CME Article

Low and minimal flow inhalational anaesthesia

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Purpose: To describe the pharmacokinetic behaviour and practical aspects of low (0.5–1 l·min^{-1}) and minimal (0.25–0.5 l·min^{-1}) flow anaesthesia.

Methods: A Medline search located articles on low flow anaesthesia, and computer simulated anaesthetic uptake models are used.

Principal findings: Most, 85–90%, of anaesthetists use high fresh gas flow rates during inhalational anaesthesia. Low/minimal flow anaesthesia with a circle circuit may avoid the need for in-circuit humidifiers, raise the temperature of inspired gases by up to 6°C, reduce cost by about 25% by reduction of fresh gas flows to 1.5 l·min^{-1}, and reduce environmental pollution with scavenged gas. Knowledge of volatile anaesthetic pharmacokinetic behaviour facilitates the use of minimal/low flow rates. Small amounts of nitrogen or minute amounts of methane, acetone, carbon monoxide, and inert gases in the circuit are of no concern, but the degradation of desflurane (to carbon monoxide by dry absorbent) and sevoflurane (to compound A by using a fresh gas flow of >2 l·min^{-1}) must be avoided. With modern gas monitoring technology, safety should be no more of a concern than with high flow techniques.

Conclusion: The use of fresh gas flow rates of < 1 l·min^{-1} for maintenance of anaesthesia has many advantages, and should be encouraged for inhalational anaesthesia with most modern volatile anaesthetics.

Objectif : Décrire le comportement pharmacocinétique et les aspects pratiques de l'anesthésie à débit bas (0,5–01 L·min^{-1}) et minimal (0,25–0,5 L·min^{-1}).

Méthodes: Recherche sur Medline des articles publiés sur l'anesthésie à bas débit et étude sur des modèles anesthésiques d'absorption simulée par ordinateur.

Principales constatations : Pendant l'anesthésie inhalatoire, la plupart (85–90%) des anesthésistes utilisent des débits élevés de gaz frais. L'anesthésie à débit bas ou minimal en circuit fermé peut éliminer les humidificateurs intégrés au circuit, augmenter la température des gaz inpirés de 6°C, et réduire les coûts d'opération d'environ 25% (débit diminué à 1,5 L·min^{-1}) tout en permettant l'épuration des gaz. Il est plus facile d'utiliser des débits bas ou minimaux si on connaît le comportement pharmacocinétique des anesthésiques volatils. Les petites quantités d'azote ou des quantités infinitésimales de méthane, d'acétone ou de gaz inertes dans le circuit n'ont rien d'inquiétant, mais la dégradation du desflurane (en monoxyde de carbone en présence d'un absorbant anhydre) et du sévoflurane (en composé A avec un débit de gaz frais >2 L·min^{-1}) doit être évitée. Grâce à la technologie moderne de monitorage des gaz, on doit se sentir autant en sécurité qu'avec les techniques à hauts débits.

Conclusion : Avec les anesthésiques volatils modernes, l'utilisation de débits aussi bas que 1 L·min^{-1} pour le maintien de l'anesthésie inhalatoire a plusieurs avantages et devrait être encouragée.

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MANY anaesthetists have received little or no training in the use of low flow rates (0.5–1 l·min^{-1})[1] during their residency, and use high flows without considering the waste and environmental pollution. Low (0.5–1 l·min^{-1}) and minimal (250–500 ml·min^{-1})[1] flow anaesthetic techniques have been used since the early days of general anaesthesia. Popularity has varied over the years, with a resurgence of interest over the last few years because of:

- economic concerns
- environmental factors
- advances in monitoring technology
- introduction of new, expensive anaesthetics.

This review will focus on the practical application of low and minimal flow anaesthesia with established and newer inhalational anaesthetics available in Canada. Neonates and small children who are often considered to be too small for the use of a circle circuit, constitute a special case and will not be considered here.

How do we define flow rates?

Baker[1] has suggested the following modification of Simionescu's[2] classification of flow rates of gases into anaesthetic circuits:

metabolic flow	~250 ml·min^{-1}
minimal flow	250–500 ml·min^{-1}
low flow	500–1000 ml·min^{-1}
medium flow	1–2 l·min^{-1}
high flow	2–4 l·min^{-1}
very high flow	>4 l·min^{-1}

While metabolic flow conditions can only be achieved with the injection of liquid anaesthetic into the circle circuit, it is possible to approximate this using pharmacokinetic knowledge of drug uptake. Metabolic flow is oxygen alone, while the other flows consist of metabolic oxygen with varying amounts of extra oxygen, nitrous oxide or air.

