Fresh gas flow and carbon dioxide rebreathing in a low pressure semi-open anaesthesia system

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We have constructed a simple system for field anaesthesia by using a Farman entrainer and a semi-open circuit to convert a draw-over apparatus to a continuous flow air/O₂ system. Compressed O₂ was the driving gas for the entrainer; fresh gas (FG) delivered to the semi-open circuit was a mixture of O₂, entrained air and anaesthetic vapour. The purpose of this study was to examine FG flow rate and CO₂ rebreathing during intermittent positive pressure ventilation (IPPV). A non-rebreathing inflation valve (Laerdal) placed at the end of the expiratory (efferent) limb of the circuit vented both expiratory gas and excess FG. Ambient air IPPV was applied through the Laerdal valve from a self-inflating bag or ventilator. Since this circuit is functionally similar to a T-piece, the gas from the efferent limb (340 ml, containing FG) entered the lungs first. If tidal volume was larger than 340 ml the balance was ambient air. Minute ventilation of the lungs with efferent limb gas was defined as $\dot{V}_{\text{eff}}$. Respiratory gas was sampled at the endotracheal tube and the CO₂ tension was measured with a NIHON-KOHDEN CO₂ analyzer. Thirty-seven adult patients having intra-abdominal or pelvic surgery under general tracheal anaesthesia were studied. Four FG flow rates (5.7, 8.0, 9.3, and 10.4 L·min⁻¹), corresponding to driving gas pressures of 40, 60, 80, and 100 mmHg, were introduced in random order. Although inspired CO₂ was detected at FG flow rates of 5.7–9.3

L·min⁻¹, there were no differences in PETCO₂ among the four groups. We conclude that clinically important rebreathing does not occur when $\dot{V}_{\text{FG}}$ is 1.67 times $\dot{V}_{\text{eff}}$. For general use we recommend a $\dot{V}_{\text{FG}}$ of more than twice the $\dot{V}_{\text{eff}}$, which for this circuit configuration would be about 8 L·min⁻¹. This requires a minimum O₂ flow of 1.6 L·min⁻¹ or driving gas pressure of 60 mmHg.

Nous avons fabriqué un appareil de campagne pour l'anesthésie avec un entraîneur Farman et un circuit semi-ouvert pour convertir un appareil à débit intermittent en débit continu air/O₂. De l'O₂ comprimé constitue la force motrice de l'appareil. Le gaz frais (GF) délivré à l'appareil consiste en un mélange d'O₂, d'air entraîné et de vapeur anesthésique. L'objectif de l'étude consiste à déterminer le débit de GF et l'importance du rebreathing pendant la ventilation mécanique. Une valve sans rebreathing (Laerdal) installée à l'extrémité du circuit élimine les gaz expiratoires et l'excédent de gaz frais. À la valve de Laerdal, la ventilation mécanique fonctionne à l'air ambiant mû par un ballon réservoir auto-insufflé ou un ventilateur. Le circuit fonctionne comme une pièce en T et le gaz de la branche expiratoire (tube réservoir contenant 340 ml de gaz frais) pénètre d'abord dans le poumon. Si le volume courant est plus grand que 340 ml, le reste est constitué d'air ambiant. La ventilation-minute par la branche expiratoire est appelée $\dot{V}_{\text{eff}}$. Les gaz respiratoires sont prélevés au niveau du tube endotrachéal et la pression partielle du CO₂ est mesurée par un analyseur Nihon-Kohden. Trente-sept adultes soumis à une chirurgie viscérale ou pelvienne sous anesthésie générale endotrachéale sont étudiés. Quatre débits de GF (5,7, 8,0, 9,3, et 10,4 L·min⁻¹) correspondant à une pression motrice de 40, 60, 80 et 100 mmHg, sont introduits de façon aléatoire. Bien qu'on puisse détecter du CO₂ à des débits de GF de 5,7 à 9,3 L·min⁻¹, on ne trouve pas de différence de PETCO₂ entre les quatre groupes. Nous concluons qu'il n'existe pas de rebreathing cliniquement important avec des GF de 1,67 fois le volume courant. Pour usage général, nous recommandons un $\dot{V}_{\text{GF}}$ doubles du $\dot{V}_{\text{eff}}$ qui avec la configuration du circuit équivaut à environ 8 L·min⁻¹. Ceci requiert un débit minimum d'O₂ de 1,6 L·min⁻¹ ou une pression motrice de 60 mmHg.

