Anaesthesia Apparatus

Re-evaluation of the Farman entrainer in a low-pressure system for field anaesthesia

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The aim of this project was to develop a portable anaesthesia system that was compatible with modern anaesthesia practice under field conditions, when compressed gas supplies are limited. We assembled and evaluated a low-pressure plenum system, based upon the Farman entrainer, which was adaptable to spontaneous, assisted or intermittent positive pressure ventilation (IPPV). The entrainer was tested using a low flow of compressed gas, O₂ at 1–3 L · min⁻¹. We measured the fresh gas flow (FGF) and O₂ concentrations (FIO₂) delivered at various source gas flow rates (O₂ flow), and with various breathing circuits. Entrainment ratio, FGF, and FIO₂ were highly dependent upon resistance to flow in the different breathing circuits. With a wide bore T-piece the air/O₂ entrainment ratio was 6:1, and the FIO₂ was 0.3. When circuit resistance was higher, e.g., with the Bain circuit, air entrainment and FGF were reduced, but FIO₂ was higher. Because it offered the lowest resistance, the T-piece circuit was selected for a clinical trial.

Le but de ce projet était de développer un système d'anesthésie ambulant qui serait compatible avec la pratique de l'anesthésie moderne dans les champs de bataille quand la fourniture de gaz comprimé est limitée. On a assemblé et évalué un système de souffleur à base pression basé sur le « Farman entrainer » qui a

été adapté pour une ventilation intermittente à pression positive ou spontanée ou assistée. Ce souffleur fut testé utilisant des bas flots de gaz comprimés, ou de O₂ à 1–3 L · min⁻¹. On a mesuré le flot de gaz frais (FGF) et les concentrations O₂ (FIO₂) délivrées à des taux variables de flots gazeux (O₂ flow) et avec différents circuits respiratoires. Le ratio d'entraînement, FGF, et FIO₂ ont été énormément dépendants de la résistance au flot dans les différents circuits respiratoires. Avec pièce en T à grand calibre, le ratio d'entraînement air/O₂ était de 6:1, et la FIO₂ était de 0,3. Quand la résistance du circuit était élevée, e.g., avec le circuit de Bain, l'entraînement de l'air et la FGF fut réduite, et la FIO₂ était plus élevée. Parce qu'elle offrait la résistance la plus basse, le circuit comprenant la pièce en T a été sélectionné pour l'essai clinique.

Key words

ANAESTHETIC TECHNIQUES: inhalation;
EQUIPMENT: anaesthesia machines.

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Anaesthesia systems for field use are based on draw-over, vaporizer-in-circuit, non-rebreathing circuits.^{1–6} Although suitable for most field conditions these systems have distinct limitations: the resistance of a draw-over circuit is too high for paediatric anaesthesia, manually controlled ventilation is both awkward and tiring, and modern vaporizers are not designed for draw-over flow.

We began these studies with the premise that anaesthesia equipment for field or emergency use should be compatible with modern anaesthesia practice including the use of muscle relaxants, controlled ventilation, and modern inhalational anaesthetics, and should be adaptable for use in either the draw-over or plenum mode.

Modern anaesthesia machines are plenum systems, routing compressed gases through pressure reducing valves and calibrated flow meters. Because of their bulk, cost, and dependency on compressed gases these machines are unsuitable for field use, particularly in developing countries.^{6–8} The simplest plenum system is based upon air entrainment, using a low pressure compressed gas source (oxygen cylinder, concentrator, or air com-

pressor) and a Venturi entrainer. John Farman, in 1965, designed a simple entrainer to convert a draw-over system to a plenum system for paediatric anaesthesia.⁹

We studied the gas flow characteristics of a simple plenum anaesthesia system, incorporating the Farman entrainer, to assess its suitability for field anaesthesia. This paper reports bench studies in which we measured the fresh gas flow rates and oxygen concentrations delivered by the entrainer at various source gas flow rates and with various anaesthesia circuits. In an accompanying paper we report a clinical trial using the apparatus for general anaesthesia with both controlled and spontaneous respiration.

Methods

These studies were commenced in the anaesthesia laboratory at University Hospital, London and completed at Tribhuvan University Teaching Hospital, Kathmandu. Since the results were identical they have been combined for presentation in this paper.

In London, gas flows were measured with a basic water displacement spirometer; in Kathmandu we used a Medi-shield RM 121 (Wright's) respirometer which had been calibrated with an ACOMA PH-3F rotameter type flow meter (ACOMA Medical Instrument Co. Ltd., Japan). Circuit pressures were measured with a Mera anaeroid manometer, calibrated with a mercury manometer, and oxygen concentration with an ACOMA model AS-25 oxygen analyzer, calibrated with room air. Each recorded measurement was the mean of 3–5 readings.

