A low-pressure portable anaesthesia system for field use: clinical trials

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This is a report of our experience with a portable anaesthesia system that was developed for use under field conditions, when compressed gas supplies are limited. We first assembled and bench-tested a low-pressure plenum system, based upon the Farman entrainer. The entrainer required a low flow of compressed gas, O_2 at $1-2\text{ L}\cdot\text{min}^{-1}$, and generated a low-pressure mixture of O_2 and air which was directed through an Oxford miniature vaporizer, a non-return valve, and a wide-bore T-piece circuit. With this system we anaesthetized 24 patients with intermittent positive pressure ventilation (IPPV) and nine patients breathing spontaneously. During IPPV, the circuit resembled a T-piece and provided effective gas exchange with a FGF of 1.2 times minute ventilation. Inspiratory and expiratory valves were arranged so that the spontaneous mode was non-rebreathing, and FGF was adjusted to equal minute ventilation. The system was very economical, using $1-2\text{ L}\cdot\text{min}^{-1}$ O_2 and $20-25\text{ ml}\cdot\text{hr}^{-1}$ liquid halothane to produce a FGF of $6-10\text{ L}\cdot\text{min}^{-1}$, an FiO_2 of 0.33, and Fi_{hal} of 1-1.5 per cent. We have demonstrated that this is a versatile, safe, and economical system, compatible with the practice of modern inhalational anaesthesia under field conditions. It can be readily assembled from commercially available components.

On reporte notre expérience avec un système d'anesthésie ambulatoire qui a été développé pour l'utilisation dans les conditions de champ de bataille quand la réserve de gaz comprimé est limitée. On a initialement assemblé et testé au laboratoire un système de soufflerie à basse pression basée sur le « Farman entrainer ». Le souffleur a fonctionné à des flots bas de gaz comprimé O_2 à $1-2\text{ L}\cdot\text{min}^{-1}$, et généré un mélange à basse pression d'oxygène et d'air et a été dirigé vers un vaporisateur miniature Oxford, une valve uni-directionnelle, et

un circuit comprenant une pièce en T de grand calibre. Avec ce système, on a anesthésié 24 patients avec une ventilation intermittente à pression positive (IPPV) et les neuf patients respiraient spontanément. Durant l'IPPV, le circuit ressemblait à la pièce en T et fournissait un échange gazeux efficace avec un FGF de 1,2 fois de ventilation à la minute. Les valves respiratoires et expiratoires ont été arrangées afin d'éviter la réinspiration lors de la ventilation spontanée et le FGF fut ajusté pour égaler la ventilation à la minute. Le système fut très économique utilisant $1-2\text{ L}\cdot\text{min}^{-1}$, O_2 et $20-25\text{ ml}\cdot\text{heure}^{-1}$ d'halothane liquide afin de produire un FGF de $6-10\text{ L}\cdot\text{min}^{-1}$ et FiO_2 de 0.33 et une Fi halothane de 1-1.5 pour cent. On a démontré que ce système versatile, sécuritaire et économique est compatible avec la pratique de l'anesthésie d'inhalation moderne dans les conditions de champs de bataille. Ce système pourrait être assemblé sur le champs à partir d'éléments disponibles commercialement.

In an accompanying report we describe the components and gas flow characteristics of a low-pressure, plenum anaesthesia system incorporating the Farman entrainer¹ to deliver a fresh gas mixture of ambient air and oxygen. This system was designed for general anaesthesia in field conditions and under-served areas, especially where supplies of compressed gases are limited. It requires only a low flow of source gas to drive the Farman entrainer, i.e., $1-2\text{ L}\cdot\text{min}^{-1}$ O_2 at a pressure of less than 200 mmHg.

