Review Article

Low-flow anaesthesia – underused mode towards "sustainable anaesthesia"

Address for correspondence:
Dr. Madhusudan Upadya, Department of Anaesthesiology, Kasturba Medical College, Manipal University, Mangalore - 575 001, Karnataka, India.
E-mail: madhusudan.upadya@manipal.edu

Access this article online

Website: www.ijaweb.org

DOI: 10.4103/ija.IJA_413_17

Quick response code

Madhusudan Upadya, PJ Saneesh[1]

Department of Anaesthesiology, Kasturba Medical College, Manipal University, Mangalore, Karnataka, India, [1]Department of Anesthesia, Sultan Qaboos University Hospital, Muscat, Sultanate of Oman

ABSTRACT

Any technique that employs a fresh gas flow that is less than the alveolar ventilation can be classified as low-flow anaesthesia. The complexities involved in the calculation of uptake of anaesthetic agents during the closed-circuit anaesthesia made this technique less popular. However, the awareness of the dangers of theatre pollution with trace amounts of the anaesthetic agents and the prohibitively high cost of the new inhalational agents, have helped in the rediscovery of low-flow anaesthesia. Moreover, the time has arrived for each of us, the practicing anaesthesiologists, to move towards the practice of low-flow anaesthesia, to achieve lesser theatre and environmental pollution and also to make anaesthesia more economical. The article also reviews low-flow anaesthesia (LFA) in paediatrics, recent advances such as automated LFA and updates on currently undergoing research to retrieve and reuse anaesthetic agents.

Key words: Economical, environmental, low-flow anaesthesia, rebreathing, sustainable anaesthesia

INTRODUCTION

Ever since the evolution of anaesthetic technique from the era of ether, using open-drop method, through the semi-closed and closed breathing systems, the concept of reusing the anaesthetic agents in the exhaled gas gained significant attention. The development of modern anaesthetic machines, gas analyser monitors, precision vapourisers and introduction of more potent volatile agents with minimal uptake were some of the breakthroughs encouraging low-flow anaesthesia enthusiasts. The staggering amount of environmental pollution due to anaesthetic gases during the present day practice virtually mandates every anaesthesia provider to take that extra bit of effort to use the available facilities to implement low-flow anaesthesia (LFA).[1]

HISTORICAL LANDMARKS IN THE EVOLUTION OF LOW-FLOW ANAESTHESIA

Snow had concluded that if the exhaled anaesthetic gases such as chloroform and ether can be re-inspired, their narcotic effect will be markedly prolonged.[2] The to-and-fro absorption system was introduced by Waters in 1924 as a solution to avoid CO_2 rebreathing.[3] In 1930, Brian Sword first described the circle breathing system with soda lime absorber for closed circuit anaesthesia.[4]

Introduction of agents like cyclopropane since 1933 compelled to minimise the excessive overflow of agents to minimise the risk of explosion. After 1954, highly potent volatile anaesthetic agents with narrow therapeutic indices, like halothane, were introduced.

Although circle systems were available, use of high fresh gas (FG) flows with negligible rebreathing (semi-closed use of rebreathing systems) became the common practice.[5] Virtue, in 1974, reduced gas flows even further in his minimal flow anaesthesia technique.[6] Early 1980s witnessed efforts to actively revive the ideas of low-flow and closed system anaesthesia by Aldrete *et al*.[7] and Lowe and Ernst.[8] The mathematical

How to cite this article: Upadya M, Saneesh PJ. Low-flow anaesthesia – underused mode towards "sustainable anaesthesia". Indian J Anaesth 2018;62:166-72.

approach involving complicated equations to the clinical practice of inhalation anaesthesia was not widely accepted by the anaesthesia fraternity.

Authors like Logan and Farmer in 1989 attracted the attention to the environmental hazards due to anaesthetic agents. The modern volatile anaesthetics (which are partially substituted halogenated hydrocarbons) and nitrous oxide contribute to both the depletion of the stratospheric ozone layer and greenhouse effect.[9]

The advantages of LFA in improving the heat and humidity of rebreathed anaesthetic gases, thus preserving functional and anatomical integrity of epithelial cells in the respiratory tract were highlighted by Kleemann in 1990.[10] In 1995 Baum and Aitkenhead resurrected the LFA enthusiasm by stressing on the unquestionable advantages from economic and environmental perspectives.[11]

