Functional closed-system anesthesia using a function-equipped anesthesia machine and time-cycled ventilator

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Introduction

Closed-system anesthesia is a very economical method, but it is technically complicated by the requirement for balanced supply and consumption of both anesthetic agents and oxygen. Low-flow anesthesia (LFA) is technically simple, and we studied modifications to further reduce the volume of anesthetic agents supplied. A device that automatically shut off delivery of nitrous oxide, depending on the oxygen concentration in the respiratory circuit, was attached to a standard anesthesia machine. The anesthesia machine was connected to a time-cycled artificial ventilator by a tube of 3 l capacity (using three breathing tubes in series) that far exceeded the tidal volume. We performed functional closed-system anesthesia (FCA) using this system, and examined the changes in concentration and delivered volume of anesthetics in the respiratory circuit during anesthesia for 5 h.

Subjects and methods

We studied 10 patients aged 45 ± 14 years, weighing 61 ± 9 kg, of ASA class I or II without liver or renal dysfunction, who were scheduled for surgery for 5 h or longer. Informed consent was obtained from each patient after the anesthetic method was explained.

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FCA was conducted using a conventional general anesthesia machine (type CT-7, Acoma, Tokyo, Japan) equipped with additional functions (CT-7-WO, Acoma) that we devised, as follows:

1. A high-precision oxygen and nitrous oxide flow meter with digital display that allows adjustment in units of $10\,\mathrm{ml \cdot min^{-1}}$.
2. A display of cumulative oxygen and nitrous oxide delivery.
3. An oxygen monitor of the respiratory circuit that generates an alert when the oxygen concentration drops to 28.5% or lower, and simultaneously activates a nitrous oxide breaker, shutting off nitrous oxide delivery.
4. An automatic nitrous oxide breaker.

Nitrous oxide delivery was stopped automatically when the oxygen concentration in the respiratory circuit dropped to 28.5% or lower, and was redelivered at the same flow rate as before when the oxygen concentration recovered to 31.5%. During anesthesia, controlled ventilation was performed using a time-cycled artificial ventilator for anesthesia (type ACE 3000 a, Acoma). Isoflurane was delivered from an extracircuit vaporizer (type I MK III, Acoma).

The anesthesia machine was connected to the artificial ventilator by a tube of 3 l capacity (using three breathing tubes in series), which far exceeded the tidal volume. Anesthesia was induced with 300 mg thiopental, and endotracheal intubation was performed with 8 mg vecuronium. Nitrous oxide and isoflurane were used as inhalation anesthetics. After denitrogenation by 100% oxygen at $6\,\mathrm{l \cdot min^{-1}}$ for several minutes, inhalation anesthesia was begun. The tidal volume was fixed at 500 ml, and the respiratory rate was adjusted to obtain $P_{ET}CO_2$ at 35 to 45 mmHg. Nitrous oxide and isoflurane were delivered to the respiratory circuit from the common gas outlet of the anesthesia machine, but oxygen was not delivered from the com-

mon gas outlet. The flow rate of nitrous oxide was set at $5.25\,ml\cdot kg^{-1}\cdot min^{-1}$ and the isoflurane vaporizer at 5%; the rates were unchanged during FCA for 5 h. Oxygen was delivered automatically from the artificial ventilator, depending on the oxygen concentration in the respiratory circuit. The following items were recorded or calculated by the method described:

1. The oxygen and anesthetic concentrations in inspired and expired gases and SpO_2 were measured by an anesthesia gas monitor (POET IQ, Criticare, WI, USA) and recorded every minute. The anesthesia gas monitor was connected to the respiratory circuit as in Fig. 1 to prevent entry of air into the circuit, which is a cause of dilution of anesthetic gas and decreasing oxygen concentration [1].
2. Isoflurane delivery was calculated in gaseous form as equivalent to 5% of the nitrous oxide delivered.
3. The temperature of the soda lime was measured continuously by inserting a thermometer into the canister.

After surgery, delivery of nitrous oxide and isoflurane was terminated, and the patient was wakened with oxygen at $6\,l\cdot min^{-1}$ from the anesthesia machine, as usual. All values are expressed as mean ± SD.

Results

At 26 ± 7 min, the inspired concentrations of nitrous oxide and oxygen were equal at 46 ± 1%. Surgery was started 28 ± 22 min after the initiation of FCA. At this time, the oxygen concentration was 50 ± 11%/47 ± 13% (inspired/expired gas), the nitrous oxide concentration was 43 ± 12%/39 ± 13%, and the isoflurane concentration was 0.9 ± 0.1%/0.6 ± 0.1%. At this time the sum of anesthetic potency in nitrous oxide and isoflurane corresponded to 1.1 ± 0.2/0.9 ± 0.3 minimal alveolar concentration. At 56 ± 13 min after the initiation of FCA, the oxygen concentration in the respiratory circuit dropped to 28.5%, and the nitrous oxide

delivery was stopped automatically. From then, isoflurane delivery was intermittent, corresponding to the intermittent nitrous oxide supply. No SaO_2 lower than 95% by pulse oximetry appeared during this study. The concentrations of oxygen, nitrous oxide, and isoflurane and the amounts of isoflurane and nitrous oxide delivered per hour or per kilogram per hour during FCA for 5 h are described in Table 1.