Key words

ANAESTHETIC TECHNIQUES: inhalation;
ANAESTHESIA COMPLICATIONS: rebreathing;
EQUIPMENT: breathing systems, semi-open circuit.

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In poor countries like Nepal most inhalational anaesthesia is given with draw-over systems using ambient air (often supplemented with O₂) as the carrier gas.^{1,2} However, draw-over systems were not designed for the practice of modern anaesthesia and in the Western world we have come to equate modern anaesthesia with high pressure plenum systems and sophisticated anaesthesia machines. These are not affordable in underdeveloped countries, where less sophisticated delivery systems are required.

We have previously described a modification of the draw-over system for continuous flow air/O₂ anaesthesia.³ By incorporating a Farman entrainer⁴ and a Y-type semi-open circuit we converted the draw-over system to an economical low pressure plenum system.⁵ However, in the initial field trials we were not able to assess CO₂ rebreathing. The purpose of this study was to examine the relationship between fresh gas flow rate ($\dot{V}_{FG}$) and end-tidal CO₂ during intermittent positive pressure ventilation (IPPV) using this system.

Methods

Anaesthesia circuit

The basic system shown in Figure 1 consisted of a source of compressed O₂, a Farman entrainer, an Oxford Miniature Vaporizer (OMV), and an Oxford Inflating Bellows (OIB)* connected in series, and a low resistance Y-type semi-open circuit. A non-rebreathing (NR) Laerdal inflation valve placed at the end of the expiratory (efferent) limb vented expired gas and excess fresh gas (FG). By Conway's classification⁶ this was an efferent reservoir system. For these studies the efferent limb was a standard 32 in (82 cm) long corrugated black rubber tubing with a volume of 340 ml (V_{eff}). Positive pressure ventilation with ambient air could be provided by attaching a self-inflating bag or an air-entraining ventilator to the Laerdal inflation valve. Like a T-piece circuit, FG accumulated in the efferent limb during the expiratory phase of the ventilatory cycle. The first 340 ml of inspiratory tidal volume (V_T) was composed of efferent limb gas (V_{eff}); the remainder was ambient air.

DEFINITIONS

- $\dot{V}_{O_2}$ – Oxygen (source gas) flow rate to the Farman entrainer.
- $\dot{V}_{FG}$ – Flow rate of fresh gas (O₂, entrained air and anaesthetic vapour) to the anaesthetic circuit.
- V_{eff} – Volume of the efferent limit of the circuit.
- $\dot{V}_{eff}$ – Minute ventilation of the lungs with efferent limb gas ($\dot{V}_{eff} \times RR$).
- P_{dr} – Entrainer driving pressure.

Measuring instruments and calibration

Respiratory gas was sampled from a T-connector attached to the endotracheal tube, the CO₂ tension was measured with a Nihon-Kohden CO₂ analyzer and the capnograph trace was displayed on their Life-Scope 12 monitor.† The CO₂ analyzer was adjusted for the altitude of Kathmandu, 1300 metres, and was zeroed with room air and internally calibrated to 40 mmHg before each study. Inspired O₂ concentration (FiO₂) in the afferent limb of the circuit was measured with a Mera model OX-161 oxygen analyzer which was calibrated with room air. The pulse oximeter was a Nelcor model 200.