The use of newer volatile agents such as sevoflurane and desflurane becomes more economically acceptable when used with low-flow anaesthetic techniques.[12] This is more applicable if Xenon were to be used as an anaesthetic gas in clinical practice.[13]

CONCEPT OF LOW-FLOW ANAESTHESIA

At the outset, we administer FG mixture with a given composition of the anaesthetic gases. The uptake of agents into the body occurs as per the physical characteristics of each agent. The exhaled gas mixture, which eventually mixes with the FG, will have a different composition due to the uptake of agents and addition of CO_2. The idea of LFA is to replenish the consumed gases with as minimum FG as possible; while making sure to remove CO_2 before recirculating. This minimises the loss of anaesthetic agents into the environment.

The challenge is to control the dynamic equilibrium of FG composition as the uptake and metabolism are time-sensitive and many factors influence the consumption and production of gaseous components. This can be achieved only through frequent adjustments in the gas flow controls. Complex equations are used to estimate the uptake of agents such as oxygen, nitrous oxide and volatile agents. Monitoring the inspired and end-tidal concentrations using gas analyser is more accurate and convenient method for the safe conduct of LFA.

DEFINITION OF LOW-FLOW ANAESTHESIA

There is no universally accepted definition for LFA. Any technique that employs an FG flow that is less than the alveolar ventilation can be designated as low-flow anaesthesia.[14]

Low-flow anaesthesia is defined to be an inhalation anaesthetic technique in which the rebreathing fraction at least amounts to 50%, where at least 50% of the exhaled gas mixture is returned to the patient after CO_2 removal in the next inspiration. Using modern anaesthetic machines, this can be achieved when FG flow (FGF) is reduced to at least 2 L/min or less.[11]

Baker[14] has classified the FGF used in anaesthetic practice as medium/low/minimal/metabolic flow [Table 1].

ADVANTAGES OF LOW-FLOW ANAESTHESIA

The salient advantages of LFA may be physiological, economical, ecological and environmental [Table 2].

REQUIREMENTS FOR THE USE OF LOW-FLOW TECHNIQUES

a. Flow meters calibrated to flows down to 50 ml/min
b. A leak-proof circle breathing system and airway devices like cuffed endotracheal tube (ETT) (LFA

Table 1: Fresh gas flow categories, as described by Baker

FGF category	FGF	Remarks
Medium flow	1-2 L/min	The fresh gas volume is more than sufficient for the basic requirements and to compensate the problems
Low flow	500-1000 ml/min	If the inspiratory O_2-concentration falls below 30%, the O_2-flow must be increased by 10% of the total gas flow (about 100 ml/min)
Minimal flow	250-500 ml/min	If the inspiratory O_2-concentration falls below 30%, the O_2-flow must be increased by about 50 ml/min
Metabolic flow	About 250 ml/min	O_2 should be used as sole carrier gas since 250 ml/min is the absolute minimal oxygen requirement for metabolic processes at rest in a normothermic patient. Anaesthesia provider should precisely detect whenever the metabolic demands exceed oxygen supply

FGF – Fresh gas flow

Table 2: Advantages of low-flow anaesthesia

Physiological
Preserves heat and humidity of inspired gas, thereby conserves body temperature and reduces water loss
Improves the flow dynamics of inhaled anaesthetic gases
Increases mucociliary clearance
Improves airway epithelial health
Reduces accumulation of dried airway secretions
Economical
Reduced anaesthetic gas consumption
Significant savings of the order of 60%-75% with regard to volatile anaesthetic agents
Ecological
Reduced overflow of fluorocarbons and nitrous oxide which damage the earth's ozone layer
Reduced greenhouse effect due to nitrous oxide and volatile agents
Environmental
Reduced operating room pollution
Since Less exposure to anaesthetic vapours during filling

may be possible with well-fitting supraglottic airway devices also)

c. Gas monitoring system providing inspired and end-tidal concentrations of agents. The measurement of expiratory gas concentrations closer to the Y-piece (reflects patient's alveolar gas concentrations) is of crucial importance
d. Vapourisers capable of delivering high concentrations and calibrated to be accurate at low FGF
e. The breathing system should have the minimal internal volume to minimise the reserve volume.