At the 1994 American Society of Anesthesiologists annual meeting, 90% of the anesthesiologists surveyed usually used 2–5 l·min^{-1} gas flow,[3] while in university and community hospitals flow rates <1 l·min^{-1} were used in only 12.7 and 15.2% of cases respectively.[4] Only one of 15 anaesthetists recently surveyed at the Ottawa General Hospital used low or minimal flows during maintenance anaesthesia, the mean gas flow being 2.5 l·min^{-1} with a circle circuit. The use of the Bain circuit requires even higher flows than were recorded in these surveys.[5]

Advantages of low or minimal flow anaesthesia

1. Economic

Anaesthetic drugs constitute only a small proportion of hospital pharmacy expenses; nitrous oxide is inexpensive and halothane is relatively so, but other inhalational anaesthetics are more costly and may account for more than 20% of anaesthetic drug expenditure.[6]

Anaesthetic costs are related to the amounts used and hence to flow rates. Educational efforts to encourage the reduction of gas flows to 1.5 l·min^{-1} resulted in the average anaesthetic cost decreasing from US $19.20 ± 1.16 to US $15.16 ± 0.39 at the University of Michigan, where volatile anaesthetics accounted for 25% of the anaesthetic drug expenditure in 1992–3.[7] Hourly costs for inhalational anaesthetics were reduced by >50% at Northwick Park Hospital, England, during an evaluation of the acceptability of low flow anaesthesia.[8] Total anaesthetic drug costs were about $88,000 in 1993 at the Ottawa General Hospital:[6] 24% was for inhalational anaesthetics, and reduction of flows from the mean of 2.5 l·min^{-1} would reduce this substantially.

2. Environmental[9]

Chlorinated hydrocarbon anaesthetics are broken down by ultraviolet radiation releasing chlorine atoms which deplete the protective ozone layer. While chlorinated hydrocarbon anaesthetics contribute only an estimated 0.01% of the global release of chlorofluorocarbons, reduction of unnecessary waste of anaesthetic gases could reduce this further. Also, chlorine-free halogenated anaesthetics, such as sevoflurane and desflurane, have less potential for ozone depletion.

Nitrous oxide depletes ozone through nitric oxide production, and also reflects heat back to the Earth, contributing directly to global warming. Anaesthesia is estimated to account for 3–12% of global nitrous oxide release, and this could be reduced considerably with lower fresh gas flow rates and reduction of waste. It is unlikely that physicians in other areas of medicine deliberately use excessive amounts of drugs without patient benefit and scavenge the excess, to damage the environment.

3. Conservation of heat and humidity

Inspiration of cool dry gases impairs mucociliary function, with subsequent microatelectasis, potential for infection, and impaired gas exchange. Respiratory fluid and heat loss contribute to postoperative hypothermia after prolonged anaesthesia, but use of appropriate gas flow rates can improve inspired gas humidification (Table I) and temperature (Table II).[10] While humidifiers, warming apparatus, etc., are help-

TABLE I Values for absolute humidity of inspired air under different fresh gas flow conditions after 120 min ventilation. Mean (SD). (Reproduced from Kleeman[12] with permission.)

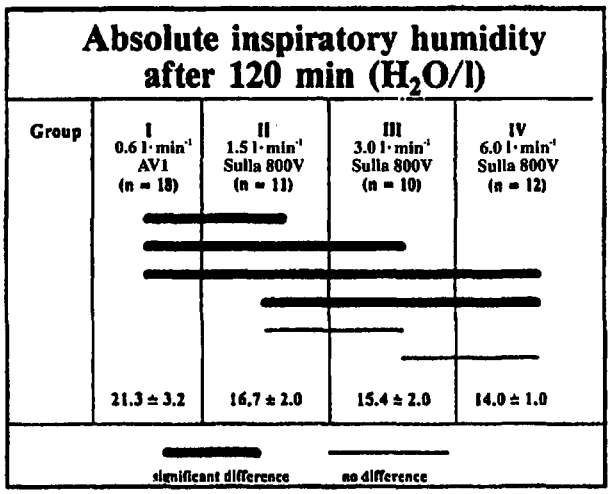
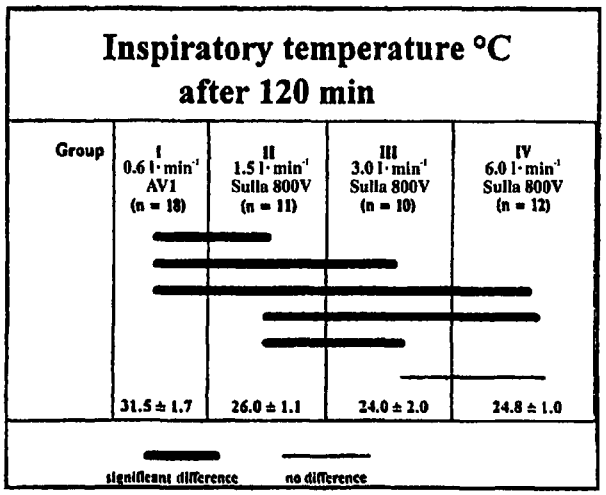


TABLE II Values for temperature of inspired air under different fresh gas flow conditions after 120 min ventilation. Mean (SD). (Reproduced from Kleeman[12] with permission.)



ful, the use of low fresh gas flow rates improved mucociliary function[10] in laboratory animals, and in patients provides relative humidity equivalent to in-circuit humidifiers.[11,12]

