CME

Managing Fresh Gas Flow to Reduce Environmental Contamination

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Anesthetic drugs have the potential to contribute to global warming. There is some debate about the overall impact of anesthetic drugs relative to carbon dioxide, but there is no question that practice patterns can limit the degree of environmental contamination. In particular, careful attention to managing fresh gas flow can use anesthetic drugs more efficiently—reducing waste while achieving the same effect on the patient. The environmental impact of a single case may be minimal, but when compounded over an entire career, the manner in which fresh gas flow is managed by each individual practitioner can make a significant difference in the volume of anesthetic gases released into the atmosphere. The maintenance phase of anesthesia is the best opportunity to reduce fresh gas flow because circuit gas concentrations are relatively stable and it is often the longest phase of the procedure. There are, however, methods for managing fresh gas flow during induction and emergence that can reduce the amount of wasted anesthetic vapor. This article provides background information and discusses strategies for managing fresh gas flow during each phase of anesthesia with the goal of reducing waste when using a circle anesthesia system. Monitoring oxygen and anesthetic gas concentrations is essential to implementing these strategies safely and effectively. Future technological advances in anesthetic delivery systems are needed to make it less challenging to manage fresh gas flow. (Anesth Analg 2012;114:1093–101)

"The economic advantage of using only the amount of oxygen and anesthetic agents consumed by the patient is timely. Ecologic consequence of reduced fluorocarbon emission from the operating rooms is an added benefit."

From Lowe and Ernst. *Quantitative Practice of Anesthesia*. 1981:15.[1]

When Harry Lowe and Edward Ernst published these words in 1981, their intent was to set the stage for their comprehensive text on the theory and practice of closed circuit anesthesia.[1] It is interesting to note that well before the widespread dialog about greenhouse gases and global warning, these authors identified "ecologic consequences" to the use of anesthetic vapors. Recent literature suggests that environmental considerations may be a compelling rationale for using practices that minimize or eliminate the anesthetic gases and vapors that leave the circuit through the scavenging system.[2,3] The goal of this article is to describe the considerations for safely and effectively managing fresh gas flow in a manner that achieves the desired clinical effect, while minimizing waste and environmental contamination.

The ability to reduce fresh gas flow to conserve anesthetics became possible with the advent of a reliable method for carbon dioxide absorption and was advocated by Dr. Ralph Waters in 1926.[4] It is a tribute to his skills that he was able to manage this technique without the aid of devices for monitoring oxygen and anesthetic concentrations. The closed circuit technique is the most efficient use of fresh gas because only enough gas and anesthetic drug are introduced into the circuit to replace what the patient consumes. When using this technique, no gases or vapors leave the circuit through the scavenging system as waste. Gases that enter the scavenging system are removed from the operating room and ultimately vented to the atmosphere where they are free to contribute to the burden of greenhouse gases. The total fresh gas flow used to administer anesthetic gases and vapors primarily determines the proportion of the administered gases that enters the scavenging system. Therefore, practices designed to reduce waste and environmental contamination by anesthetic gases and vapors must focus on careful control of total fresh gas flow.

Because the anesthesia professional caring for the patient adjusts the fresh gas flow, each individual practitioner is directly responsible for the environmental impact of anesthetic vapors and gases.[a] Although the environmental impact of a single case may be minimal, it is useful to appreciate the impact of practice patterns when compounded over an entire

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[a] Ernst and Lowe compared the waste from high fresh gas flow with filling an automobile gas tank with 10 gallons of gas and letting 8 gallons drip out through a leak in the tank while driving. They speculated that practices would be different if anesthesia professionals were required to purchase the anesthetic drugs they administered.

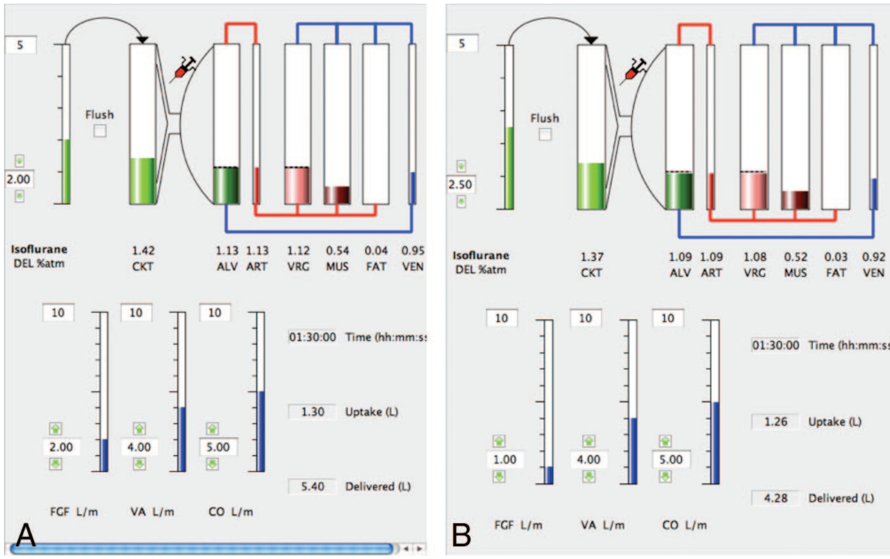

Figure 1. A, GASman simulation of 90-minute isoflurane anesthetic with isoflurane vaporizer set to 2%, 15-minute induction at 8 L/min, and 75-minute maintenance at 2 L/min total fresh gas flow. Figure indicates the distribution of isoflurane in the circuit and patient compartments at the end of a simulated 90-minute anesthetic for a 70-kg adult. Note that 5.4 L of isoflurane is delivered, and 1.3 L is taken up by the patient. Environmental contamination is 4.1 L and the efficiency, ratio of uptake to delivered, is 24%. B, GASman simulation of 90-minute isoflurane anesthetic with isoflurane vaporizer set to 2.5%, 15-minute induction at 8 L/min, and 75-minute maintenance at 1 L/min total fresh gas flow. Same simulation as in part A except for 1 L/min fresh gas flow for maintenance phase. Isoflurane vaporizer setting is increased to 2.5% to achieve a similar alveolar concentration given the lower fresh gas flow. Note that in this case, 4.28 L of isoflurane is delivered and 1.26 L is taken up by the patient. Environmental contamination is 3.02 L and the efficiency is increased to 29%.