LFA techniques are not suitable in the following settings:

a. Anaesthesiologist not familiar with LFA
b. Short-term anaesthesia with a face mask
c. Procedures with imperfectly gas-tight airways (i.e., bronchoscopies with a rigid bronchoscope)
d. Use of technically unsatisfactory equipment with a high gas leakage
e. Inadequate monitoring (i.e., malfunction of the gas analyser) or lack of machine/equipment suitable for leak-free closed breathing systems
f. LFA techniques combined with a significant overpressure of potent volatile agents should not be applied in situations when other clinical issues like haemodynamic instability require the attention of the anaesthesia provider.

CONCERNS WHILE USING LOW-FLOW ANAESTHESIA

a. Dilution of anaesthetic agents: Low FG flows are added to significantly large reserve volume (approximately 9–10 litres), consisting of breathing tubing, reservoir bag, anaesthetic ventilator, intergranular space, etc., in addition to functional residual capacity (FRC) of the patient. Hence, the rate of change of composition of gas in the reserve volume is exponential, which is related to the time constant. It requires 3 time constants (calculated by reserve volume divided by FG flow) to effect 95% change in gas composition to occur. However, once steady state is achieved, LFA provides the most economic use of anaesthetic agents
b. Differential uptake of agents modifying the composition of gas mixture: This effect is particularly important while combining N_2O as carrier gas along with oxygen. Uptake of N_2O is high initially, followed by gross reduction in its uptake. This change in the trend in differential uptake may lead to hypoxic mixtures being delivered
c. Ensuring enough oxygen for metabolism: When wide range of variations in the gas composition is possible while reducing the FG flow, scrupulous attention should be paid to provide enough oxygen to meet the metabolic demands. Pulse oximeter is a less sensitive surrogate monitor of tissue oxygenation, and an oxygen analyser is essential. Lower limit of FiO2 should be set as 0.30
d. Delay in recovery from anaesthesia: Long-time constant leads to slow reduction in concentration of volatile anaesthetic agents during the recovery phase. Change over to high FG flows (to reduce time constant) and switching off vapourisers early can accelerate washout of anaesthetic agents. Some anaesthesia machines use a special charcoal filter to absorb the volatile agents to expedite recovery.

DISADVANTAGES OF LOW-FLOW ANAESTHESIA

- The lower flow rate and long 'time constant' leads to slower induction and emergence. Quick alteration of inspired concentrations is not possible while on low flows
- Continuous vigilance and frequent flow adjustments are required to avoid hypoxic mixtures and under/over-dosage of anaesthetic agents
- Higher consumption of CO_2 absorbents and risk of hypercarbia and CO_2 rebreathing with frequent exhaustion of absorbers

- Possible accumulation of undesirable trace gases in the system. These include carbon monoxide, acetone, methane, hydrogen, ethanol, compound A – haloalkene, etc., (Most authors suggest flushing with high FG flows once an hour to reduce the concentration of most of these substances)
- The United States Food and Drug Administration recommendations limit sevoflurane exposure to 2 minimum alveolar concentration (MAC) hours at flow rates of 1 to <2 L/min of FG flow rates. FG flow rates <1 L/min are not recommended.[15]

CALCULATION OF GAS UPTAKE BY THE PATIENT DURING INHALATIONAL ANAESTHESIA

Total gas uptake is the sum of the uptakes of oxygen, nitrous oxide and anaesthetic agents.

The uptake of each gas is estimated using the formula indicated in Table 3.

USE OF NITROUS OXIDE IN LOW-FLOW ANAESTHESIA

Because of the insoluble nature of N_2O and its popularity as a carrier gas in anaesthesia practice, performing LFA with and without N_2O is widely discussed. The key characteristics of N_2O and the implications in LFA practices are summarised in Table 4.

LOW-FLOW ANAESTHESIA IN PAEDIATRIC POPULATION

The renewed interest in LFA for adults during the past few decades and use of improved anaesthetic and monitoring equipment also encouraged LFA in paediatric patients. The main concerns raised were: leaks due to use of uncuffed ETT and all the additional monitoring (sample connections, filters, heat and moisture exchangers, catheter mounts and angle connectors) and breathing valves in the circuit adding to dead space and resistance to the breathing circuit. Airway sealing with uncuffed ETT or LMA is shown to be sufficient to perform LFA in paediatric patients.[18] Recent studies have shown that LFA in paediatric patients can be both practical and safe. Frink *et al*.[19] demonstrated that the concentrations of compound A measured in children during sevoflurane anaesthesia using approximately 2 L/min FG flow are low. They found that younger the child lower should be concentrations of compound A produced if similar FGF, anaesthetic concentration and CO_2 absorbents are used.