The concentrations of oxygen and anesthetic in the circuit recorded every minute in a representative patient are shown in Fig. 2. Sixty-five minutes after inhalation anesthesia was begun, the oxygen concentration in the respiratory circuit dropped to 28.5%, and delivery of nitrous oxide was stopped automatically. Oxygen was delivered from the artificial ventilator. Recovery of the oxygen concentration in the circuit to 31.5% triggered the restart of nitrous oxide and isoflurane vaporized by the nitrous oxide from the common gas outlet of the anesthesia machine. This pattern was repetitive. Abnor-
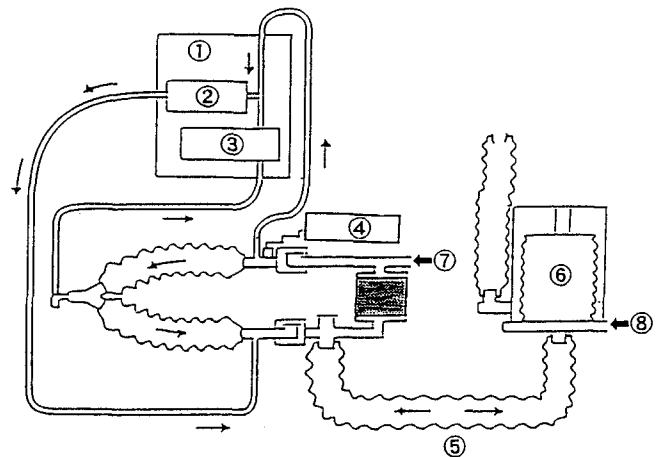

Fig. 1. Anesthesia circuit for functional closed system anesthesia (FCA). 1 Anesthesia gas monitor. 2 Pump. 3 Sensor. 4 Oxygen monitor (connected to nitrous oxide breaker). 5 Connecting tube (volume about 3000 ml). 6 Ventilator for anesthesia (time-cycled type). 7 Nitrous oxide and isoflurane inlet through the flow meter or vaporizer. 8 Oxygen inlet

Table 1. Parameters during functional closed-system anesthesia

Parameter	0 min	2 min	5 min	10 min	15 min	30 min	1 h	2 h	3 h	4 h	5 h	Units
O_2 in	96 ± 2	92 ± 2	78 ± 4	66 ± 5	57 ± 5	42 ± 7	31 ± 2	29 ± 1	29 ± 2	29 ± 2	29 ± 1	%
ex	91 ± 3	87 ± 2	76 ± 3	64 ± 5	55 ± 5	39 ± 7	26 ± 2	24 ± 1	23 ± 1	23 ± 1	23 ± 1	%
N_2O in	0 ± 0	1 ± 2	16 ± 3	28 ± 4	36 ± 5	50 ± 6	62 ± 2	65 ± 2	67 ± 1	67 ± 2	68 ± 2	%
ex	0 ± 0	0 ± 0	13 ± 3	24 ± 4	33 ± 5	47 ± 6	59 ± 3	63 ± 2	64 ± 1	65 ± 2	65 ± 2	%
Iso in	0.0 ± 0.0	0.3 ± 0.1	0.5 ± 0.1	0.7 ± 0.1	0.8 ± 0.1	1.0 ± 0.2	1.0 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	0.8 ± 0.2	%
ex	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.1	0.5 ± 0.1	0.6 ± 0.1	0.7 ± 0.1	0.8 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	%
Temp.	26.5 ± 1.5		28.9 ± 1.7	31.1 ± 2.0	33.3 ± 1.9	37.7 ± 1.8	39.9 ± 1.2	40.3 ± 0.6	40.4 ± 0.5	40.3 ± 0.5	40.2 ± 0.3	°C
D N_2O							18.0 ± 2.6	12.7 ± 2.2	10.2 ± 1.8	9.3 ± 1.9	9.0 ± 1.8	l·h⁻¹
							298 ± 14	209 ± 21	167 ± 14	152 ± 19	148 ± 16	ml·kg⁻¹·h⁻¹
D Iso							897 ± 132	635 ± 108	509 ± 92	467 ± 93	452 ± 91	ml·h⁻¹
							15 ± 1	11 ± 1	9 ± 1	8 ± 1	7 ± 1	ml·kg⁻¹·h⁻¹