Table 1. Order of Magnitude Estimation of Anesthetic Drug Used per Case and Over a 35-Year Career When 2 L/min or 1 L/min Is Used for the Maintenance Phase of Anesthesia

Technique	Delivered isoflurane per patient (L)	Delivered isoflurane, career (L)	Isoflurane uptake per patient (L)	Isoflurane uptake, career (L)	Total career isoflurane waste/ contamination (L)	Career efficiency
15-min induction	2.4	42,000	0.35	6125	35,875	15%
2 L/min maintenance	5.4	94,500	1.3	22,750	71,750	24%
1 L/min maintenance	4.28	74,900	1.26	22,050	52,850	29%
Technique difference, maintenance only	1.12	19,600	0.04	700	18,900	

Career anesthetics modeled as 500 annual inhaled anesthetics over 35 years. GASman simulation used to calculate total anesthetic vapor delivered and total taken up. Model assumes a 90-minute isoflurane anesthetic for a 70-kg adult with a goal of 1 minimum alveolar concentration. Fresh gas flow is 8 L/min for the first 15 minutes then either 2 or 1 L/min for the remaining 75 minutes. Differences in isoflurane uptake between 2 L/min and 1 L/min models are attributable to less rebreathing in the 2 L/min model and therefore slightly larger inspired and alveolar anesthetic concentrations.

career. To understand this impact, GASman (Med Man Simulations, Chestnut Hill, MA) was used to estimate the anesthetic vapor used during a typical inhaled anesthetic[b] (Fig. 1). For this simulation, the induction phase is assumed to last 15 minutes during which 2% isoflurane is delivered via a circle system with a fresh gas flow of 8 L/min. After 15 minutes, the maintenance phase is modeled for an additional 75 minutes comparing 2 L/min and 1 L/min fresh gas flows with the goal of maintaining a similar alveolar concentration. Whereas the uptake of anesthetic by the patient was similar at approximately 1.3 L, the 2 L/min technique delivered an additional 1.12 L of isoflurane (5.4–4.28 L) compared with the 1 L/min technique (Table 1).

[b] GASman is a computer-based simulator for modeling uptake and distribution of inhaled anesthetic drugs. The user sets patient variables and can adjust fresh gas flow and anesthetic vapor delivery as well as characteristics of the anesthesia breathing circuit. The program then calculates the compartment distribution over time of the anesthetic drugs as well as the volume of anesthetics both delivered and taken up by the patient. It is therefore a useful tool for estimating anesthetic waste under different clinical scenarios.

If we define efficiency of vapor delivery as the amount taken up by the patient divided by the total amount delivered to the patient, using 1 L/min for the maintenance phase increases efficiency from 24% to 29%. Assuming 500 similar cases per year over 35 years, we can see that simply reducing the maintenance fresh gas flow to 1 L/min prevents 18,900 L of isoflurane from entering the atmosphere. Another way to estimate the environmental impact is to multiply the 1.12 L of isoflurane wasted at 2 L/min flow per case by the millions of similar anesthetics administered annually. It is likely that using 1 L/min for maintenance instead of 2 L/min would reduce the environmental contamination by millions of liters of anesthetic vapor annually. Keep in mind, however, that the 1 L/min technique still wastes 52,850 L of isoflurane over the course of a career as compared with a true closed circuit technique.

Practicing true closed circuit anesthesia will come closest to the goal of eliminating environmental contamination, but the challenges of injecting liquid anesthetic vapors,

