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Patient Safety and Low-Flow Anesthesia

by Jeffrey M. Feldman, MD, MSE, and Samsun Lampotang, PhD, FSSH, FAIMBE

The benefits of low-flow anesthesia are well established and include reduced inhaled anesthetic waste, decreased cost, and fewer greenhouse gas effects.¹ For the individual patient, low-flow anesthesia reduces loss of heat and humidity from the lungs.² This article will highlight the common safety concerns of low-flow anesthesia. This is not intended to be a comprehensive guide to practicing low-flow anesthesia, which is well-described in the literature,³ and is a topic that will be covered in the upcoming APSF-ASA medical technology training initiative. (See: Thomas B. Off-label low-flow sevoflurane: Regulatory red herring or liability landmine?. *APSF Newsletter*. 2022;37:57–58.) The good news is that the risks of adopting low-flow anesthesia are readily managed, and patient safety concerns should not be a barrier to reducing fresh gas flow.

The “circle system” was designed to reduce anesthetic waste by allowing exhaled anesthetic agent to return to the patient in the inspired gases (Figure 1). Carbon dioxide (CO₂) absorption is fundamental to the design of the circle system. While CO₂ absorbents are necessary for safe use of the circle system, the presence of an absorbent does not guarantee the circle system is actually reducing waste. Effectively reducing

waste requires the anesthesia professional to reduce fresh gas flow in a manner that allows exhaled gases to return to the patient.⁴

Low-flow anesthesia is sometimes described as a total fresh gas flow of 1 liter/min. In practice however, low-flow anesthesia is not a single number. Depending upon the circumstances, 1 liter/min can be too much to achieve the desired degree of waste reduction, or too little to maintain an adequate concentration of oxygen or anesthetic in the circuit. For purposes of this discussion, the authors define the current practice of low-flow anesthesia as: *Reducing fresh gas flow below minute ventilation to the lowest level consistent with equipment capabilities and provider comfort while ensuring safe and effective care for the patient.* While reducing fresh gas flow unquestionably reduces waste, cost, and pollution, it is not without consequences that have implications for patient safety.

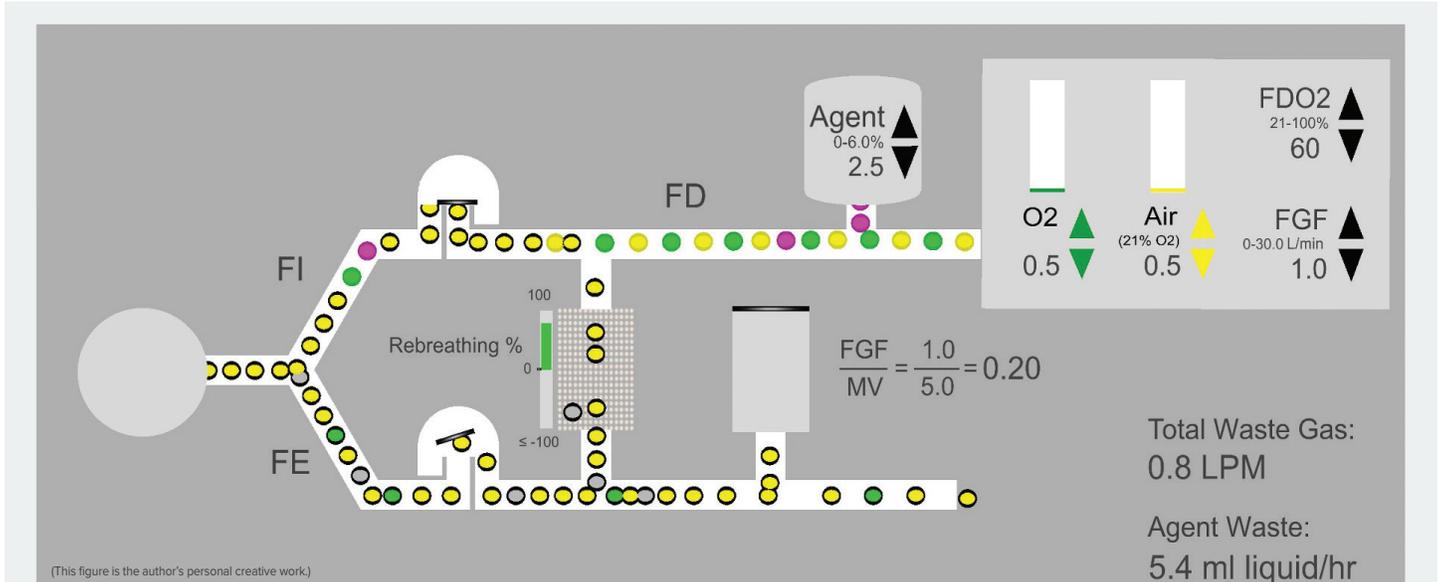
Effective oxygen delivery requires an inspired oxygen concentration that will maintain the desired concentration of oxygen in the blood. Anesthetic agent requirements are dictated by the need to maintain an adequate level of hypnosis and physiologic stability in the face of surgical stimulation and trauma. As fresh gas