Table 3: Some basic formulae to calculate uptake of gas

Gas	Formula	Remarks
Oxygen	Simplified Brody formula:[16] $VO_2=10 \times KG\ (kg)^{3/4}$ (ml/min)	Where KG is BW in kg However, for clinical purposes, oxygen consumption can be more easily calculated as: $VO_2=3.5 \times BW$ (ml/min)
Nitrous oxide	Severinghaus's formula:[17] $VN_2O=1000 \times t^{-1/2}$ (ml/min)	That implies 1st min uptake of 1000 ml 200 ml/min uptake after 25 min 140 ml/min uptake after 50 min 90 ml/min uptake after 2 h (120 min)
Anaesthetic inhalational agent	H Lowe's formula:[8] $V_{AN}=f \times MAC \times \lambda_{B/G} \times Q \times t^{-1/2}$ (ml/min)	f: Factor that defines the inhalation concentration that is sufficient for unresponsive skin incision at ~MAC 1.3 $\lambda_{B/G}$: Blood/gas partition coefficient Q: Cardiac output *t*: Time

BW – Body weight; MAC – Minimum alveolar concentration

Table 4: Arguments for and against use of N_2O

Pros	Cons
Rapid wash-in and wash-out	High initial uptake and minimal uptake in later phases make flow control adjustments more complicated
Shortens the induction time	Ozone depleting potential and 'green-house effect'
Reduction in opioid/anaesthetic agent requirement	Increased incidence of post-operative nausea, vomiting
	Increases gaseous distension of bowels, cavities and closed spaces
	Effects like immunosuppression, bone marrow suppression

CONDUCTING LOW-FLOW ANAESTHESIA

Premedication, preoxygenation and induction of sleep are performed according to the usual practice.

Initiation of low-flow anaesthesia

The objective is to achieve an alveolar concentration of the anaesthetic agent that is adequate for producing surgical anaesthesia. There are different methods of achieving this objective.

Use of high flows during initial phase

The time constant is reduced, bringing the circuit concentration to the desired concentration rapidly. Often, an FG flow of 10 L of the desired gas concentration and 2 MAC agent concentration is used. By the end of 3 min (i.e., 3 time constants), the circuit would be brought to the desired concentration. This facilitates better denitrogenation and rapid achievement of desired concentration by counterbalancing the large uptake encountered at the start of the anaesthesia.

Use of prefilled circuits

Here, we use a different circuit like Magill's for preoxygenation. Simultaneously, the circle system is fitted with a test lung and the entire circuit is filled with the gas mixture of the desired concentration. After tracheal intubation, the patient is connected to the circle system and rapid achievement of the desired concentration in the circuit occurs.

Injection of volatile agent into the breathing circuit

The usual requirement of anaesthetic agent is approximately 400–500 ml of vapour in the first 10 min (i.e., 40–50 ml/min). At 20°C, 1 ml liquid halothane yields 226 ml of vapour and 1 ml isoflurane yields 196 ml. About 2 ml of the liquid agent is injected in small increments into the expiratory limb of the circuit. The intermittent injections are often made in 0.2–0.5 ml aliquots manually. Alternatively, continuous infusion may be used with the added advantage of doing away with the peaks and troughs associated with intermittent injections. The accurate dose requirement is given by the formula:

Priming dose (ml vapour) = Desired concentration × ([FRC + circuit volume] + [cardiac output × blood gas coefficient])

Maintenance of low-flow anaesthesia

During this phase, we need to maintain steady-state concentration of the anaesthetic agents. Although the oxygen uptake remains constant at 200–250 ml/min, uptake of anaesthetic agents including N_2O will be minimal. Therefore, the role of oxygen analyser to maintain oxygen concentration of at least 30% at all times is paramount. It is prudent to return the sampling gas (usually drawn at the rate of 200 ml/min) back to the circuit to boost the economy of FGF utilisation. It should be noted that the actual dial setting in the vapourisers often over-estimates the actual output since the plenum vapourisers under delivers the agent at low flows. The achievement of the desired end tidal agent concentration may be measured most accurately using an agent analyser or by the haemodynamic stability.

The Gothenburg technique[20] of conducting LFA is depicted in Figure 1.