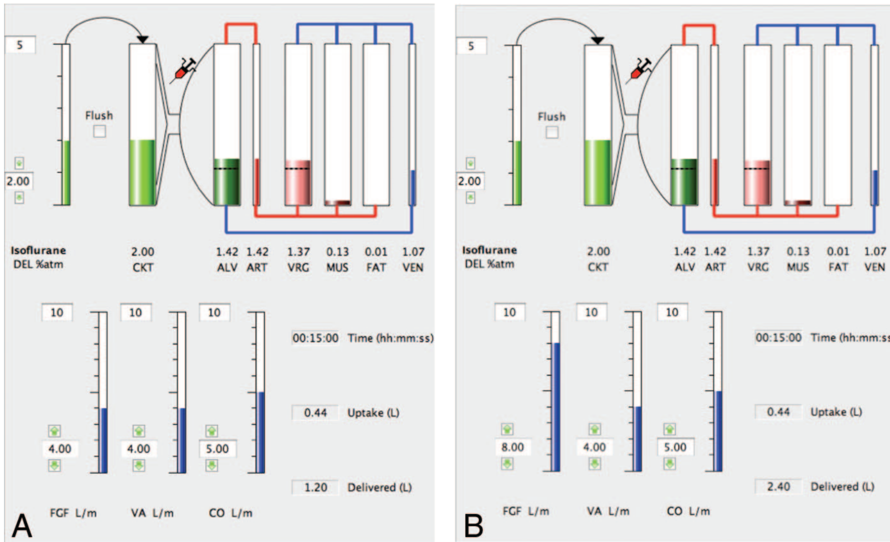

Figure 2. A, Simulation of a 15-minute induction with open circuit configuration. Fresh gas flow (FGF) and minute ventilation (VA) are equal at 4 L/min. This simulation indicates the amount of anesthetic delivered (1.2 L) and taken up (0.44 L) by a 70-kg patient during induction when fresh gas flow equals minute ventilation. The resulting circuit and alveolar concentrations are 2% and 1.42%, respectively. B, Simulation of a 15-minute induction with open circuit configuration, fresh gas flow equals 8 L/min, and minute ventilation is 4 L/min. This simulation indicates the amount of anesthetic delivered and taken up by a 70-kg patient during induction when fresh gas flow equals 2 × minute ventilation. Note that the amount taken up by the patient has not changed compared with part A and the circuit and alveolar concentrations are the same, but that an additional 1.2 L of anesthetic is delivered as waste.

tightly controlling fresh gas flow, and assessing the volume of the circuit make it impractical in modern practice. For that reason, so-called "low flow anesthesia" has become the popular term for techniques that reduce fresh gas flow but fall short of a true closed circuit technique. Much has been published about the technique of low flow anesthesia but the actual fresh gas flows that should be used throughout an anesthetic are not clearly defined. A thorough review by Baxter[5] defined low flow anesthesia as 0.5 to 1 L/min, minimal flow as 0.25 to 0.5 L/min, and metabolic flow at flows that equal oxygen consumption or approximately 250 mL/min. He concluded by recommending that flows <1 L/min be used for maintenance of anesthesia in adults but did not offer recommendations for induction and emergence. Baum and Nunn[6] have written a very comprehensive textbook on the topic, defining low flow as 1 L/min and minimal flow as 0.5 L/min. In truth, the target fresh gas flow is not a single number, and for some patients total flows <1 L/min may be inadequate depending on the fraction of gas that is oxygen. Indeed, 1 L/min will be too little fresh gas flow during induction and emergence. Managing fresh gas flow well requires an understanding of the circle system, oxygen consumption, uptake and distribution of anesthetic drugs, as well as continuous monitoring of oxygen and anesthetic concentrations. As we will see, this understanding is especially important for managing fresh gas flow during induction and emergence. Rather than use terms that are linked to a specific fresh gas flow, I prefer to use a term such as "minimum flow anesthesia," which is intended to indicate that the fresh gas flow required to manage the anesthetic effectively is not constant, but that there is a minimum possible flow at any given time.

Literature suggests that most practitioners do not use efficient fresh gas flows, and that efforts to encourage practitioners to reduce flows can have an impact, but results are variable and do not necessarily achieve a true low flow result.[7–11] Furthermore, studies of fresh gas flow administration rates typically report average rates for a procedure and focus on reducing flows during the maintenance phase of anesthesia. I recognize that the maintenance phase of anesthesia is the best opportunity to reduce flows, but I will also provide guidance for managing fresh gas flow to reduce contamination during induction and emergence.

MANAGING FRESH GAS FLOW CONCENTRATION DURING INDUCTION

The basic obstacle to reducing fresh gas flow, especially during induction, is the relationship between fresh gas flow and how rapidly the concentrations of gases in the anesthetic circuit will change. The primary reason that closed circuit anesthesia required injection of liquid anesthetics directly into the circuit is that it simply takes too long to deliver sufficient vapor into the breathing circuit to achieve the required concentration for induction when fresh gas flow is very low. During the induction process, the internal volume of the anesthesia machine, the breathing circuit, and the patient's functional residual capacity all must be filled with the desired concentrations of anesthetic gases. The ratio of the internal volume of the breathing circuit and anesthesia machine to fresh gas flow is the time constant for how quickly concentrations in the anesthesia delivery system will change. For example, if the volume of the entire breathing circuit is 5 L, and the total fresh gas flow is 5 L/min, the time constant is 1 minute. It takes 3 time constants to reach 95% of the final concentration, or in this case, 3 minutes. If the total fresh gas flow is 1 L/min, the time constant will be 5 minutes, and 15 minutes will