Calibration of the Farman entrainer

In these studies, as in Farman's original description, the source gas was O₂ and the source gas pressure, that is the entrainer driving pressure (P_{dr}), was used as a substitute measure for source gas flow rate ($\dot{V}_{O_2}$). To establish the relationship between $\dot{V}_{O_2}$ and P_{dr} we calibrated the entrainer in the following manner. The P_{dr} was measured with a Tycos aneroid manometer which had been calibrated against a mercury manometer (see Figure 1). The $\dot{V}_{O_2}$ was measured with a variable orifice rotameter type O₂ flowmeter, with a freely rotating bobbin, from a Model PH-3F anaesthetic machine.‡ Both back pressure and altitude will affect the height of the bobbin and therefore the flowmeter reading. We corrected for back pressure by first adjusting the flowmeter to a predetermined P_{dr} , then disconnecting the line to the entrainer before recording the height of the bobbin. Though the elevation of Kathmandu is 1300 metres, we did not correct the flowmeter readings for altitude. The reasons were: at low flow rates gas viscosity rather than density determines flow;⁷ we wanted the results to apply locally; and not correcting for altitude would cause a safe err by over estimating the FG flow.

Six randomized measurements were made to establish each point of correspondence and the association was tested by regression analysis (Figure 2).

Note that the relationship between $\dot{V}_{O_2}$ and P_{dr} depends only upon the design of the entrainer, but the relationship between both and the $\dot{V}_{FG}$ is related to the circuit resistance distal to the entrainer. Therefore P_{dr} can be used as a valid surrogate measure for $\dot{V}_{O_2}$ in clinical studies.

*All these components are manufactured by Penlon Limited, Abingdon, OX14 3PH, England.

†Both are manufactured by Nihon-Kohden Corp., Tokyo, Japan.

‡ACOMA Anaesthetic Apparatus, Model PH-3F, 1986, supplied by ACOMA Medical Industry Co. Ltd., Tokyo, Japan.

FIGURE 1 A schematic drawing of the low pressure semi-open system. OMV is the Oxford miniature vaporizer, OIB the Oxford inflating bellows, NR a Laerdal non-rebreathing inflation valve. The ARF-850 ventilator was used for intermittent positive pressure ventilation.

Patient sample

Adult ASA class I and II patients having intra-abdominal or pelvic surgery under general tracheal anaesthesia at the Tribhuvan University Teaching Hospital, Kathmandu, Nepal were selected for this study. The study was conducted in accordance with Departmental and Institutional standards for clinical investigations.

Anaesthetic technique

Anaesthesia was induced with thiopentone $4\text{--}5\text{ mg} \cdot \text{kg}^{-1}$ and maintained with halothane $1\text{--}2\%$ and meperidine $0.75\text{--}1.0\text{ mg} \cdot \text{kg}^{-1}$. Muscle paralysis was with pancuronium and was monitored with a peripheral nerve stimulator. After tracheal intubation, ventilation of the patients' lungs was controlled by an electrically driven air-entraining ARF-850 ventilator (Acoma Medical Instrument Co. Ltd., Japan). Tidal volume (V_T) was set at $12\text{--}13\text{ ml} \cdot \text{kg}^{-1}$, respiratory rate (RR) at ten per minute and these were not changed during the study.

Study design

After the depth of anaesthesia and end-tidal CO_2

(PETCO_2) had stabilized, four different FG flows ($\dot{V}_{FG}$) were introduced in random order. These were set by adjusting $\dot{V}_{O_2}$ to achieve P_{dr} of 40 (Group A), 60 (Group B), 80 (Group C) or 100 (Group D) mmHg. Steady state values for PETCO_2 and FiO_2 were recorded within 10–15 min after each change in $\dot{V}_{O_2}$. Rebreathing of CO_2 was estimated qualitatively by examining the capnograph trace. Differences among the four groups were tested by one-way analysis of variance and for categorical data the Chi-square test was applied.

Results

Our patients were representative of the general Nepali population, that is small and lean by North American standards. Forty studies were done on 37 patients, of which 34 were female and three were studied twice. Their age was 43 ± 11 yr and weight was 47 ± 9 kg.