Because the bench studies had demonstrated that fresh gas flow rates (FGF) in the system were dependent upon the diameter of the delivery tubing and the resistance to flow of the breathing circuit, we chose a wide-bore, low-resistance T piece for the clinical trial. The configuration of the assembled system is illustrated in Figure 1. It consisted of a compressed O_2 source, a Farman entrainer, an EMO, an Oxford Miniature Vaporizer (OMV), an Oxford Inflating Bellows (OIB), and a T-piece circuit. For clinical use the T-piece circuit was configured in four ways, for different patient and ventilatory requirements. We have used it in all four modes but report results only for controlled intermittent positive-pressure ventilation (IPPV) and spontaneous breathing.

1 In the IPPV mode a mechanical ventilator was attached

Key words

ANAESTHETIC TECHNIQUES: inhalation;
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FIGURE 1 A schematic drawing of a portable low-pressure plenum system. OMV is the Oxford miniature vaporizer, OIB is the Oxford inflating bellows. The ARF-850 ventilator was used for IPPV.

to the efferent limb. We used an electrically driven ARF-850 ventilator, supplied by Acoma Medical Instrument Co. Ltd., Japan. In this mode the circuit resembles a T-piece.

- 2 In the manual control-assist mode the ventilator was replaced by a reservoir bag and expiratory relief valve.
- 3 For spontaneous breathing the reservoir bag was removed and the open end of the expiratory relief valve was plugged. Since there were one-way valves on both inspiratory and expiratory limbs this was a non-rebreathing (NRB) circuit, and the OIB served as the fresh gas reservoir.
- 4 With the expiratory limb left open, the circuit was used as a simple low-resistance T-piece for paediatric anaesthesia. It could also be used with a Jackson-Rees attachment to the reservoir limb.

Each of these circuits facilitates scavenging of waste gases, which was usually practiced.

The clinical trial was conducted in the operating theatres of Tribhuvan University Teaching Hospital, Kathmandu.

Methods

Thirty-three patients were studied using the system, 24 with IPPV and nine breathing spontaneously. The studies were conducted in accordance with Departmental and Institutional standards.

Subjects selected for study were ASA physical status I and II patients receiving general tracheal anaesthesia. Induction was with thiopentone $3-5 \text{ mg} \cdot \text{kg}^{-1}$ and succinylcholine $1 \text{ mg} \cdot \text{kg}^{-1}$. After tracheal intubation anaesthesia

was maintained with halothane/ O_2 /air and meperidine $0.4-0.6 \text{ mg} \cdot \text{kg}^{-1}$. For IPPV, either gallamine or d-tubocurarine was given for muscle relaxation. The inspired halothane concentration was maintained at 1.0 to 1.2 per cent with the aid of an Engstrom EMMA Multigas Monitor (Gambro Engstrom AB, Box 20109, S-161, 20 Bromma, Sweden). The source gas in all cases was compressed O_2 , delivered through a rotameter flowmeter from a Mera anaesthetic machine.

Measurements were made of FGF through the circuit, expiratory minute ventilation (V_E), and inspired oxygen concentration (FiO_2). Each recorded measurement was the mean of 3-5 readings. Arterial blood was also sampled anaerobically and arterial blood gases (ABG) were analyzed with a Corning 165 Blood Gas Analyzer. Serum bicarbonate and base excess were estimated from a Siggaard-Anderson nomogram. A complete set of measurements was made after surgery had begun and stable anaesthesia conditions were established.

Gas flows were measured with a Medishield RM 121 (Wright) respirometer which had been calibrated with an ACOMA PH-3F rotameter type flowmeter, and oxygen concentration with an ACOMA model AS-25 oxygen analyzer calibrated with room air (ACOMA Medical Instrument Co. Ltd., Japan). The blood gas analyzer was calibrated with a standard gas before each analysis.

Oxygen and halothane use were estimated volumetrically. The halothane vaporizer was refilled with a 20-ml syringe at the end of each case to determine halothane consumption. Auscultatory blood pressure (BP) and heart rate (HR) were recorded every five minutes.

Kathmandu is at an altitude of 1300 metres with an average barometric pressure of 650 mmHg. These data are not corrected for temperature or pressure.

Results

Data for 33 patients is presented in the Table. Arterial blood gases were obtained from 28 patients, 22 with IPPV and six with spontaneous respiration.