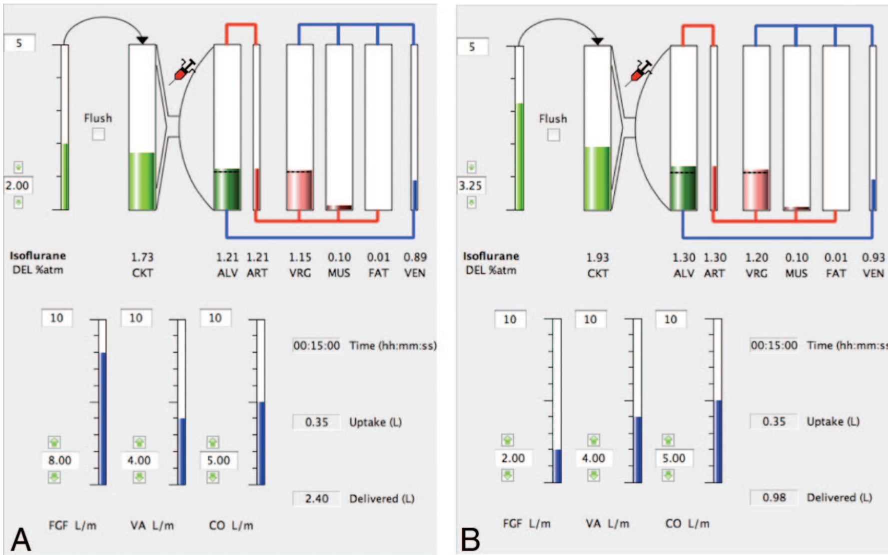

Figure 3. A, Typical induction sequence using high fresh gas flow. Results of 15-minute induction using 8 L/min fresh gas flow and isoflurane vaporizer set to 2%. Resulting alveolar concentration is 1.2%, and 2.4 L of isoflurane is delivered. B, Induction sequence using lower fresh gas flow and "overpressure" or increased vaporizer setting to compensate for reduced fresh gas flow. Results of 15-minute induction using 2 L/min, semiclosed circuit, and isoflurane set at 3.25%. Note that if the isoflurane vaporizer is set to 3.25%, it is possible to achieve the same patient uptake as induction with 8 L/min and waste less anesthetic drug. Resulting alveolar concentration actually exceeds value obtained using higher fresh gas flow and only 0.98 L of isoflurane is used instead of 2.4 L.

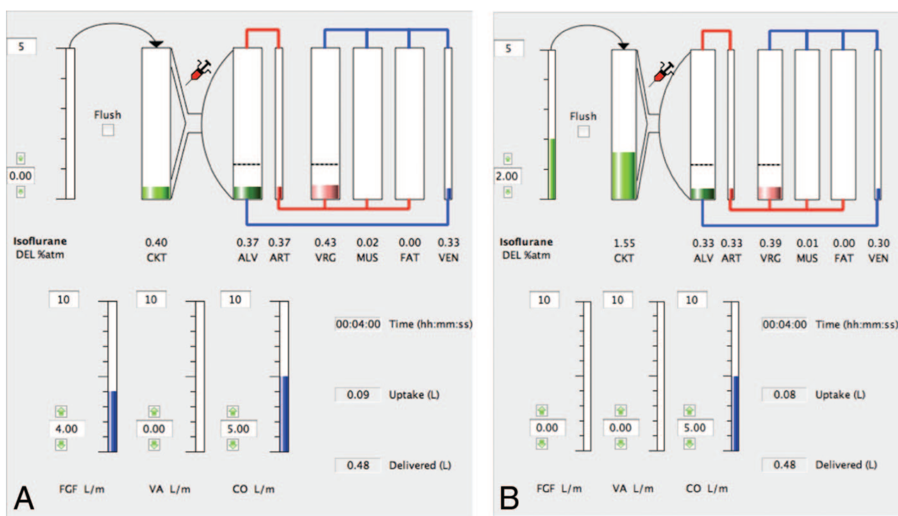

Figure 4. A, Simulation of common technique of turning off vaporizer during intubation. Simulation of 70-kg adult anesthetic with 3-minute period of mask ventilation followed by 1-minute intubation period in which vaporizer is turned off and fresh gas flow continues. Circuit concentration of isoflurane is washed out during intubation diminishing to 0.40% and alveolar concentration has decreased to 0.33%. In general, a greater fresh gas flow is required to reestablish the concentration of anesthetic vapor in the circuit after intubation. B, Simulation of technique of turning off fresh gas flow during intubation. Simulation of 70-kg adult anesthetic with 3-minute period of mask ventilation followed by 1-minute intubation period in which fresh gas flow is turned off and vaporizer setting is unchanged. Most notable difference is that the circuit concentration of isoflurane is not washed out during intubation and is preserved at 1.55%. This sustained reservoir of anesthetic can help to reestablish the alveolar concentration more rapidly after intubation and also allow for a lower fresh gas flow.

be needed to reach 95% of the desired concentration. This is why higher fresh gas flows are required to effect rapid changes in circuit concentrations, e.g., during induction. Modern anesthesia machines are designed to reduce the volume of the internal components to facilitate more rapid changes in gas concentration at a given fresh gas flow. Depending on the circuit connected to the anesthesia machine, the total internal volume of the circuit, machine, and ventilator typically exceeds 5 L in most machines.

When managing fresh gas flow with a circle anesthesia system, it is useful to understand the distinctions between closed circuit, open circuit, and semiclosed circuit conditions. The open circuit condition occurs when fresh gas flow is high enough that no exhaled gas is rebreathed, i.e., all of the exhaled gases exit the circuit through the scavenging system and all of the inspired gases are supplied by the fresh gas flow. During an open circuit condition, inspired gas concentrations will equal the concentrations in the fresh gas flow. At the other end of the spectrum, there is a closed circuit condition when only enough fresh gas is supplied to replace what the patient consumes. In that case, all of the exhaled gas is rebreathed and none of the gases enter the scavenging system. During closed circuit conditions, the concentrations of gases in the circuit change very slowly. As fresh gas flow is increased from a closed to an open circuit condition, progressively more gas enters the scavenging system and the concentrations in the circuit change more rapidly to approach those in the fresh gas. The total fresh gas flow determines both the proportion of fresh gas entering the scavenging system, and how quickly the concentrations of gases in the circuit change.