The relationship between $\dot{V}_{O_2}$ and P_{dr} at the Farman entrainer was non-linear (Figure 2), and the line of best fit was a multiplicative model of the form $\dot{V}_{O_2} = a(P_{dr})$, ($r = 0.996$, $r^2 = 0.993$). For each P_{dr} the corresponding

FIGURE 2 The relationship between O_2 driving pressure (P_{dr} of 40–120 mmHg) and flow ($\dot{V}_{O_2}$ of 1.29–2.28 $L \cdot min^{-1}$) at the Farman entrainer. Individual data points are not shown since all fell on or very near the line of best fit. Regression analysis identified the best fit to be a multiplicative model:

$$\dot{V}_{O_2} = 0.19(P_{dr})^{0.52}, r = 0.996, P < 0.0001.$$

$\dot{V}_{O_2}$ was calculated from the model and is shown in row 3 of the Table.

Both experimental and derived data are presented in the Table. The mean FiO_2 was 0.36 for groups B, C and D, that is for P_{dr} of 60 to 100 mmHg. A constant FiO_2 indicates that the air/ O_2 entrainment ratio (A) was constant over this range of P_{dr} . The following formula relates FiO_2 and A and can be solved for A:

$$FiO_2 = (1 + 0.2A)/(1 + A),$$

where A is the air/ O_2 entrainment ratio.

The average FiO_2 of 0.36 corresponds to an entrainment ratio of 4:1 ($A = 4$). In group D (P_{dr} of 40 mmHg), the FiO_2 was higher (0.38, $P < 0.0001$) and A was 3.4. Average $\dot{V}_{FG}$ (O_2 plus entrained air) for each group was calculated from the values for $\dot{V}_{O_2}$ and A [$\dot{V}_{FG} = \dot{V}_{O_2}(1 + A)$]. The range was 5.7 to 10.4 $L \cdot min^{-1}$.

Inspiratory CO_2 was detected in 100%, 75%, 28%, and 0% of studies in groups A to D respectively ($P < 0.0001$), but there were no differences in $PETCO_2$ among the four groups. The statistical power of this experiment to detect a true difference in mean $PETCO_2$ of 10% between any two adjacent groups was over 0.95.

There was also no difference in O_2 saturation and no saturations less than 90% were observed.

Discussion

Since the $\dot{V}_{FG}$ is a derived value based on the measurement of P_{dr} and FiO_2 , the relationships between $\dot{V}_{O_2}$, P_{dr} and air entrainment are central to its accurate estimation. We used a variable orifice rotameter type O_2 flowmeter to measure $\dot{V}_{O_2}$. The accuracy of this type of flowmeter is stated to be between ± 2 to $\pm 5\%$.^{7,8} Flow (F) and pressure (P) at the entrainer are related by the Bernoulli equation. For a fixed venturi the flow is predicted by the approximate formula $F = kP^{1/2}$, where k is a constant.⁹ Our data are an almost exact fit to that model and validate our use of pressure as an indicator of flow. We measured FiO_2 of the downstream gas and used it to calculate the air/ O_2 entrainment ratio (A) for each group. With this number and the $\dot{V}_{O_2}$ we calculated the average $\dot{V}_{FG}$ (O_2 plus entrained air) for each group. Farman described the entrainer's operation only at a driving gas pressure of 100 mmHg, and reported that the consumption of driving gas was 2 $L \cdot min^{-1}$, the total gas flow was 10 $L \cdot min^{-1}$, and when O_2 was the driving gas the oxygen content of the final mixture was about 36%.¹⁰ The small difference between our estimate of $\dot{V}_{O_2}$ at 100 mmHg and Farman's may be due to measurement error, differences in entrainers, or an effect of altitude. We are reasonably confident that our estimates are accurate to within about the error of the flowmeter, that is $\pm 5\%$. However, since we were unable to confirm this, our recommendations for clinical use are conservative.