Demographic data are shown first. Most patients in this study, as in the general Nepali population, were small by North American standards, muscular, and lean. The surgical procedures of the IPPV group were mainly abdominal and gynaecological, but chiefly orthopaedic and ENT for those breathing spontaneously. Halothane consumption was higher with spontaneous respiration, in part because they required a higher concentration to maintain clinical anaesthesia, and also because FGF was higher.

Data for pulmonary ventilation and FGF rates are normalized for body weight. Tidal volume was smaller, rate higher, and total minute ventilation greater in spontaneously breathing patients. FGF was 1.18 times V_E

FGF WITH THE ENTRAINER SYSTEM DURING FREE FLOW AND IPPV

FIGURE 2 Fresh gas flow at various O₂ flow rates during IPPV (rate of 12 bpm and I:E ratio of 1:2), compared with that measured during free-flow conditions, that is with the patient connector open to atmosphere. The air/O₂ entrainment ratio during free flow was about 6:1 and during IPPV about 4:1.

during IPPV; 1.02 times V_E during spontaneous breathing.

The ABG results are shown next. PCO₂ was higher in spontaneously breathing patients, but both groups were within the clinically acceptable range for general anaesthesia. The same applies to BP and HR, with a decrease in systolic BP and no change in HR characteristic of halothane anaesthesia.

Figure 2 compares FGF measured during bench testing, with the patient connector open and the circuit free flowing, with actual FGF during IPPV (I:E ratio of 1:2 and rate of 12 bpm). During free flow the air/O₂ entrainment ratio was about 6:1, but it was reduced to about 4:1 during IPPV anaesthesia.

Discussion

Most modern anaesthesia machines are unsuitable for use under field conditions and in under-serviced areas of the world. The major limiting factor is that compressed gases are often unavailable or very scarce.² For the same reasons rebreathing systems, dependent on CO₂ absorbers, are impractical. The practical solution is to use ambient air as the main carrier gas for inhalational anaesthesia. This is the principle of the EMO and OMV which were designed by the Oxford group in the 1950s and 60s, the Triservice apparatus, and similar systems which are still widely used.^{3,4} However, such equipment was not designed for the practice of modern anaesthesia.

We began these studies with the premise that modern anaesthesia could be practised in under-serviced and remote areas of the world by adapting existing equipment. A continuous flow or plenum system was required, but

TABLE Patient data

Variable	Controlled		Spontaneous		P
	Mean	SD	Mean	SD	
Age yr	36.8	12.8	31.7	11.2	NS
Weight kg	46.4	7.4	54.1	17.2	NS
Anaes. time hr	1.35	0.48	1.93	0.93	<0.05
Halothane used ml · hr ⁻¹	20.8	5.0	25.7	4.8	<0.05
Tidal vol ml · kg ⁻¹	9.7	0.8	4.1	0.8	<0.000
Resp rate	12		37	5	
Minute vent. ml · kg ⁻¹ · min ⁻¹	116	10	150	24	<0.000
FGF ml · kg ⁻¹ · min ⁻¹	137	18	154	55	NS
FGF/min vent	1.18	0.1	1.02	0.32	<0.05
Driving press. mmHg	51	6	57	6	0.001
FiO ₂	0.33	0.02	0.33	0.01	NS
PCO ₂	44	5	49	6	NS
PO ₂	127	27	127	40	NS
pH	7.35	0.07	7.36	0.04	NS
Bicarb meq · L ⁻¹	26.2	4.1	28.2	1.5	NS
BE meq · L ⁻¹	1.4	4.4	3.2	1.2	NS
Syst BP mmHg pre-ind.	115	16	111	16	NS
Lowest	96*	11	93*	10	NS
Heart rate bpm pre-ind.	83	14	79	6	NS
Lowest	86	17	85	16	NS

Data for 24 patients during general anaesthesia with IPPV and 9 breathing spontaneously. Statistical comparison was by the unpaired t-test.