When using a circle system and a traditional vaporizer, it is impossible to change the concentration of anesthetic gases in the circuit during induction as rapidly as is clinically desirable without causing environmental contamination. A relatively high fresh gas flow is required during induction but how much fresh gas flow is sufficient? From an environmental perspective, the goal should be to use enough fresh gas flow during induction to achieve the desired inspired anesthetic concentrations rapidly enough, but no additional fresh gas flow. Recall that an open circuit condition exists when fresh gas flow is sufficient to eliminate rebreathing of exhaled gases. This is desirable during induction when uptake is highest and rebreathing exhaled gases would reduce the inspired concentration thereby slowing the induction process. However, increasing the fresh gas flow even further once there is an open circuit condition will only push more gas out the scavenging system without any benefit to the induction process. There is no benefit to increasing fresh gas flow beyond the amount required to eliminate rebreathing.

A general rule of thumb is that fresh gas flow must exceed minute ventilation to eliminate rebreathing (Fig. 2). A basic strategy during induction is to set the fresh gas flow to be slightly greater than minute ventilation. In a real circuit, the point at which rebreathing is eliminated will depend on a number of factors. The gas monitor will indicate when there is an open circuit because the inspired concentration of oxygen and anesthetic gases will approach the concentrations set to be delivered by the ratio of fresh gas flows and the vaporizer. Once the set and measured inspired concentrations approach one another, there is little to no benefit to increasing fresh gas flow further and the additional fresh gas is wasted through the scavenging system.

It is possible to use a semiclosed circuit technique during induction to reduce environmental contamination, but it requires increasing the vaporizer concentration setting, following the measured anesthetic concentrations, and progressively reducing the vaporizer setting as induction proceeds (Fig. 3). This concept has been called "overpressure."[12] Overpressure is based on the concept that the concentration of anesthetic vapor in the breathing circuit is determined by both the vaporizer setting and the total fresh gas flow. As fresh gas flow is reduced, the same inspired anesthetic concentration can be achieved by increasing the vaporizer setting. Once comfortable with using the agent monitor to adjust anesthetic concentrations, semiclosed techniques can be used during induction but care must be taken to avoid overdosage if the vaporizer is set higher than the target minimum alveolar concentration (MAC) value to facilitate the increase in circuit concentration. Over time, as uptake by the patient slows, if the vaporizer setting is not reduced, the inspired concentration will ultimately exceed the target MAC value. The concentration change will occur slowly and may not be appreciated. Setting a high exhaled anesthetic concentration alarm can help to alert the clinician to the accumulation of anesthetic vapor beyond the desired level.

MANAGING FRESH GAS FLOW DURING INTUBATION

I previously reviewed the goal of not turning up the fresh gas flow beyond an open circuit condition during induction. Another common practice during the induction phase of anesthesia is to mask ventilate the patient using a high fresh gas flow, and turn off the vaporizer when the mask is removed to intubate the patient. The goal of this practice is to avoid contaminating the operating room with anesthetic gases. In reality, however, the gases that have accumulated in the circuit during mask ventilation are washed into the room by the continued high fresh gas flow. Room contamination is not avoided and the gases in the circuit are wasted. Furthermore, a high fresh gas flow is required after intubation to reestablish the concentrations of anesthetic gases desired for induction.

Alternatively, one can turn off the fresh gas flow during intubation and leave the vaporizer on. In the absence of fresh gas flow, none of the anesthetic gases are washed into the room, and the gases that have built up in the circuit are preserved. The primary advantage of this strategy is to preserve the concentration of anesthetic gases in the circuit (Fig. 4). As a result, there is no environmental contamination during intubation and it is possible to use a lower fresh gas flow than would otherwise be needed to maintain the circuit concentration subsequent to intubation.[13] Because the alveolar concentration of anesthetic vapor decreases quickly during intubation because of uptake from the lungs, this technique facilitates restoring the alveolar concentration since the anesthetic concentration in the circuit is maintained.

This process of turning off the fresh gas flow and not the vaporizer is often critiqued because an extra step of turning on the fresh gas flow is required in the event of a difficult airway and the need to continue mask ventilation. Each practitioner should make a decision about their own comfort level with airway management and fresh gas flow changes. However, turning off the vaporizer during intubation while leaving fresh gas flow high does not achieve the goal of avoiding room contamination, and does contribute to wasting anesthetic vapor and environmental contamination.

I have identified that it is necessary to use a higher fresh gas flow during induction than desired from an environmental perspective to achieve the desired rate of change in anesthetic concentration. At what time in the induction process is it possible to reduce the fresh gas flow? Once uptake of anesthetic from the lungs slows, the concentration changes in the circuit are not as significant and fresh gas flow can be reduced. Again, the anesthetic agent monitor is useful to identify when uptake has slowed. When the expired agent concentration approaches the inspired concentration and approximates the desired MAC value, uptake by the patient has slowed and there is an opportunity to reduce the fresh gas flow. Keep in mind that uptake from the lungs continues, albeit at a progressively slower rate, and when fresh gas flow is reduced, rebreathing increases and there is a possibility that anesthetic drug concentration will diminish. The exhaled concentration of vapor measured by the gas analyzer is the closest approximation to the alveolar concentration and should be monitored to assess the current MAC value for a patient. A low exhaled anesthetic drug alarm set appropriately can indicate whether the fresh gas flow is too low to sustain the desired anesthetic concentration due to continued uptake. An increase in fresh gas flow and/or vaporizer setting will restore the desired concentration of anesthetic vapor.

WHAT IS THE MINIMUM SAFE FRESH GAS FLOW DURING THE MAINTENANCE PHASE OF ANESTHESIA?

In the simulated anesthetic presented in Figure 1, maintenance fresh gas flow of 1 L/min reduced anesthetic waste significantly compared with a 2 L/min fresh gas flow. These results are indeed consistent with prior studies.[7–11] The simulation raises a number of questions when we try to translate these results into practice. Is 1 L/min the optimal fresh gas flow? Could we reduce fresh gas flow further and prevent even more contamination? How will we know if 1 L/min is not enough fresh gas flow? The simulation did not specify the gases used in the fresh gas flow and in practice, combinations of oxygen, air, and nitrous oxide are used. How can fresh gas flow be minimized when oxygen is combined with air or nitrous oxide?