Pharmacokinetics

The strategy of minimal flow anaesthesia is to add to the circuit only the amount of anaesthetic taken up by the patient, thus reducing waste. Detailed descriptions of

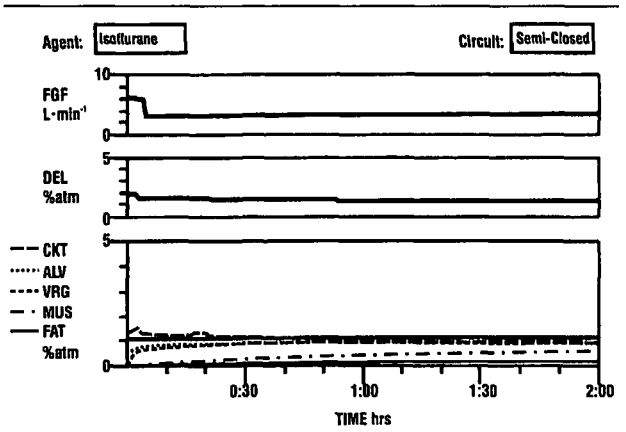


FIGURE 1 Gasman® simulation (used with permission) of two hours of isoflurane anaesthesia, using gas inflow rates of 6 l·min^{-1} for the first few minutes, 3 l·min^{-1} for the remainder, with a semi-closed circuit, showing the isoflurane concentration in the various compartments, adjusting the vaporizer to maintain an end-tidal concentration of 0.66 MAC isoflurane. The grey line indicates MAC.

FGF	fresh gas flow
DEL	vaporizer concentration
CKT	volatile anaesthetic concentration in the anaesthetic circuit
ALV	" " " " " alveoli
VRG	" " " " " vessel rich group
MUS	" " " " " muscle
FAT	" " " " " fat

anaesthetic uptake are found in texts and reviews,[13] but a simplified practical approach will be presented here. Computer simulations can help describe the disposition of anaesthetics in the various body compartments, and the approximate relative costs of different anaesthetics and techniques. Gasman® simulations are used here to illustrate the uptake of anaesthetics, the large wastage with moderate and high flows, and the potential economic benefits of flow rate reduction.

Figure 1 shows a Gasman® simulation of two hours of *isoflurane* anaesthesia, using typical carrier gas flow rates with a semi-closed circle circuit. Isoflurane uptake is large in the first few minutes, requiring high flow and concentration to deliver sufficient anaesthetic to the circuit and alveoli, and blood and vessel-rich compartment concentrations soon increase. As the blood concentration increases, uptake progressively decreases, but the soluble isoflurane continues to be taken up in muscle and fat compartments. With a three litre maintenance carrier gas flow, and the vaporizer adjusted to maintain an arbitrary end-tidal concentration of 0.66 minimum alveolar concentration (MAC), most of the isoflurane delivered to the circuit is in excess of uptake and enters the scavenging system. If higher maintenance gas flow rates are used, for

TABLE III Gasman® simulation derived approximate relative costs of moderate (3 l·min^{-1} total fresh gas flow) and low/minimal flow anaesthesia in simulations. Ottawa General Hospital 1997 price $37.09 for 100 ml isoflurane, $74.75 for 250 ml enflurane, $17 for 250 ml halothane, $300 for 250 ml sevoflurane, $50.82 for 6000 l nitrous oxide, and $98.00 for 240 ml desflurane. All variables were kept constant apart from flow rates, and the data give an appreciation of the potential economies achievable by reducing fresh gas flow rate.

Anaesthetic	Approximate cost ($) of two hours of anaesthesia using moderate flow rates (3 l·min^{-1})		Approximate cost ($) of two hours of anaesthesia using minimal flow rates	
	Anaesthetic taken up by patient	Anaesthetic delivered to circuit	Anaesthetic taken up by patient	Anaesthetic delivered to circuit
Nitrous oxide	0.17	2.31	0.15	0.46
Halothane	1.62	5.09	1.52	2.70
Isoflurane	2.31	10.12	2.29	4.87
Enflurane	3.09	12.01	3.10	6.27
Sevoflurane	6.96*	37.69*	Not recommended	
Desflurane	3.40	38.31	3.28	14.99

*using 2 l·min^{-1} flow rate

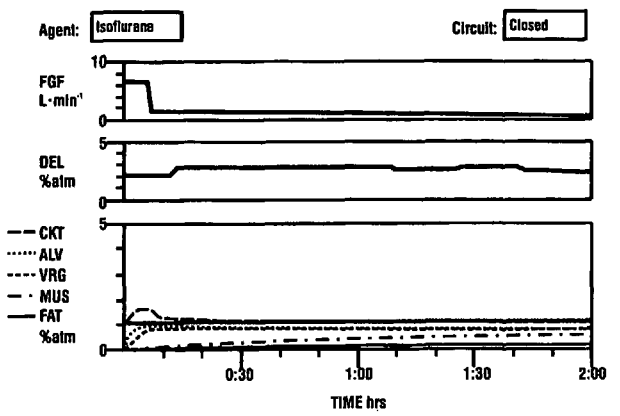


FIGURE 2 Gasman® simulation as in Figure 1, but reducing gas flow after the first few minutes to 800 ml·min^{-1} for the next 20 min and reducing further every 15–20 min thereafter, again adjusting the vaporizer to maintain an end-tidal concentration of 0.66 MAC isoflurane.