A constant value for FiO_2 at P_{dr} between 60–100 mmHg ($\dot{V}_{O_2}$ of 1.59 to 2.08 $L \cdot min^{-1}$) indicates that the air/ O_2 entrainment ratio (A) was constant. At a P_{dr} of 40 mmHg ($\dot{V}_{O_2}$ of 1.29 $L \cdot min^{-1}$) air entrainment decreased and FiO_2 increased. At this level the pressure downstream from the entrainer is very low, probably no more than 2–3 mmHg,⁶ and the resistance of the valves and tubing becomes a limiting factor. Therefore, we do not recommend using the entrainer at P_{dr} of less than 60 mmHg. We did not attempt to quantitate CO_2 re-breathing, but only to identify it qualitatively from the capnograph trace. Deviation of the inspiratory CO_2 trace from baseline was detected at 40, 60, and 80 mmHg entrainer pressures, but there were no differences in end-tidal CO_2 among the four groups. This suggests either that the amount rebreathed was clinically inconsequential, or that it occurred late in inspiration and went to the anatomical dead space. Although true differences may exist among the groups, they are likely not more than 3 mmHg, and clinically unimportant. Despite the observation that CO_2 removal was adequate at an entrainer

TABLE Experimental results. Data (mean $\pm$ SEM)

Group	A	B	C	D	
P_{dr} mmHg	40	60	80	100	
$\dot{V}_{O_2}$ L $\cdot$ min $^{-1}$	1.29	1.59	1.85	2.08	
FiO_2	0.38 $\pm$ 0.00	0.36 $\pm$ 0.00	0.36 $\pm$ 0.00	0.36 $\pm$ 0.00	$P < .0001$
$\dot{V}_{FG}$ L $\cdot$ min $^{-1}$	5.7	8.0	9.3	10.4	
PETCO $_2$ mmHg	34.4 $\pm$ 0.6	33.4 $\pm$ 0.6	33.1 $\pm$ 0.6	32.6 $\pm$ 0.5	NS
Rebr.CO $_2$	40	30	11	0	
No.(%)	(100)	(75)	(28)		$P < 0.0001$
O $_2$ Sat %	98.4 $\pm$ 0.3	98.6 $\pm$ 0.2	98.7 $\pm$ 0.2	98.4 $\pm$ 0.2	NS

The $\dot{V}_{O_2}$ for each P_{dr} was determined from the best fit equation (Figure 2). Total FG flow ($\dot{V}_{FG}$) equals $\dot{V}_{O_2}$ plus entrained air and was estimated from the $\dot{V}_{O_2}$ and FiO_2 by the following formulae:

$$FiO_2 = (1 + 0.2A)/(1 + A) \quad (1)$$

$$\dot{V}_{FG} = \dot{V}_{O_2} (1 + A) \quad (2)$$

Formula (1) is solved for A, the air/O $_2$ entrainment ratio.

pressure of 40 mmHg we do not use the entrainer at this pressure for the reason given above.

With this circuit configuration CO $_2$ rebreathing will depend on only three factors: the volume of the efferent limb of the circuit (V_{eff}), the $\dot{V}_{FG}$, and the respiratory pattern. The V_{eff} should exceed the alveolar volume per breath; in these studies it was 340 ml or an average of 7.2 ml $\cdot$ kg $^{-1}$ body weight. For a population of different habitus a larger size efferent tubing might be required. Since the RR was 10 min $^{-1}$ minute ventilation of the lungs with gas from the efferent limb ($\dot{V}_{eff}$) was 3.4 L $\cdot$ min $^{-1}$ or 72 ml $\cdot$ kg $^{-1}$ $\cdot$ min $^{-1}$. When all of the expired gas in the efferent limb was replaced by FG there would be no CO $_2$ rebreathing and the effective ventilation of the lungs with FG would be equal to $\dot{V}_{eff}$. With the usual T-piece circuit the balance would be rebreathed expired gas; with this circuit it was ambient air. To prevent clinically significant rebreathing we recommend a $\dot{V}_{FG}$ of about twice the $\dot{V}_{eff}$ which requires a minimum P_{dr} of 60 mmHg.