The minimum safe fresh gas flow during maintenance supplies enough oxygen to satisfy the patient's oxygen consumption, plus enough additional gas flow to replace gases lost because of leaks in the circuit and/or via a sidestream gas analyzer. Oxygen consumption during anesthesia varies among patients and even phases of the anesthetic. Brody[14] is typically credited with establishing the relationship between weight and oxygen consumption in mammals to be $10 \times kg^{3/4}$. A simpler estimate of oxygen consumption that has been used is 3 to 5 mL/kg/min. Calculating the ¾ power of weight is not very convenient, and an easier rule of thumb is to use 5 mL/kg/min as an approximate estimate of oxygen consumption. This rule of thumb will overestimate oxygen consumption, especially for larger patients, relative to the Brody formula and create a margin of safety when setting oxygen flow to match the needs of an individual patient (Fig. 5). Using our model of a 70-kg adult, oxygen consumption can be estimated to be 350 mL of oxygen per minute.

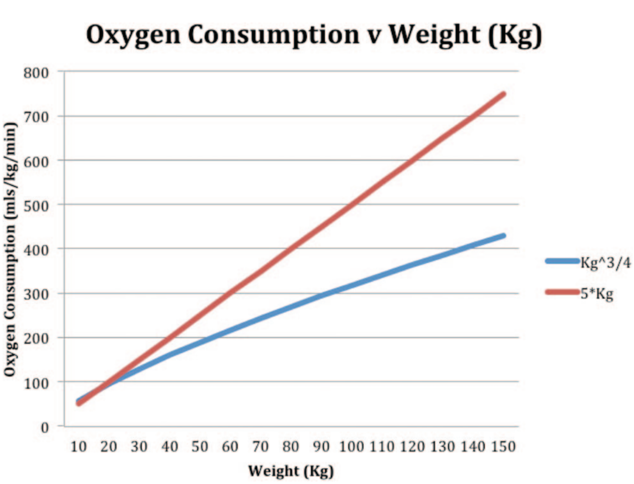

Figure 5. Comparison of oxygen consumption as a function of body weight in kilograms using Brody formula and linear estimate of 5 mL/kg/min.

Leaks (or potential leaks) from the circuit need to be considered to determine the minimum safe fresh gas flow. If an aspirating (sidestream) gas analyzer is being used to sample gas from the breathing circuit, the volume removed (typically 200 mL/min) must be replaced by the fresh gas flow. In some machines, the aspirated gas is returned to the breathing circuit and can therefore be ignored when setting fresh gas flow; i.e., a lower fresh gas flow can be used. True leaks from the circuit should be minimal when a quality anesthesia machine and breathing circuit are used. If one is using a sidestream gas analyzer that does not return gas to the circuit, add 200 mL/min to the calculated oxygen consumption. Some anesthesia machines quantify the circuit leak during the self-test process and the measured leak value should be accommodated by additional fresh gas flow. In the absence of a quantified leak, because most anesthesia machines are not completely leak free, another 100 mL/min should be added to determine the target fresh gas flow to accommodate any leaks from the circuit. The actual amount of leak will be related to the pressure in the circuit during mechanical ventilation.

The volume of oxygen provided in the fresh gas flow is the total flow from the oxygen flowmeter plus 21% of the flow from the air flowmeter if air is being used. When nitrous oxide is being used, all of the oxygen comes from the oxygen flowmeter. A true closed circuit technique manages fresh gas flow with air or nitrous oxide so that there is no environmental contamination, but it can be difficult to accomplish. Once oxygen flow is set to match the patient's oxygen consumption, the nitrogen in air, or the nitrous oxide flow that exceeds oxygen consumption, will ultimately displace an equivalent amount of gas out the scavenging system. Nevertheless, careful attention to matching oxygen flow to consumption and setting the minimum flow of other gases can minimize the environmental impact of the anesthetic vapors. The oxygen concentration monitor is essential to safely minimizing fresh gas flow. If oxygen delivered is too low to meet the patient's demands, the measured oxygen concentration in the circuit will decrease and the oxygen flow can be increased.

With this background, let us consider how to set the minimum fresh gas flow during maintenance for a 70-kg adult patient where gas sampled for analysis is returned to the breathing circuit. Once the exhaled concentration of isoflurane is close to the inspired concentration and the desired MAC value, uptake from the lungs has slowed and the fresh gas flow can be reduced. Assuming oxygen consumption to be approximately 350 mL/min, the total oxygen flow can be set to 350 mL/min. The air flowmeter can be set to 500 mL/min, which would deliver an additional 105 mL/min oxygen to compensate for any leaks, and the total fresh gas flow will be 850 mL/min. If nitrous oxide is used, the oxygen flowmeter will supply all of the oxygen, and the flow setting needs to be sufficient to account for oxygen consumption and leaks from the circuit. A nominal setting of 450 mL/min oxygen is therefore required. An equal flow of nitrous oxide will result in a nitrous oxide concentration that exceeds 50% because much of the oxygen supplied is used by the patient. The inspired oxygen concentration that results from these settings will be determined by the patient's oxygen consumption and oxygen flow can be adjusted to achieve the desired inspired oxygen concentration.