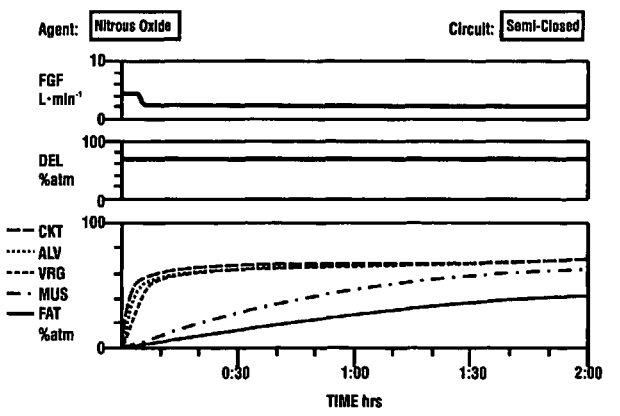


FIGURE 3 Gasman® simulation of two hours of anaesthesia using nitrous oxide at 4 l·min^{-1} for the first few minutes, and then 2 l·min^{-1} for the remainder, with a semi-closed circle circuit.

example with a Bain circuit, uptake remains the same but more isoflurane is wasted. However, if the carrier gas flow is reduced after the first few minutes (Figure 2) and then again every 15–20 min thereafter (as nitrous oxide uptake decreases), uptake is the same but wastage is reduced by about 50% (Table III).

Nitrous oxide is usually used as a carrier gas for more potent volatile anaesthetics. Figure 3 shows a Gasman® simulation of two hours of anaesthesia using nitrous oxide at typical carrier gas flows, with a semi-closed circle circuit. Blood and vessel-rich compartment concentrations rapidly rise because of its low solubility, then uptake reduces much earlier than with the more soluble isoflurane. Most of the maintenance nitrous oxide gas flow is vented to the scavenging system, and this waste can be minimized by reducing nitrous oxide flow to 500 ml·min^{-1} after the first few minutes, and reducing further every 15–20 min thereafter (Figure 4). Nitrous oxide is inexpensive and the cost reduction is small (Table III), but the volume of nitrous oxide which would otherwise be scavenged to the atmosphere is large.

Techniques involving the injection of liquid anaesthetic directly into the circuit may be used for metabolic flow anaesthesia.[14–16] The volume of liquid to be injected at each time interval during anaesthesia can

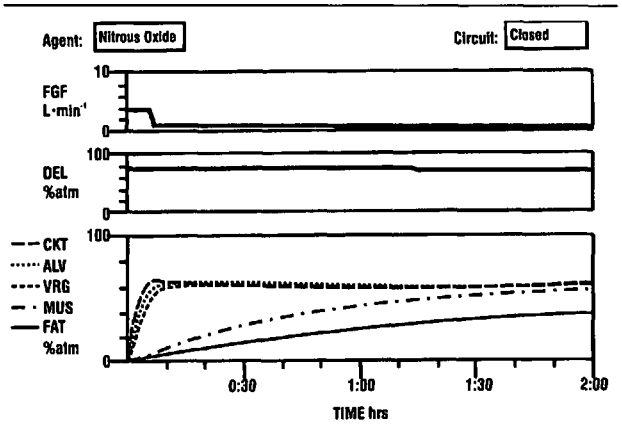


FIGURE 4 Gasman® simulation as in Figure 3, but reducing nitrous oxide flow after the first few minutes to 500 ml·min^{-1} for the next 20 min, with further reductions every 15–20 min thereafter, to maintain inspired oxygen concentration at 30%.

be calculated using formulae and nomograms, and infusions can be used to smooth the fluctuations in concentrations with bolus injections. Lowe's nomogram[17] allows calculation of the volume of liquid anaesthetic to be injected into the circuit per unit time (at 0, 1, 4, 9, 16 min etc, i.e., with 1, 3, 5, 7, 9, 11 min etc. between injections). While this approach is fascinating for the enthusiast, it makes anaesthesia unnecessarily complicated for the practitioner, for whom the vaporizer technique is simpler, more familiar, and acceptable.[8]

Sevoflurane and *desflurane* have recently been introduced in Canada, after extensive experience in other countries.[18] While most clinical properties are similar to isoflurane, halogenation with fluorine alone results in much lower blood-gas solubility with rapid induction and recovery, and more rapid adjustment of blood concentration and depth of anaesthesia (Table IV). Table III shows the economic benefit suggested by Gasman® simulations using minimal flow rates with desflurane relative to moderate flow anaesthesia. However, economical low or minimal flow anaesthesia with sevoflurane is limited because of compound A production and the minimum flow recommended is 2 l·min^{-1}.