Kathmandu is situated at an altitude of 1300 meters with an average barometric pressure of 650 mmHg. No corrections have been made to this data for barometric pressure.

In all studies compressed O₂ was the source gas, delivered through a rotameter type flow meter from a Mera anaesthetic machine. The Farman entrainer was first studied attached to a basic anaesthesia system consisting of an Oxford Miniature Vaporizer, an EMO vaporizer, and an Oxford Inflating Bellows in series, but with no patient circuit. Various anaesthesia circuits which might be suitable for field use were then attached to the basic system. Fresh gas flow (FGF) was measured during continuous flow conditions, that is with the patient connector open to atmosphere, but circuit pressures were measured with the patient connector occluded. The FGF, occlusion pressure, and O₂ concentration were recorded while source gas flow rates were varied from 1–3 L·min⁻¹. In Farman's initial description of the entrainer the source gas driving pressure was used as a substitute measure for flow rate. The commercial version of the entrainer also has a side port which can be connected to a pressure manometer. Driving pressure and flow are

O₂ FLOW AND FGF WITH THE FARMAN ENTRAINER AND VARIOUS CIRCUITS

FIGURE 1 Oxygen flow (O₂ flow) and fresh gas flow (FGF) with the Farman entrainer and different breathing circuits. The results of simple linear regression analysis are as follows: Entrainer system alone: FGF = 7.1 O₂ flow - 0.4 L·min⁻¹, $r = 0.99$, $P < 0.01$. Entrainer with wide-bore T-piece: FGF = 7.4 O₂ flow - 1.5, $r = 1.00$, $P < 0.0001$. Entrainer with paediatric T-piece: FGF = 5.9 O₂ flow - 2.7, $r = 1.00$, $P < 0.001$. Entrainer with Bain circuit: FGF = 4.2 O₂ flow - 0.5, $r = 0.99$, $P < 0.01$.

directly though not linearly related (pressure = flowⁿ) so that either a pressure manometer or a flow meter can be used to adjust source gas flow.

The circuits studied were the paediatric T-piece (gas delivery tubing 58 cm long × 0.8 cm ID), Bain circuit (inner co-axial tubing 250 cm long × 0.6 cm ID), and a wide-bore low-resistance T-piece (150 cm long × 2.2 cm ID).

Circuit pressure and FGF were related to source gas flow rate by simple linear regression analysis.

Results

Continuous FGF rates obtained with different breathing circuits attached to the basic system are illustrated in Figure 1. The line labelled ENTRAINER SYSTEM depicts FGF through the basic system with no breathing circuit attached. Source gas flow rate (O₂ flow) was varied between 1–3 L·min⁻¹. Figure 1 shows that with O₂ flow up to 3 L·min⁻¹ the relationship to FGF was linear for each circuit. When O₂ flow was increased above 3 L·min⁻¹ there was no further increase in FGF, probably because of excessive turbulence. For each circuit configuration the air/O₂ entrainment ratio, and therefore the FiO₂, were constant over the range studied and calculated $FiO_2 = 1 + (\text{air} \times 0.21) / (1 + \text{air})$.

The correspondence between calculated and measured FiO₂ is depicted in the Table.

Figure 1 and the Table demonstrate that FGF and air/O₂

FIGURE 2 Static (occlusion) pressures developed in the breathing circuit by the Farman entrainer. Occlusion press. = 0.061 driving press + 0.34 , $r = 0.99$, $P < 0.001$.

enainment ratio are dependent upon the circuit resistance and are different for each circuit. That is as expected in a low-pressure Venturi driven system. However, the resistance of the wide bore T-piece circuit was very low, little more than that of the basic system alone, and it achieved highest FGF delivery with low O_2 flow.

Figure 2 shows circuit pressures when circuit outflow was occluded. Since occlusion pressure was measured during zero flow the linear relationship between static occlusion pressure and O_2 driving pressure was identical for all circuits. Occlusion pressure represents the potential driving pressure for FGF distal to the Farman entrainer. Within the clinically useful range, O_2 flow of $1\text{--}2\text{ L}\cdot\text{min}^{-1}$ and FGF of $5\text{--}10\text{ L}\cdot\text{min}^{-1}$, that pressure is quite low, $3\text{--}8\text{ mmHg}$. ($0.4\text{--}1.0\text{ kPa}$).