Managing this technique requires that the inspired oxygen concentration be monitored. If oxygen consumption exceeds the total oxygen delivered, the inspired oxygen concentration will diminish, indicating that oxygen flow needs to be increased. One can find the absolute minimum flow by progressively reducing the flows of oxygen and nitrous oxide and then observing the monitored oxygen concentration over several minutes. If the inspired oxygen concentration begins to decrease, the oxygen flow can be increased in small increments until the oxygen concentration stabilizes. In a true closed circuit technique, the flows can be managed by observing the ventilator bellows, or reservoir bag in a piston ventilator device, because the volume in the circuit will diminish if the oxygen supplied is inadequate. When oxygen is mixed with air or nitrous oxide, the volume of the circuit does not indicate inadequate flow because the nitrogen or nitrous oxide administered compensates for any volume shortfalls due to inadequate oxygen flow.

There is still some environmental contamination with this technique, because the total fresh gas flow exceeds what is consumed, but it is easier to manage than a true "closed circuit" technique. Unless the patient has a large oxygen consumption (e.g., during pregnancy), it should be possible during the maintenance phase of anesthesia in most adults to limit the fresh gas flow to a maximum of 1 L/min. For many patients, even lower flows are possible and can be achieved by reducing flows and monitoring the effect on inspired oxygen and expired anesthetic concentrations. Because the minimum flow required is ultimately determined by the patient's oxygen consumption, the patient's weight will influence the minimum required fresh gas flow settings. Oxygen flows can be safely reduced during the maintenance phase as long as inspired oxygen concentration is maintained. A low oxygen concentration alarm set at the minimum desired concentration is useful because the concentration will change slowly. Keep in mind also that the exhaled anesthetic agent concentration must also be monitored when using low fresh gas flows to ensure that the vaporizer setting is sufficient to replace the anesthetic taken up by the patient and maintain the desired MAC value.

FRESH GAS FLOW DURING EMERGENCE

During emergence, the primary goal is to remove the anesthetics from the patient. Because most anesthesia systems in use today are equipped only with scavenging systems that exhaust to the atmosphere, it is impossible to manage emergence and avoid environmental contamination. Nevertheless, the manner in which fresh gas flow is managed can reduce the environmental impact.

Timing the dosing of anesthetic drug to ensure a prompt emergence is the art of anesthesia. One must estimate the surgical duration and manage the vaporizer setting, fresh gas flow setting, and minute ventilation all in relation to the duration of the procedure to achieve an optimal result. Because of the many factors that have a role in managing emergence, it is difficult to give a specific formula for how to manage fresh gas flow. A common practice is to increase the fresh gas flow toward the end of a procedure and gradually reduce the vaporizer setting. In general, there will be less waste if one can manage emergence by keeping fresh gas low until the vaporizer is turned off completely.

CHOICE OF ANESTHETIC VAPOR

Although the fresh gas flow strategies described will help to reduce environmental contamination for any of the anesthetic drugs, sevoflurane has some special considerations. Sevoflurane interacts with carbon dioxide absorbents containing sodium and potassium hydroxides to produce compound A, which can have deleterious effects on renal function in laboratory animals. For that reason, when sevoflurane was first introduced, the minimum recommended fresh gas flow approved was 2 L/min. Subsequent studies in humans have failed to demonstrate a significant impact on renal function, and the approved minimum fresh gas flow is now 1 L/min for up to 2 MAC hours of dosage.[15,16] With the advent of carbon dioxide absorbents that do not interact with sevoflurane, and in the absence of compelling human data that compound A is injurious, it is reasonable to question the fresh gas flow limitations when using sevoflurane. Nevertheless, at the time of this writing, one would want to use an alternative to sevoflurane at flows <1 L/min to comply with approval requirements in the United States.

Desflurane may have a greater potential environmental impact than the other drugs because of the higher concentrations required and its intrinsic properties as a greenhouse gas.[17] Isoflurane may therefore be the best drug to use purely from an environmental perspective because it does not have as potent a greenhouse effect as desflurane and there is no lower limit on fresh gas flow. Because of the lower solubility of desflurane, it is possible to reduce fresh gas flow sooner during induction relative to isoflurane.[18] It is unlikely, however, that this difference will be sufficient to offset the environmental impact of desflurane compared with isoflurane because of the greater global warming potential of the former.

TECHNOLOGY AND FRESH GAS FLOW

The circle anesthesia circuit was designed as an alternative to open delivery where none of the exhaled gases could be rebreathed. Using a circle system, the anesthesia provider can reduce fresh gas flow and allow for exhaled anesthetic gases to be rebreathed. Because of the need to use higher fresh gas flows to change the concentration of gases in the circuit rapidly, the circle system remains a design that is difficult to use efficiently. The circle system is most efficient during the maintenance phase of anesthesia, when gas concentrations are stable and fresh gas flow can be minimized.

Technology has some promise for reducing or eliminating environmental contamination by anesthetic vapors. Some anesthesia delivery systems provide tools to guide fresh gas flow settings during the maintenance phase such as the Low Flow Wizard™ (Draeger Medical, Luebeck, Germany). This tool can help to reduce fresh gas flow but has some limitations. The Low Flow Wizard indirectly measures the volume in the circuit by assessing pressure changes in the reservoir bag during exhalation. It does not assess changes in anesthetic gas concentrations and therefore is only useful during the maintenance phase of anesthesia. A previous anesthesia delivery system, the Physioflex, was designed to deliver anesthetic vapors using a closed circuit technique. That machine is no longer available, but some of the technology from that device has been incorporated into the Zeus™ anesthesia delivery system (Draeger Medical). GE Healthcare has recently introduced a closed loop method of anesthetic vapor delivery called ET Control™ for the Aisys™ workstation (GE Healthcare, Helsinki, Finland). This system allows the user to set a minimum fresh gas flow and target concentrations for oxygen and anesthetic gases. The machine will then monitor gas concentrations and adjust fresh gas flow automatically to maintain the set gas concentrations in the circuit while attempting to match the minimum fresh gas flow setting if possible. This system has the potential to make it easier to use lower fresh gas flows, but whether or not it reduces environmental contamination compared with manual control remains to be demonstrated.[19] Neither the Zeus nor ET Control is currently approved for use in the United States. We await the development of an anesthesia delivery system that makes it possible to use a true closed circuit anesthesia technique for the entire anesthetic.