Inhalational induction is rapid and smooth with sevoflurane in children and in adults, but is less satisfactory with desflurane because of pungency at concentrations >6%. These low blood-gas solubility anaesthetics soon reach steady state with reduced uptake and, under low or minimal flow conditions, the vaporizer setting approximates the circuit concentration even with low fresh gas flows.[19] Elimination and emergence are rapid, with psychomotor recovery being faster than with isoflurane. Desflurane is more rapid than sevoflurane, but this may not necessarily lead to earlier hospital discharge and cost savings.[18] Prompt emergence necessitates a pain management strategy be in place before the end of anaesthesia. While many factors are involved in calculating the cost-effectiveness of these new anaesthetics, optimization of drug delivery will be essential[20] for economical utilization. Low solubility favours low/minimal flow anaesthesia,[19] but a minimum fresh gas inflow of 2 l·min^{-1} for sevoflurane limits its economical use during the maintenance of anaesthesia. The beneficial effect of the low solubility of desflurane in reducing uptake is partly offset by its high MAC, but it is predicted[20] to be less expensive than isoflurane at fresh gas flow rates <1 l·min^{-1} (depending on the relative prices of the drugs – see Table III).

Other gases in the circuit

1. After initial washout of *nitrogen* from the FRC (two litres) and circuit (four litres in a typical five to six litre circle circuit), there is ongoing slow washout of the nitrogen (0.7 l) from rest of the body, and this may lead to minor nitrogen accumulation in the circle.[21] Calibration air from some respiratory gas monitors (RGM), if vented into the circuit, also adds nitrogen to the gas mixture.

TABLE IV Partition coefficients, etc for volatile anaesthetics. (Reproduced from Eger[18] with permission.)

	Partition Coefficients		*Vapor Pressure**	*MAC in 30-60-year-old patients (%)*	*% Anesthetic Taken up and Recovered as Anesthetic Metabolites*
	Blood/Gas	*Brain/Blood*	*at 20°C (mmHg)*		
Desflurane	0.45	1.3	669	6.0	0.02
Sevoflurane	0.65	1.7	170	2.0	3.0
N_2O	0.47	1.1	–	105	0.004
Isoflurane	1.4	1.6	240	1.15	0.2
Enflurane	1.8	1.3	172	2.0	2.4
Halothane	2.4	1.9	244	0.75	15–20

*Values are from manufacturers

These small amounts of nitrogen are insignificant providing that oxygen concentration is monitored and maintained, but the potential entrainment of air from leaks when using falling bellows ventilators is of more concern.

2. *Methane* is produced by intestinal organisms, and will equilibrate with the circuit gases during low and minimal flow anaesthesia.[21,22] Intestinal methane production is variable: up to 100 ppm is excreted in expired gas. Small amounts (e.g., 5 ppm) may be found in medical gases (1.2 ppm in atmospheric air) and this could accumulate during low flow anaesthesia. Blood methane levels of 2000 ppm (0.02%) have been recorded, without apparent detrimental effect.[22] Methane toxicity is by asphyxiation in sufficient concentration, but lower concentrations (5.4% in oxygen) support combustion. About 14 hr of minimal flow anaesthesia with maximal bowel gas secretion are required to approach combustible concentrations of methane.[21] Methane may also cause an artifactual elevation of infrared vapor measurements.[22]

3. *Acetone* is produced by hepatic metabolism, excreted in the expired gas, and equilibrates in the anaesthetic circuit. During prolonged anaesthesia, blood acetone concentration may rise, especially in patients with preoperative starvation or increased production (diabetes, cirrhosis).[23] This can be reduced by ventilation with high fresh gas flows, but blood concentrations will rise during low or minimal flow anaesthesia. Concentrations >50 ppm may cause nausea, vomiting, and slow emergence.

4. Other *inert gases* come from medical gases or RGM and may accumulate in the circuit in trace amounts with prolonged low flow anaesthesia, but have not been shown to be of any clinical importance.

5. *Degradation of volatile anaesthetics* within the circuit

a) *Carbon monoxide* from carboxyhamoglobin in the blood of smokers is expired, equilibrates in the circuit with prolonged low or minimal flow anaesthesia,[24] and has been blamed for postoperative headaches and nausea. Intra-operative carbon monoxide accumulation has been reported after a period of anaesthesia machine inactivity, and has been attributed to degradation of volatile anaesthetic (desflurane > enflurane > isoflurane, with halothane and sevoflurane being stable). More degradation occurs with Baralyme® (Allied Healthcare Products, Inc., St. Louis, MO) than with soda lime, increased absorbent temperature, and high anaesthetic concentration. If the anaesthesia machine is left over the weekend with gas flowing through the absorber, the absorbent may dry out from the usual water content of 14–19%, and lead to anaesthetic degradation when next used.