Termination of low flow anaesthesia

Because of long-time constants, recovery is delayed in LFA. However, switching over to high flows to accelerate the wash-out of anaesthetic agents or use of activated charcoal to remove the potent vapours by absorption can result in rapid recovery. Nitrous oxide gets washed off while changing over to 100% oxygen.

AUTOMATED LOW-FLOW ANAESTHESIA

This uses proprietary software algorithms to determine agent and carrier gas administration to attain the targets with the lowest surplus. Currently available ALFA machines include the ZEUS® (Dräger, Lubeck, Germany), the AISYS® (GE, Madison, Wisconsin) and FLOW-i® (Maquet, Solna, Sweden).[20,21] The Zeus uses closed-circuit anaesthesia, the Aisys minimal flow anaesthesia (500 mL/min FG flow). First, the anaesthesiologist selects a target alveolar concentration (FAt) of inhaled anaesthetic and a target

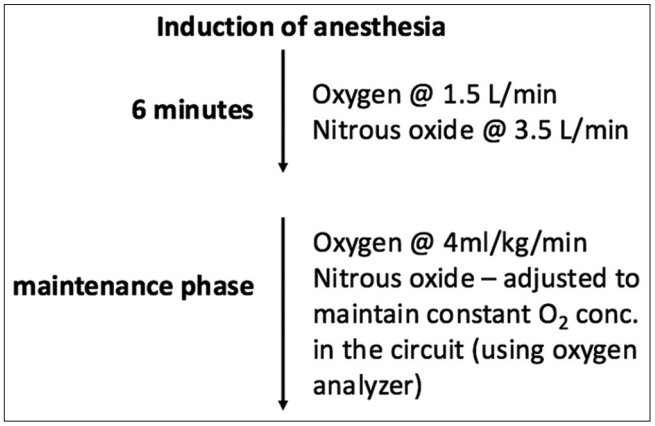

Figure 1: The Gothenburg technique of conducting low-flow anaesthesia

O_2%, either inspired (FiO_2, the Zeus) or end-expired (FaO_2, the Aisys). This automated gas control is a new addition to our automated low flow armamentarium, which helps to reduce anaesthetic waste, cost and pollution while minimising the ergonomic liability of LFA.[21,22]

LOW-FLOW ANAESTHESIA FOR 'SUSTAINABLE' ANAESTHESIA

Anaesthesiologists should take up environmental stewardship as a prime priority. Because the anaesthesia professional decides FGF, we are directly responsible for the environmental impact of anaesthetic vapours and gases. It is mentioned that during an average working day each anaesthesiologist, administering N_2O or desflurane can contribute the CO_2 equivalent of more than 1000 km (620 miles) of car driving.[23] A relatively simple way to reduce and reuse anaesthetic agents is to utilise low FGFs during the maintenance phase of the anaesthetic. In addition to the technological advancements mentioned above, research is underway to collect and reuse anaesthetic gases. One system currently available for commercial use in Canada uses zeolite filters (Deltasorb®) in the scavenging system of the anaesthesia machine to adsorb the anaesthetic, later retrieving and purifying the anaesthetic agents for reuse.[24,25]

SUMMARY

The safety features of anaesthetic machines and the availability of accurate gas monitoring today overcome most of the technical shortcomings and offset former resistance to the routine performance of low-flow anaesthesia techniques. Widespread availability of gas analysers for monitoring FiO_2, $ETCO_2$ and agent monitoring in modern anaesthesia workstations aid in the smooth, practical conduct of LFA.

The clinical application of low-flow anaesthesia is simplified (without the need to resort to difficult mathematical calculations) by the availability of reliable guidelines for the safe performance of these techniques in routine clinical practice.[26,27] Anaesthesiologists should take up LFA as their professional obligation to the present and future generations on the planet earth.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