Discussion

Despite the growing demand for anaesthesia services in developing countries and remote areas of the world,^{10,11} the technology has advanced little since the pioneering work in Oxford in the 1950s and 60s.¹² The present work was begun with the premise that modern anaesthesia could be provided under field conditions using simple, readily available equipment. Reduced to the simplest terms such a system must be able to deliver a mixture of air, O_2 and anaesthetic vapour while using a minimal amount of compressed gases. One way to achieve this is by using a Venturi to entrain ambient air. This is the principle of a device described by Jorgensen *et al.*,¹³ who used a Venturi injector with a Mapleson D system to draw part of the exhaled gas mixture through a soda-lime

canister before it was rebreathed. They also reduced the FGF requirements of the Magill circuit by using the injector to entrain room air.¹⁴

The Farman entrainer⁹ is the prototype of the air entraining Venturi system. Farman designed his entrainer to convert the draw-over EMO system to a plenum system for paediatric anaesthesia. His investigations were limited to flows obtained with the EMO system and a standard paediatric T-piece circuit, about $10\text{ L}\cdot\text{min}^{-1}$ at a source gas driving pressure of 100 mmHg . These initial studies have not been repeated or expanded.

The present studies were done with clinical instruments that have an expected error of $5\text{--}10$ per cent. We attempted to minimize random error by averaging several readings for each data point, and we calibrated each instrument with the best standards available. The close agreement between data obtained in London and Kathmandu, using different instruments, gives us confidence in the results.

We have examined the function of the Farman entrainer in a basic anaesthetic system with various patient breathing circuits, and over a range of source gas flow rates. As expected, FGF generated by the entrainer was dependent upon downstream circuit resistance. While continuous flow through the paediatric T-piece was as originally described by Farman, it was lower through the Bain circuit which has a longer delivery limb. In these studies we did not measure the effect of additional resistance imposed by a patient or a ventilator. It seems prudent to advise, therefore, that any new use of the Farman entrainer should be preceded by careful measurements of FGF during both static and dynamic conditions.

We have also seen that the static pressure developed in the breathing circuit, when outflow was totally occluded, was directly related to driving pressure of the source gas, i.e., injector pressure. In the clinically useful range, O_2 flow of $1\text{--}2\text{ L}\cdot\text{min}^{-1}$ (driving pressure of $40\text{--}120\text{ mmHg}$), occlusion pressure was $3\text{--}8\text{ mmHg}$. It is evident that this is a very low-pressure system with little risk of pulmonary barotrauma. However, flow was sensitive to changes in resistance, and may also vary with different ventilatory patterns and patient respiratory impedance. Therefore clinical use of the system must include means to monitor changes in FGF.

Because the wide-bore T-piece circuit offered the lowest resistance to gas flow it was chosen for clinical testing. The total system including vaporizers (EMO and OMV), Oxford Inflating Bellows with valves, and circuit had a resistance of 0.5 cm of water per $10\text{ L}\cdot\text{min}^{-1}$ continuous flow. This circuit had the highest FGF at low O_2 flow rates, that is the highest air/ O_2 entrainment ratio. At the same time it would not deliver an FiO_2 of less than 0.3 . It could be easily adapted for different ventilatory

TABLE Operational characteristics of different breathing circuits with the Farman entrainer anaesthesia system

	Entrainer system, no circuit	Bain circuit	Paediatric T-piece	Wide-bore T-piece
FGF/O ₂	7.1	4.2	5.9	7.4
Air/O ₂	6.1	3.2	4.9	6.4
FiO ₂ Calc.	0.32	0.40	0.34	0.32
Meas.	0.31	0.40	0.37	0.31
Resistance				
at 5 L·min ⁻¹	—	—	0.3	—
at 10 L·min ⁻¹	—	0.6	0.4	0.06
at 15 L·min ⁻¹	—	—	0.5	—
at 20 L·min ⁻¹	—	—	—	0.05

FGF/O₂ is the ratio of total fresh gas to source gas (O₂) flow.

Air/O₂ is the air/oxygen entrainment ratio.

FiO₂ is the oxygen concentration of inspired gas, with comparison of calculated and measured values.

Resistance was measured in cm of water pressure per litre/minute gas flow.

modes: controlled IPPV, manual bag ventilation, manual assist, or spontaneous. Also, it fulfilled other criteria: ease of scavenging and elimination of bulky hardware and valves from the patient end of the circuit.

These studies have defined the flow characteristics of a portable Venturi-driven, low pressure, low resistance anaesthesia system. An accompanying paper will describe a clinical trial using this system.

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