b) *Nephrotoxic degradation products*

Sevoflurane is degraded to produce compound A, especially with high minute ventilation,[26] lower fresh gas flow,[26] higher absorbent temperature,[26] Baralyme® >sodalime,[27] increasing anaesthetic concentration,[28] and possibly increased carbon dioxide absorption.[26] While renal tubular damage occurs in rats, nephrotoxicity has not been a problem in humans, probably because of the lower ß-lyase concentration in the human kidney, and the high minute ventilation and cardiac index in rats which increase threefold the relative compound A load presented to the rat kidney. There has been no deleterious effect on renal function in small numbers of patients after prolonged sevoflurane anaesthesia using minimal flow rates[29] or low flow rates (1 $l \cdot min^{-1}$),[30] and more than two million sevoflurane anaesthetics have been given in the USA and Japan (though mainly using higher flow rates)[28] without clinical nephrotoxicity. Higher flow rates reduce circuit compound A concentration (19.7 ± 4.3 ppm at 1 $l \cdot min^{-1}$ and 8.1 ± 2.7 ppm at 3 $l \cdot min^{-1}$, [31] 7.6 ± 1.0 ppm at 5 $l \cdot min^{-1}$,[32]) and 2 $l \cdot min^{-1}$ is the recommended minimum fresh gas flow when using sevoflurane in Canada at present.

Molecular sieves[33] are being investigated as a reusable alternative to soda lime or Baralyme.® These are alumino-silicate zeolites, tetrahedra with 4–7 Angstrom pores, which retain carbon dioxide by Van der Waal's forces, and can be regenerated for reuse.

While the clinical importance of small amounts of other gases found with prolonged low or minimal flow anaesthesia is questionable,[35] some anaesthetists flush the circuit by:

a) venting the RGM sample gas to the scavenging system instead of returning it to the circuit, and increasing the fresh gas flow to compensate (150–200 $ml \cdot min^{-1}$).

b) or intermittent use of high flow rates for a few minutes every 30–60 min.

Practical aspects[36]

Equipment and monitoring requirements for providing low and minimal flow inhalational anaesthesia are similar to those for any anaesthetic technique:

Monitors:

Oxyhaemoglobin saturation

End-tidal carbon dioxide

Inspired oxygen

Tidal volume – reservoir bag, ventilator bellows, pneumotachograph or spirometer.

Volatile anaesthetic and nitrous oxide analyzers are desirable but not essential

Equipment:

Leak free circle circuit with carbon dioxide absorber

Flow meters calibrated to < 1 l·min^{-1} flow.

Ascending bellows ventilator

High flow rates (e.g., 2 l·min^{-1} oxygen, 4 l·min^{-1} nitrous oxide) are used for first 5–10 min, to flush the circuit and FRC, and to deliver a sufficient mass of volatile anaesthetic to provide for early uptake. "Over pressure" vaporizer concentrations are used at this time with soluble (but not insoluble) anaesthetics (e.g., isoflurane 1–3%).

Metabolic rate is fairly constant under anaesthesia, and oxygen requirements are about 3 ml·kg^{-1}. *Nitrous oxide* uptake decreases with time (Figures 3 and 4). Therefore, if used as the carrier gas providing approximately 0.66 MAC anaesthesia, its inflow into the circuit must be reduced when using minimal flow anaesthesia (0.5 l·min^{-1} for the next 15–20 min, then reducing to 0.4 l·min^{-1} for the next 15–20 min, 0.3 l·min^{-1} for next 30 min, 0.2 l·min^{-1} for next 30 min etc.) maintaining the circuit F_I0_2 at about 30%. Without this reduction, progressively more nitrous oxide is left in the circuit as uptake decreases which results in a slow decrease in oxygen concentration.[37] The slow time constant for circuit composition changes at low flow rates allows longer for detection and response before dangerous levels of hypoxia develop should an hypoxic mixture be delivered from the flow meters than when using high flow rates (Figure 5).[38] The routine use of inspired oxygen monitoring further reduces the potential for hypoxia.

With isoflurane, the vaporizer setting will typically be 1–3% for the first 20–30 min, reducing to 1–2% later, depending on the desired anaesthetic depth. Anaesthetic uptake decreases with time so that progressively less drug is added to the circuit. The actual time course varies with the anaesthetic solubility, the decrease occurs earliest with nitrous oxide, desflurane, and sevoflurane, but later for more soluble anaesthetics.

Circuit vapor concentration is typically about 50% lower than the vaporizer setting with low or minimal flow rates (Figure 6)[39] with soluble anaesthetics, but with the less soluble desflurane and sevoflurane, there is less ongoing uptake and the vaporizer and circuit concentrations are closer.[18] While care is necessary with older equipment, present generation vaporizers are accurate at low flows, e.g., the Ohmeda Tec 5 series of vaporizers are claimed to be accurate at low flows rates,[40] losing a minor degree of accuracy only at higher concentrations. If a rapid change in circuit vapor concentration is required, flows are transiently increased

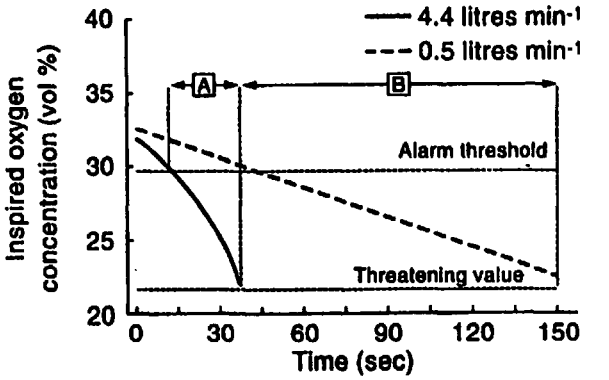


FIGURE 5 Accidental setting of an hypoxic fresh-gas mixture. The reaction period (the time available for corrective measures) is considerably shorter in high-flow (A: 4.4 l·min^{-1}) than in low-flow anaesthesia (B: 0.5 l·min^{-1}). (Reproduced from Baum[35] with permission.)