REFERENCES

1. Sherman JD, Ryan S. Ecological responsibility in anesthesia practice. Int Anesthesiol Clin 2010;48:139-51.
2. Snow J. On narcotism by the inhalation of vapours. Part XV. The effects of chloroform and ether prolonged by causing the exhaled vapour to be reinspired. Lond Med Gaz 1850;11:749-54.
3. Waters RM. Clinical scope and utility of carbon dioxide filtration in inhalation anaesthesia. Anesth Analg 1924;3:20-2.
4. Baum JA. Who introduced the rebreathing system into clinical practice? In: Schulte Am Esch J, Goerig M, editors. Proceedings of the Fourth International Symposium on the History of Anaesthesia. Lübeck: Dräger; 1998. p. 441-50.
5. Onishchuk JL. The early history of low-flow anaesthesia. In: Fink BR, Morris LE, Stephen CR, editors. The History of Anesthesia. Third International Symposium, Proceedings, Park Ridge, Illinois: Wood Library-Museum of Anesthesiology; 1992. p. 308-13.
6. Virtue RW. Minimal-flow nitrous oxide Anesthesia. Anesthesiology 1974;40:196-8.
7. Aldrete JA, Lowe HJ, Virtue RW. Low Flow and Closed System Anaesthesia. New York, San Francisco, London: Grune & Stratton; 1979.
8. Lowe HJ, Ernst EA. The Quantitative Practice of Anesthesia: Use of Closed Circuit. Baltimore: Williams & Wilkins, 1981; 67-97.
9. Logan M, Farmer JG. Anaesthesia and the ozone layer. Br J Anaesth 1989;63:645-7.
10. Kleemann PP. The climatisation of anesthetic gases under conditions of high flow to low flow. Acta Anaesthesiol Belg 1990;41:189-200.
11. Baum JA, Aitkenhead AR. Low-flow anaesthesia. Anaesthesia 1995;50 Suppl 10:37-44.
12. Eger EI 2nd. Economic analysis and pharmaceutical policy: A consideration of the economics of the use of desflurane. Anaesthesia 1995;50 Suppl 10:45-8.
13. Lachmann B. Xenon anesthesia: Prerequisite for its use in a closed circuit system. Appl Cardiopulm Pathophysiol 1995;5 Suppl 2:59-61.
14. Baker AB. Back to basics – A simplified non-mathematical approach to low flow techniques in anaesthesia. Anaesth Intensive Care 1994;22:394-5.
15. Ultane (sevoflurane) volatile liquid for inhalation. Food and Drug Administration. Available from: http://www.accessdata.fda.gov/drugsatfda_docs/label/2006/020478s016lbl.pdf [Last accessed on 2018 Jan 12].
16. Kleiber M. Body size and metabolic rate. Physiol Rev 1945;27:511-39.
17. Severinghaus JW. The rate of uptake of nitrous oxide in man. J Clin Invest 1954;33:1183-9.
18. Fröhlich D, Schwall B, Funk W, Hobbhahn J. Laryngeal mask airway and uncuffed tracheal tubes are equally effective for low flow or closed system anaesthesia in children. Br J Anaesth 1997;79:289-92.
19. Frink EJ Jr., Green WB Jr., Brown EA, Malcomson M, Hammond LC, Valencia FG, *et al.* Compound A concentrations during sevoflurane anesthesia in children. Anesthesiology 1996;84:566-71.
20. Dale O, Stenqvist O. Low flow anaesthesia: Available today – A routine tomorrow. Surv Anesthesiol 1992;36:334-6.
21. Meyer JU, Kullik G, Wruck N, Kück K, Manigel J. Advanced technologies and devices for inhalational anesthetic drug

dosing. Handb Exp Pharmacol 2008;182:451-70.
22. Dehouwer A, Carette R, De Ridder S, De Wolf AM, Hendrickx JF. Accuracy of inhaled agent usage displays of automated target control anesthesia machines. J Clin Monit Comput. 2016; 30(5):539-43.
23. Ryan SM, Nielsen CJ. Global warming potential of inhaled anesthetics: Application to clinical use. Anesth Analg 2010;111:92-8.
24. Doyle DJ, Byrick R, Filipovic D, Cashin F. Silica zeolite scavenging of exhaled isoflurane: A preliminary report. Can J Anaesth 2002;49:799-804.
25. Mehrata M, Moralejo C, Anderson WA. Adsorbent comparisons for anesthetic gas capture in hospital air emissions. J Environ Sci Health A Tox Hazard Subst Environ Eng 2016;51:805-9.
26. Baum JA, Nunn G. Low-flow anaesthesia. The theory and practice of low-flow, minimal flow and closed system anaesthesia. English Text Revised. Oxford: Butterworth Heinemann; 1996.
27. Baum J, Berghoff M, Stanke HG, Petermeyer M, Kalff G. Low-flow anesthesia with desflurane. Anaesthesist 1997;46:287-93.