As with other semi-open T-piece circuits the respiratory pattern is an important determinant of CO $_2$ rebreathing. Optimal efficiency will be achieved with a slow rate and a long expiratory pause.¹¹

This system has three important limitations. Should the O $_2$ supply fail during IPPV the expiratory limb would become dead space with the risk of severe hypercapnia and hypoxaemia. Also, because of the low pressure downstream from the entrainer, stable $\dot{V}_{FG}$ is dependent upon low circuit resistance. Anything which might increase resistance to flow, such as sticking valves, small bore or kinked tubing, must be carefully avoided. We leave the bellows of the OIB unlocked as a visual monitor of the FG flow. A less serious limitation is the inability to vary FiO_2 . For those situations which require 100% O $_2$ we

recommend that an alternative circuit, such as a Bain circuit, be kept on standby.¹²

In this study we have examined the operational characteristics of a low pressure continuous flow system that balance economy of operation against the risk of CO $_2$ rebreathing. A high FG flow wastes both O $_2$ and volatile anaesthetic. This is more serious with halothane, because of its cost, than with ether. At low driving gas pressures, less than 60 mmHg, the entrainer becomes unreliable and the risk of CO $_2$ rebreathing increases. The entrainer operates effectively with a source gas flow rate of between 1.6–2.0 L $\cdot$ min $^{-1}$ or an entrainer driving pressure of 60–100 mmHg. This yields $\dot{V}_{FG}$ of 8–10 L $\cdot$ min $^{-1}$, which is the range for optimal accuracy of both the OMV halothane and the EMO ether vaporizers.¹³

With this simple system one can practice economical, modern anaesthesia, especially where compressed gases are in short supply. It can be readily assembled from components that are available in most underdeveloped countries.

References

- 1 Tweed WA, Amatya R, Tuladhar TM, Maltby JR, Gurung CK. Anaesthesia services and the education of anaesthetists in Nepal: a model for sustainable development? *Can J Anaesth* 1993; 40: 993–9.
- 2 Ezi-Ashi TI, Papworth DP, Nunn JF. Inhalational anaesthesia in developing countries. Part 1. The problems and a proposed solution. *Anaesthesia* 1983; 38: 729–35.
- 3 Tweed WA, Amatya R, Spoerel WE. Re-evaluation of the Farman entrainer in a low-pressure system for field anaesthesia. *Can J Anaesth* 1990; 37: 924–7.
- 4 Farman JV. Economical anaesthesia overseas: air entrainment device for use with draw-over vaporizers in children. *BMJ* 1965; 2: 1428.

- 5 Tweed WA, Amatya R, Spoerel WE. A low-pressure portable anaesthesia system for field use: clinical trials. *Can J Anaesth* 1990; 37: 928–31.
- 6 Conway CM. Anaesthetic breathing systems. *Br J Anaesth* 1985; 57: 649–57.
- 7 Macintosh R, Mushin WW, Epstein HG. *Physics for the Anaesthetist* (3rd ed). Oxford: Blackwell Scientific Publications Ltd., 1963; 202.
- 8 Lunn JN. The measurement of gas flow and volume. *In*: Scurr C and Feldman S (Eds.). *Scientific Foundations of Anaesthesia*. Chicago: Year Book Medical Publishers, Inc., 1974: 71–9.
- 9 Barker SJ, Tremper KK. Physics applied to anesthesia. *In*: Barash PC, Cullen BF, Stoelting RK (Eds.). *Clinical Anesthesia*. Philadelphia: JP Lippincot Company, 1989: 97–8.
- 10 Farman JV. The use of an air-entrainment device in conjunction with a draw-over vaporiser. A method for small children. *Acta Anaesthesiol Scand* 1966; Suppl 23: 485–90.
- 11 Byrick RJ, Janssen RT. Respiratory waveform and rebreathing in T-piece circuits: a comparison of enflurane and halothane waveforms. *Anesthesiology* 1980; 53: 371–8.
- 12 Lowe DM, McFadzean W. Drawover anaesthesia and preoxygenation. *Br J Anaesth* 1991; 66: 196–9.
- 13 Schaefer HG, Farman JV. Anaesthetic vapour concentrations in the EMO system. *Anaesthesia* 1984; 39: 171–80.