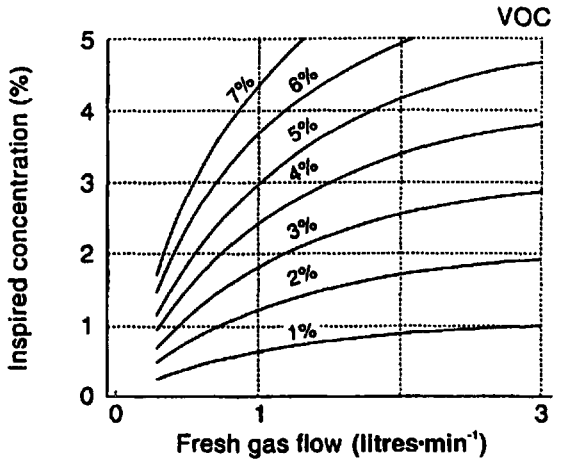


FIGURE 6 Relationship between inspired concentration of halothane and fresh gas flow rate in relation to the concentration set on the vaporizer (represented by percentage values attached to each line) using a vaporizer outside the circle (VOC) system. (Reproduced from Mapleson,[37] with permission.)

(e.g., to 1–2 l·min^{-1} oxygen and 2–4 l·min^{-1} nitrous oxide). However, if the vaporizer is inadvertently set high, then toxic blood vapor concentrations take longer to build up when using low flows (Figure 7).[38]

Low/minimal flow anaesthesia can be used for surgical procedures of any duration, but advantages increase with increasing duration. Opioid infusion or bolus injection techniques are used as desired. The vaporizer may be turned off 10–15 min before the end of surgery, after which the circuit anaesthetic concentration decreases slowly when using minimal flow rates with soluble anaesthetics, and it is necessary to increase flows for the last few minutes to flush out the volatile anaesthetic. Desflurane washout is much faster, and "coasting" is not possible.

The reservoir bag or ventilator bellows indicate the volume of circuit gas. If the volume of gas entering the circuit is less than the total patient uptake plus any leaks, then the reservoir bag or bellows will refill less with each breath. This gives an indication of the *total volume of gas flow* needed, while oxygen, nitrous oxide, and anaesthetic analyzers indicate the *composition* of the circuit contents.

A leakfree circuit is required for low/minimal flow anaesthesia. Leaks should be detected by the pre-anaesthesia equipment check, regardless of the flow rates to be used, but low/minimal flow rates may reveal the presence of previously undetected or new leaks as loss of circuit volume is revealed by depletion of reservoir bag or ventilator bellows volume. If it is necessary to open the circuit (for patient positioning, airway suctioning, etc.), then flow rates are increased for a few minutes to denitrogenate the circuit again. Air can be used as the carrier gas instead of nitrous oxide, with oxygen added to achieve the desired F_I0_2, and there is less change in the circuit composition if the circuit is opened. Airway management may be by tracheal intubation, laryngeal mask airway, or face mask, etc. A gas-tight patient-circuit interface is required, and any small leaks must be compensated by an increase in fresh gas flow.

During mechanical ventilation, flow of gas into the circuit during inspiration adds to the tidal volume set on the ventilator and contributes to the tidal volume delivered to the patient. This is much smaller with low/minimal flow anaesthesia (e.g., at a respiratory rate of 10 breaths·min^{-1} and an inspiratory:expiratory ratio of 1:2, the contribution of fresh gas flow to each tidal volume would be 20 ml at a total fresh gas flow of 600 ml·min^{-1}, compared with 100 ml with a fresh gas flow of 3 l·min^{-1}), and ventilator adjustment may be required.

With gas flow rates approaching the minute ventilation of the patient, most of the carbon dioxide is flushed from the circuit rather than absorbed; with low flow rates, more reliance is placed on carbon dioxide absorption,[41] and this is complete with minimal flows. The absorber should be regularly inspected and absorbent replaced when necessary, and carbon dioxide monitoring continually assesses the efficacy of the system.