Other technologies are being developed to capture anesthetic vapors as they leave the scavenging system and prevent them from entering the atmosphere.[20,c] Whether or not these technologies will be economically viable and allow us to recycle the captured vapors for use remains to be seen.

DISADVANTAGES OF MINIMAL FLOW ANESTHESIA

One of the obvious disadvantages of minimal flow anesthesia is the challenge to managing changes in circuit concentrations. There are some more subtle disadvantages. Because reducing fresh gas flow increases the amount of rebreathing, carbon dioxide absorbents will be consumed more rapidly. There is an environmental consequence to using more absorbents and the impact relative to anesthetic vapors saved has not been determined, although it is unlikely that the added impact of producing and wasting more absorbents will exceed the impact of anesthetic vapors. Another consequence of reducing fresh gas flow is the potential to accumulate gases in the breathing system. Gases that have been traditionally of concern are nitrogen, carbon monoxide, methane, acetone, and compound A. Compound A was discussed previously.[5] Nitrogen, methane, and acetone accumulate in small amounts, and as long as the oxygen concentration is adequate, are of no concern. Carbon monoxide is produced in small amounts by the body but in potentially larger concentrations when potent anesthetics interact with carbon dioxide absorbents containing strong alkalis such as potassium hydroxide. Newer formulations of the absorbent materials have minimized these alkalis eliminating the concern for significant carbon monoxide accumulation. Strategies that are typically used to eliminate the concern for toxic gas accumulations include (1) using absorbents that have minimal to no strong alkali, (2) avoiding desiccation of absorbents caused by running fresh gas continuously when the machine is not in use, (3) diverting gas sampled for analysis to the scavenging system instead of back into the breathing circuit, and (4) using high fresh gas flow (e.g., 5 L/min for 3 minutes) every 30 minutes to flush the circuit. If the first strategy is used, there is little reason to be concerned about toxic gas accumulations. Failing that, diverting the sampled gas to the scavenging system is practical, but fresh gas flow must be increased to account for the sampled gas.

CONCLUSIONS

Using a true closed circuit technique can eliminate virtually all of the environmental contamination. The technique of closed circuit anesthesia is well documented but has proven impractical. The techniques described here will still result in some degree of waste and environmental contamination as compared with a closed circuit technique. Nevertheless, using these techniques will reduce waste, and when multiplied by a lifetime of anesthetics delivered will reduce the impact of personal practice on the environment. Technology advances are needed to make true closed circuit anesthesia convenient.

Summary of Recommendations for Managing Fresh Gas Flow

During Induction

- Use a total fresh gas flow that approximates minute ventilation and increase the fresh gas flow only if the measured (inspired) concentrations of oxygen and anesthetic vapor are less than the set concentrations.
- When intubating, turn off the fresh gas flow, not the vaporizer.
- After intubating, turn on the fresh gas flow to half of the minute ventilation and progressively reduce fresh gas flow according to the measured anesthetic concentrations. Consider increasing the vaporizer setting above the desired level (Overpressure) to maintain the desired expired anesthetic concentration.
- Decrease vaporizer setting as the difference between exhaled and inspired anesthetic concentrations diminish. Monitor the exhaled concentration of anesthetic vapor to ensure adequate anesthetic depth.

During Maintenance

(When expired anesthetic concentration approaches the inspired concentration)

- Estimate patient oxygen consumption to be 5 mL/kg/min.
- Set total oxygen flow (oxygen +21% of air flow if used) to equal estimated oxygen consumption.
- Add 200 mL/min to total oxygen flow if using a sidestream gas analyzer that does not return sampled

[c] Berry J, Lancaster L. Recycled Anesthetic Technology Saves Dollars, Environment. Vanderbilt Magazine Online. Available at: http://www.vanderbilt.edu/magazines/vanderbilt-magazine/2009/03/recycled-anesthetic-technology-saves-dollars-environment/. Accessed January 14, 2012.

gas to the circuit. Note that this flow can be eliminated if gases sampled for analysis are returned to the breathing circuit.

- If the leak is not quantified by the anesthesia machine and positive pressure ventilation is used, add 100 mL/min to total oxygen flow to account for any leaks from the circuit.
- Oxygen flow can be reduced in 50 mL/min increments until the inspired oxygen concentration begins to decrease.
- Monitor inspired oxygen concentration and set low oxygen concentration alarm at desired level.
- Monitor exhaled anesthetic vapor concentration to ensure adequate MAC. Set alarm for desired level of expired vapor concentration.

During Emergence

- Maintain a low fresh gas flow setting until the vaporizer can be turned off completely.

DISCLOSURES

Name: Jeffrey M. Feldman, MD, MSE.
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Conflicts of Interest: The author has served as a consultant or compensated lecturer in the past for Draeger Medical, GE Healthcare, and Oricare.
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