*Indicates $P < 0.01$ compared with pre-induction.

one that did not make a heavy demand on compressed gases. An O₂-driven Venturi with a high air/O₂ entrainment ratio, the Farman entrainer, was selected and its flow characteristics were examined in a preliminary study. Based on those results we designed a simple system with a low-resistance T-piece breathing circuit and tested it in a clinical trial.

This study was not conducted with precise measuring instruments. We used clinical instruments, calibrated against the best available standards, and attempted to reduce random error by averaging several readings for each data point. It is likely, however, that overall measurement error was in the range of 5–10 per cent. This also applies to ABG analyses, since the analyzer was used infrequently, replacement electrodes were unavailable, and standard gases were of dubious purity. The high estimated values for bicarbonate and base excess, where there was no expectation of a metabolic alkalosis, suggests that there was a systematic overestimation of PCO₂. We intend, therefore, to repeat these studies under better controlled conditions. Despite that reservation this trial is of unique value, since there is no substitute for evaluating new equipment under the actual conditions of intended use.

We chose the Oxford miniature vaporizer (OMV) because of its reliable performance under field condi-

tions.⁵ It is a very low-resistance vaporizer and works equally well with plenum or draw-over flow⁶ and over a wide range of flow rates.^{7,8} Although a fluid reservoir provides temperature buffering it is not thermal-compensated, and output varies with both temperature and time. In this study the output seldom varied more than ten per cent from the dial setting.

The source gas for the entrainer was O₂, delivered through a Mera rotameter flowmeter. However, any low-pressure compressed gas source would do: a portable O₂ cylinder with a flow control valve or an oxygen concentrator.⁹ If O₂ were not available compressed air could be substituted, or the entrainer could be removed converting the system to a draw-over mode. In normal clinical use we found this to be a very economical system, consuming 20–25 ml liquid halothane per hour and 1–2 L·min⁻¹ of O₂.

The Oxford inflating bellows (OIB), with both valves functioning, is an integral part of the system. During the inspiratory phase of IPPV the distal valve of the OIB prevents back flow through the vaporizer. The bellows was left unlatched, acting as a secondary reservoir and allowing continuous forward flow from the entrainer through the vaporizer. The open bellows serves another important safety function as a visible monitor of continuous FGF. The distal valve of the OIB remains closed throughout inspiration, and opens early in expiration so that all FGF occurs during the expiratory phase. Functionally, therefore, this circuit resembles the T-piece circuit, and our studies suggest that adequate gas exchange can be achieved if FGF is 1.2 times minute ventilation. Some rebreathing undoubtedly occurred under the conditions of this study, and further investigations with capnography are required.

The circuit for spontaneous respiration was non-rebreathing, with separate inspiratory and expiratory non-return valves. This was confirmed many times; reverse flow was never observed in either limb. Waste gas was readily scavenged from the expiratory relief valve. In this mode the OIB bellows was the primary reservoir, and FGF equalled minute ventilation.

Although we believe the system as described is suitable for field anaesthesia, there are some necessary precautions in its use. Because it is a low-pressure system FGF is sensitive to changes in circuit resistance (Figure 2). This is particularly important during IPPV since a decrease in FGF would increase rebreathing. Although using the OIB as a secondary reservoir provides a visual check on FGF, an accurate flow meter is advisable until one becomes experienced with the system. When O₂ is used as the source gas, FiO₂ will not fall below 0.3, and an O₂ analyzer is unnecessary. However, a relatively fixed FiO₂

is a limitation, and further developments will address the problem of O₂ enrichment.

In summary we have described a simple anaesthesia system that allows the practice of modern anaesthesia under field conditions. In a clinical trial with both controlled and spontaneous ventilation, safe and efficient use of the apparatus was demonstrated. The total system can be readily assembled from commercially available components, and EMO draw-over systems can be easily converted. Improvements in anaesthesia technology, as we have proposed, in concert with increased training opportunities,¹⁰ can greatly improve the quality of anaesthesia available in remote and under-served areas.

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