inspired gas,

so the exhaled plateau concentration was taken as the end-tidal or alveolar value of the model. The mid-inspiratory portion of the waveform often showed a peak due to carbon dioxide re-breathing. The minimum and peak values of $F_{I\text{CO}_2}$ were averaged for estimation of $\dot{V}\text{CO}_2$.

EXPERIMENTAL DESIGN

Evaluation of the dynamics of carbon dioxide production and elimination in the model

We studied the short-term dynamics of the production and elimination of carbon dioxide by the model and the circuit by alternately turning the carbon dioxide flow and the recirculating pump on and off, while tidal motion of air was maintained.

Determination of recirculating flow required to prevent re-breathing

The recirculating flow required to reduce the mid-inspiratory peak of carbon dioxide (i.e., re-breathing) to clinically insignificant levels was assessed. The $\dot{V}_R$ was increased from $1.2 \times \dot{V}_E$ stepwise to about $5 \times \dot{V}_E$. We sought a peak of less than 0.6 per cent carbon dioxide at an $F_{A\text{CO}_2}$ of 5 per cent ($F_{I\text{CO}_2}$ less than 12 per cent of $F_{A\text{CO}_2}$), since this has been said to be the maximum acceptable $F_{I\text{CO}_2}$ in the investigation of carbon dioxide absorber performance.^{8,9}

Assessment of endurance of the carbon dioxide absorber

We performed an endurance test on the carbon dioxide absorber in this system. With a freshly charged canister, we ran the system to exhaustion of the absorbant as demonstrated by a rise of the peak $F_{I\text{CO}_2}$ to above 0.6 per cent at about five per cent $F_{A\text{CO}_2}$ ($P_{A\text{CO}_2}$ about 37 torr or 4.7 kPa). $\dot{V}_R$ during this part of the study was $3 \times \dot{V}_E$, a level demonstrated to prevent significant re-breathing; occasionally we increased $\dot{V}_R$ to exceed the inspiratory flow rate, to differentiate the re-breathing effect on $F_{I\text{CO}_2}$ from the effect of absorbant exhaustion. The $\dot{V}\text{CO}_2$ was also briefly increased periodically (for $F_{A\text{CO}_2}$ of 13–14 per cent) to acutely stress the elimination capacities of the system.

RESULTS

Dynamics of carbon dioxide production and elimination

Figure 2 illustrates the dynamics of carbon dioxide production and elimination in the patient

FIGURE 2 Action of recirculation pump on carbon dioxide concentration in closed Bain circuit (fresh gas flow = 0, $\dot{V}\text{CO}_2 = 240$ ml/min, $\dot{V}_R = 4.7 \times \dot{V}_E$. Activation of the pump eliminates re-breathing and returns end-tidal carbon dioxide to normal levels.

model and the experimental circuit. $F_{A\text{CO}_2}$ rises about eight per cent per minute (59 torr/min) (7.6 kPa/min) in the patient model at 240 ml/min carbon dioxide input, since the model has no buffering capacity. When the pump is activated at a rate of $4.7 \times \dot{V}_E$ (30 l/min), the $F_{A\text{CO}_2}$ decays with a half-time of about 14 seconds, determined graphically. A $\dot{V}_R$ of $3 \times \dot{V}_E$ results in a half-time of about 19 seconds, indicating that the rapidity of removal of a volume of carbon dioxide from the circuit depends in small part on the magnitude of $\dot{V}_R$. In every such trial, the minimum $F_{I\text{CO}_2}$ fell to nil on the inspiration following activation of the pump. The course of elimination of the acute additions of carbon dioxide during the endurance test confirmed that the circuit maintained its ability to normalize the $F_{A\text{CO}_2}$ quickly.

Recirculating flow required to prevent re-breathing

A $\dot{V}_R$ of $1.2 \times \dot{V}_E$ (110 ml $\cdot$ kg⁻¹/min for a 70 kg model) resulted in a large inspiratory carbon dioxide peak (Figure 3a). Its height was about one-third of the $F_{A\text{CO}_2}$ and a visual estimate (equal areas) of the average $F_{I\text{CO}_2}$ was about one-fifth of the $F_{A\text{CO}_2}$. At a $\dot{V}_R$ of $2.5 \times \dot{V}_E$ (230 ml $\cdot$ kg⁻¹/min) the peak was reduced to insignificant levels, with a height of about seven per cent of the $F_{A\text{CO}_2}$ (Figure 3b). With the increase in $\dot{V}_R$ the $F_{A\text{CO}_2}$ fell, consistent with the fall in $F_{I\text{CO}_2}$. When $\dot{V}_R$ equaled the peak inspiratory flow rate ($4.7 \times \dot{V}_E$ in this model), re-breathing was consistently absent, but the minimum $F_{I\text{CO}_2}$ rose slightly, from 0.35 to 0.4 per cent at 13 per cent $F_{A\text{CO}_2}$, possibly because the transit time through the absorber was too brief to allow complete absorption.

FIGURE 3 a) Inspiratory carbon dioxide peak at $\dot{V}_R$ of $1.2 \times \dot{V}_E$, and b) its reduction by a $\dot{V}_R$ of $2.5 \times \dot{V}_E$. Ventilation and $\dot{V}_{CO_2}$ were held constant between a and b.

FIGURE 4 Peak and minimum values of FI_{CO_2} during the endurance test of the carbon dioxide absorber (FA_{CO_2} about 5 per cent). Failure of the absorber occurred at 226 minutes.