Values are mean ± SD O_2 in, Inspired oxygen concentration; O_2 ex, expired oxygen concentration; N_2O in, inspired nitrous oxide concentration; N_2O ex, expired nitrous oxide concentration; Iso in, inspired isoflurane concentration; Iso ex; expired isoflurane concentration; Temp.: Temperature of the soda lime; D N_2O, nitrous oxide delivery; D Iso, isoflurane delivery
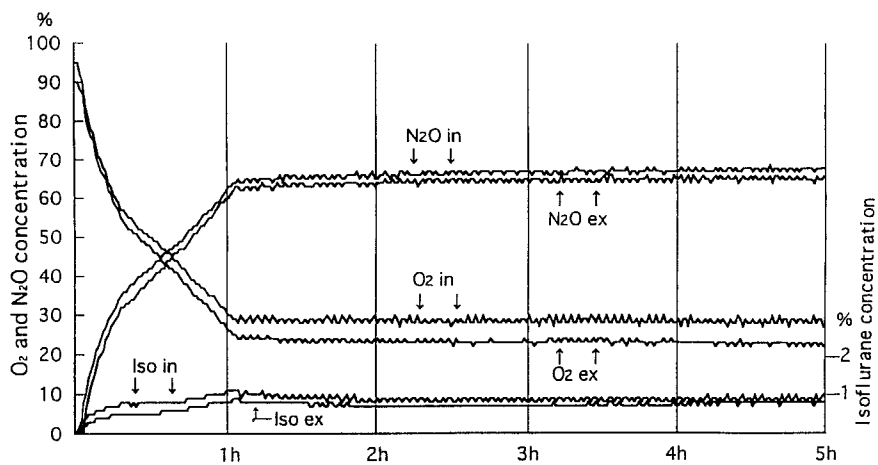
Fig. 2. Trendgram of oxygen and anesthetic concentrations during FCA for 5 h. 31 year-old woman, 55.5 kg, RN_2O = 290 ml·min^{-1}. O_2 in, Inspired oxygen concentration; O_2 ex, expired oxygen concentration; N_2O in, inspired nitrous oxide concentration; N_2O ex, expired nitrous oxide concentration; Iso in, inspired isoflurane concentration; Iso ex, expired isoflurane concentration

mal pressure in the respiratory circuit was not detected in any case.

Discussion

Closed-system anesthesia and LFA are recommended because of improved environmental protection, medical economy, maintenance of humidity in the respiratory organs [2], and maintenance of optimal body temperature [3]. In closed-system anesthesia, the fresh gas flow (FGF) and gas consumption and should be balanced, and this method requires delivery of the smallest amounts of anesthetic and oxygen. However, regulation of FGF is technically difficult; an excess may result in barotrauma to the lung, and a deficit may cause impaired ventilation, hypoxemia, or induction delay.

We added various functions to a standard anesthesia machine and performed FCA easily and safely. The anesthesia machine was connected to the ventilator by a connecting tube system composed of three breathing tubes. The system of connecting tubes between the anesthesia machine and the ventilator had an internal volume of approximately 3000 ml, far exceeding the 500 ml tidal volume. This ensured that the anesthetic gas did not reach the ventilator during respiration. The anesthetics also could not escape into the atmosphere from the gas pocket. The FCA system was theoretically a closed system, because the mixture of anesthetic and oxygen was isolated from the atmosphere by the pure oxygen inside the connecting tube. However, anesthetic gas actually diffused through the connecting tube into the atmosphere, and therefore, strictly speaking, the system was not completely closed. For this reason, the amount of anesthetic agents delivered was somewhat larger than in the closed system. The working in error of electronic apparatus used in this FCA should be avoided for the safety of patients. Although the flow

rates of both oxygen and nitrous oxide are controlled by a needle valve as usual and confirmed by the rotameter and the digital display of the high-precision oxygen and nitrous oxide flow meter, large errors of flow rate of oxygen and nitrous oxide do not occur. The only problem that may cause hypoxia is an error in the oxygen monitor in the respiratory circuit connected to the automatic nitrous oxide breaker. However, there is no chance of hypoxia, because oxygenation is monitored in three ways by the oxygen monitor in the respiratory circuit, anesthesia gas monitor, and pulse oximeter.

When it is necessary to increase FIO_2, delivery of nitrous oxide should be stopped, and/or oxygen should be delivered from the anesthesia machine. When the total flow rate of oxygen and nitrous oxide from the anesthesia machine increases, the setting of the isoflurane vaporizer must be decreased.