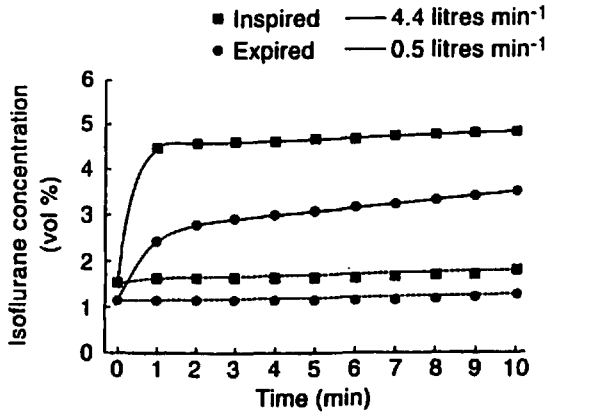


FIGURE 7 Accidental error in adjustment of the vaporizer to its maximum output. There is a risk of very rapid overdosage in a high-flow system but not in low-flow anaesthesia. The data are for a patient weighing 75 kg with an expired minute volume of 5.6 l·min^{-1}. Reproduced from Baum[35] with permission.

Routine circuit changes between patients and/or the use of bacterial/viral filters to protect the circuit and absorber nosocomial infection through anaesthesia equipment should be considered. While higher flow rates may reduce organism counts by flushing the circuit, the use of bacterial/viral filters appears to confer adequate protection regardless of the flow rates used.[42–44]

Conclusions

With most volatile anaesthetics, the use of low fresh gas flow rates of <1 l.min^{-1} for maintenance of anaesthesia has economic and environmental advantages, and improves the humidification and temperature of the inspired gas. There are no extra safety concerns relative to the use of higher flow rates, especially with present monitoring technology.

Desflurane and sevoflurane have several advantages, but not are not ideal volatile anaesthetics. The degradation of sevoflurane by carbon dioxide absorbents limits its potential for use at economical low or minimal flow rates. Desflurane has advantages for low/minimal flow anaesthesia, but its pungency limits its use for inhalational induction. The economic aspects of the new drugs require further evaluation.

Footnotes

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CME questions

Directions

For each of the questions below, **one or more** of the answers are correct. Select:

A) if only **a, b,** and **c** are correct
B) if only **a** and **c** are correct
C) if only **b** and **d** are correct
D) if only **d** is correct
E) if **all** are correct

1. Which of these statements about "soluble" volatile anaesthetics is/are correct? They:
   a) are soluble in water
   b) rapidly reach equilibrium during anaesthetic uptake
   c) are associated with a rapid and lucid emergence from anaesthesia
   d) have a relatively high blood-gas partition coefficient

   Answer: D (only d)

2. Which of the following is/are "insoluble" anaesthetics?
   a) Desflurane
   b) Nitrous oxide
   c) Sevoflurane
   d) Isoflurane

   Answer: A (only a, b, c)

3. Advantages of low/minimal flow anaesthesia include:
   a) reduced expenditures on anaesthetic drugs
   b) improved humidification of circuit gas
   c) increased temperature of circuit gas
   d) reduced risk of nosocomial infection

   Answer: A (only a, b, c)

4. Degradation of sevoflurane to Compound A is increased by:
   a) increased sevoflurane concentration
   b) reduced fresh gas flow rate
   c) increased absorbent temperature
   d) use of Baralyme® instead of sodalime

   Answer: E (all are correct)

5. Carbon monoxide production from desflurane is increased by:
   a) use of Baralyme® instead of sodalime
   b) increased carbon dioxide absorption
   c) dehydration of the carbon dioxide absorbent
   d) exhaustion of the carbon dioxide absorbent

   Answer: B (only a & c)

6. Which of the following statements about blood-gas partition coefficients is/are true?
   a) sevoflurane < desflurane
   b) desflurane > nitrous oxide
   c) isoflurane > enflurane
   d) sevoflurane < isoflurane

   Answer: D (only d)

7. Which of the following statements is/are true?
   a) sevoflurane is more appropriate for inhalational induction than desflurane
   b) emergence is faster after anaesthesia with desflurane than sevoflurane
   c) desflurane is chemically more stable than sevoflurane during anaesthesia
   d) desflurane is better suited to low/minimal anaesthesia than isoflurane

   Answer: E (all are correct)

8. Low flow anaesthesia is dangerous because of:
   a) inaccuracy of modern vaporizers at flow rates < 4 l·min–1
   b) patients hypoventilate when low fresh gas flow rates are used
   c) it is difficult to assess the depth of anaesthesia when low flow rates are used
   d) none of the above

   Answer: D (only d)

9. Techniques involving the injection of liquid anaesthetic:
   a) maximize economy
   b) use "metabolic" flow rates
   c) require sophisticated nomograms or tables
   d) require sophisticated equipment

   Answer: A (only a, b, c)

10. Which of the following statements about low flow anaesthesia is/are true?
   a) uptake of soluble anaesthetics continues for hours during prolonged anaesthesia
   b) small amounts of methane, acetone, and inert gases pose a difficult problem during low flow anaesthesia
   c) an hypoxic inspired gas mixture may occur if nitrous oxide flow into the circuit is not progressively reduced, as nitrous oxide uptake gradually falls during anaesthesia
   d) "over-pressurization" is essential at the beginning of the anaesthesia to facilitate uptake, regardless of the drug used

   Answer: B (only a & c)