Endurance of carbon dioxide absorber

Figure 4 illustrates the peak and minimum values of FI_{CO_2} at about five per cent FA_{CO_2} . The true average FI_{CO_2} lies somewhere between the lines. We considered absorber failure to have occurred at 226 minutes with an average $\dot{V}_{CO_2}$ of 294 ml/min during this period, since the peak FI_{CO_2} was just over 0.6 per cent at that point. Note also that the rate of rise of FI_{CO_2} was beginning to increase.

DISCUSSION

The lack of patient-operated valves in the Mapleson D circuit results in minimal resistance to breathing and the position of the fresh gas inflow allows rapid control of inspired gas concentrations. Its main disadvantage is the relatively large flow of fresh gas required to assure elimination of carbon dioxide. The interactions of fresh gas flow, variations in patients' respiratory parameters and the resulting carbon dioxide elimination have been well studied.⁷⁻¹⁰ While compensation for rebreathing is possible, a non-rebreathing circuit represents the optimum in patient care.

Closed circuits utilizing carbon dioxide absorption offer another set of advantages. Some of these were enumerated by Waters¹¹ as effective conservation of patients' heat and humidity, greater economy of anaesthetic gases and less anaesthetic exposure for operating-room personnel.

This study demonstrated that the Mapleson D circuit can be closed by recirculating the effluent gas and that carbon dioxide elimination by an absorber is adequate. Rebreathing was completely avoided by adjustment of the recirculating flow rate and rebreathing was reduced to minimal levels when $\dot{V}_R$ approximated the fresh gas flow recommended by Mapleson. This minimal rebreathing resulted in a reduction of about 10 per cent in effective absorber endurance, since rebreathing contributed to the 0.6 per cent FI_{CO_2} cutoff point before the concentration passing the absorber reached 0.6 per cent. The absorption capacity⁹ (11 litres of carbon dioxide per 100 gm) and the endurance factor⁸ (17 minutes use per ounce at 200 ml/min $\dot{V}_{CO_2}$) of the absorbant used in this experimental system were about 20 per cent less than those reported for similar absorbers in circle systems. Besides the effect of rebreathing, this decrement could have been due to $\dot{V}_{CO_2}$ measurement problems in this study or, less likely, to the presence of continuous rather than tidal flow through the absorber. The average $\dot{V}_{CO_2}$ calculated for the endurance test was undoubtedly low, since the infrared analyser reads less than the true value at the high concentrations encountered during the stresses.¹² This effect was confirmed in calibrating the analyser.

Revell demonstrated that using a circulating pump to provide movement of gas within the circle system beyond that provided by the patient's breathing improved carbon dioxide elimination by reducing equipment deadspace.^{13,14} This concept has also been applied to reduce the work of breathing by one-third in a mask circle system in conscious adults.¹⁵ The contribution of a circulator to the care of the paediatric patient may be much more important.¹⁶ The "D circle" breathing system depends on a circulating pump for its operation and the demonstrated advantages of a circulator could apply directly to it, given properly designed mask fittings.

The production of heat and water by a carbon dioxide absorber represents an advantage in the operation of a Mapleson D circuit. A non-rebreathing system used without a humidifier can be expected to present nearly dry gas to the trachea through a tracheal tube. The presence of

controlled flow through an absorber¹⁷ in the "D circle" system may allow a scheme to be developed to present gas to the trachea which is of proper humidity and temperature to preserve ciliary action and reduce heat loss, without the addition of complicating humidifiers.

The configuration of a "D circle" system for clinical use would of necessity be different from that shown in Figure 1. A pop-off valve would logically be in its usual position on the Bain circuit. Fresh gas should flow through the pump and absorber before reaching the patient; this would result in higher humidity, more rapid control of inspired gas concentrations and more economy in absorbant use. This arrangement would require a pump that would passively allow flow of fresh gas and a check valve to prevent backflow of fresh gas in the event of pump failure. A pump for clinical use should also be compatible with anaesthetic gases and vapors; it should generate quiet flow free of oil mists or other debris; and it should be easy to sterilize, robust and dependable. Given our experience with water condensation, a water trap will be necessary. Monitoring of such a circuit would require some indicator of flow in the delivery limb in addition to the devices required to monitor closed-circuit anaesthesia.

SUMMARY

A method of converting a Mapleson D (Bain) circuit to closed-circuit operation is presented, utilizing a laboratory air pump and a Waters carbon dioxide absorber canister to recirculate exhaled gas. The elimination of carbon dioxide from the circuit was studied and found to be adequate. The circuit would allow the use of low fresh gas flows for the maintenance of anaesthesia without the danger of carbon dioxide rebreathing. We suggest that such a circuit could provide appropriate conditions of gas humidity and temperature for endotracheal anaesthesia, while realizing the advantage of a circulator in mask anaesthesia is possible. Further design considerations for a "D circle" breathing system for clinical use are discussed.

RÉSUMÉ

Les auteurs présentent une méthode de conversion d'un montage Mapleson D (Bain) en circuit fermé. Pour obtenir la recirculation de l'air expiré on utilise une pompe à air de laboratoire ainsi qu'un canister Waters pour l'absorption du gaz carbonique dont l'élimination a été étudiée et jugée adéquate. Ce circuit permet l'emploi de

volumes de gaz frais peu élevés pour le maintien de l'anesthésie sans danger de rebreathing. Les données recueillies semblent indiquer que le circuit tel que modifié pourrait fournir une humidification et une température suffisantes pour l'anesthésie endotrachéale ainsi qu'une circulation avantageuse pour l'anesthésie au masque. Les auteurs font part de modifications désirables pour l'usage clinique du système "D" selon ce mode.

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