In this method of FCA, isoflurane delivery was dependent only on nitrous oxide flow. No oxygen was delivered from the common gas outlet of the anesthesia machine. Immediately after the initiation of FCA, oxygen inside the respiratory circuit was consumed while nitrous oxide and isoflurane were delivered, resulting in a temporary decrease of oxygen concentration, which was replaced mainly by nitrous oxide. When the oxygen concentration inside the circuit dropped to 28.5%, the nitrous oxide breaker was activated, stopping the delivery of both nitrous oxide and isoflurane. Since the gas volume inside the circuit was reduced due to oxygen consumption and uptake of anesthetic agents by the body, pure oxygen from the ventilator flowed into the respiratory circuit. When the oxygen concentration in the circuit reached 31.5%, nitrous oxide delivery was resumed, and the concentrations of oxygen and nitrous oxide in the circuit were maintained at approximately the same level. The maximum isoflurane vaporization was fixed at 5%, but a suitable concentration was maintained during the course of FCA (Table 1). When

the nitrous oxide level in the body reached saturation, uptake of nitrous oxide from the circuit stopped. The concentration of nitrous oxide in the circuit increased, and the oxygen concentration decreased to 28.5% or lower. Because the stopping of nitrous oxide delivery was accompanied by the stopping of isoflurane vaporization, isoflurane delivery after 2h decreased, resulting in a low isoflurane concentration in the circuit. At the beginning of surgery, the sum of anesthetic potency was 1.1 ± 0.2 MAC in the inspired gas and 0.9 ± 0.3 MAC in the expired gas, giving rather light anesthesia. Thirty minutes after the beginning of FCA, the nitrous oxide and isoflurane in the inspired gas were maintained at 1.3 MAC, indicating a suitable depth of anesthesia.

The nitrous oxide flow was set at $5.25\,ml\cdot kg^{-1}\cdot min^{-1}$ for the following reason. We determined the FGF using Foldes' equation [4] LFA:

$$(RO_2 - VO_2)/(RO_2 + RN_2O - VO_2) = F_IO_2 \qquad (1)$$

Where RO_2 = oxygen flow $(ml\cdot min^{-1})$, RN_2O = nitrous oxide flow $(ml \cdot min^{-1})$, VO_2 = oxygen consumption $(ml\cdot min^{-1})$, and F_IO_2 = inspired oxygen fraction.

The F_IO_2 in this equation is only valid when there is no diffusion of nitrous oxide from the surgical wound or anesthesia apparatus such as the breathing tube, bag, or machine. Because nitrous oxide diffuses constantly, the actual F_IO_2 should be slightly higher than the value obtained from this equation. Therefore, when F_IO_2 is set at 0.25, the actual value will be approximately 0.3. VO_2 remains at almost $3.5\,ml\cdot kg^{-1}\cdot min^{-1}$ during anesthesia. These values were substituted into equation (1), and nitrous oxide and oxygen flow was calculated to be $5.25\,ml\cdot kg^{-1}\cdot min^{-1}$, assuming equal flow.

For the purpose of comparison with previously studied LFA, we chose a nitrous oxide flow of $5.25\,ml\cdot kg^{-1}$. The total volume of nitrous oxide administered in FCA was 60l, approximately 5% of that in a semiclosed-system anesthesia. Three liters of isoflurane were administered, equivalent to approximately 16% of the amount for semiclosed-system anesthesia. These amounts are obviously larger than those required for closed-system anesthesia. Although the nitrous oxide delivery was set at the same level as that used in LFA, since nitrous oxide is delivered intermittently in FCA, the total quantity of nitrous oxide delivery was smaller than in LFA.

For LFA conducted in a patient weighing 61 kg, such as in this study, the FGF is $5.25 \times 61 \times 2 = 640$ $(ml\cdot min^{-1})$: $(RO_2 = RN_2O = 320\,ml\cdot min^{-1})$.

FGF for 5h is 192l. Because the vaporizer was set at 3% in LFA of our previous study [5], the isoflurane delivery was calculated to be 5.76l $(192 \times 0.03 = 5.76)$. In this study of FCA, the isoflurane delivery was 2960ml for 5h, which is half that delivered in LFA (average weight, 61kg; Table 1).

Isoflurane reacts with soda lime or baralyme to produce carbon monoxide. When dry or warm soda lime is used, the risk of carbon monoxide production increases [6]. In the present study, the temperature of the soda lime increased up to about 40°C, but the relative humidity around it was probably nearly 100%, as judged from the dew in the canister. The risk of carbon monoxide production was suspected to be low because of the high humidity, but this aspect requires further investigation.

We draw the following conclusions:

1. This technique of FCA is technically simple and more economical than LFA, and poses less risk of barotrauma to the lung than conventional closed-system anesthesia.
2. Although in FCA the anesthesia was somewhat light at the beginning of surgery, the starting time of surgery was not affected, and the inspired and expired anesthetic concentrations were suitable 30min after the beginning of FCA.
3. The anesthetic machine with the additional functions used in this study was useful for FCA.

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