flow is reduced and rebreathing increases, the concentrations delivered in the fresh gas and the concentrations inspired by the patient can be quite different. Furthermore, gas and agent concentrations change in the circuit more slowly as fresh gas flow is reduced. Managing the relationship between delivered and inspired concentrations is the art and practice of low-flow anesthesia. It is important to note that control of carbon dioxide concentration is determined by minute ventilation and is unaffected by fresh gas flow.

ENSURING ADEQUATE OXYGEN DELIVERY

Concern for inadequate oxygen delivery leading to hypoxemia or inadvertent low inspired concentration of oxygen is reasonable as fresh gas flow is reduced. The concentration of oxygen in the exhaled gas (F_EO₂) is always less than the inspired concentration (F_IO₂) due to the patient’s oxygen consumption. As the percentage of rebreathed gas increases, F_EO₂ mixes with the oxygen delivered to the patient in the fresh gas (F_DO₂) to yield the F_IO₂. The more exhaled gas is allowed to return to the patient, the greater the impact of F_EO₂ on F_IO₂ (Figure 1).

See “Low-Flow Anesthesia,” Next Page



(This figure is the author’s personal creative work.)

Figure 1: Idealized schematic of a circle system where FGF is a fraction of the minute ventilation at 1 L/min—0.5 L/min Air and O₂ respectively. Air = Yellow circles, Oxygen = Green circles, and Agent = purple circles. Circles with the black border = exhaled gases or anesthetic, some of which return to the inspired limb. Note that due to recirculation of exhaled gases, the concentration of oxygen and anesthetic delivered in the fresh gas flow (F_DO₂ 60% and F_DA 2.5%) will be different from the inspired concentrations (F_IO₂ and F_IA) due to mixing of fresh gas with exhaled gases (F_EO₂ and F_EA). The exact concentration differences will depend upon the phase of the procedure with the difference diminishing over time. F_D = delivered fraction, F_I = inspired fraction; F_E = expired fraction; FGF = fresh gas flow; MV = minute ventilation.

Continuous Monitoring of Inspired and Expired Anesthetic Agent Concentration Is Essential to Safe Practice of Low-Flow Anesthesia

From “Low-Flow Anesthesia,” Preceding Page

Continuous monitoring of inspired oxygen concentration is essential to the safe and effective practice of low-flow anesthesia. As flows are reduced, the practitioner estimates the delivered oxygen concentration (F_{D,O_2}) that will maintain the desired inspired concentration (F_{I,O_2}). Ultimately, the patient's oxygen consumption and any leaks in the circuit will determine the F_{I,O_2} delivered to the patient. Continuous F_{I,O_2} monitoring will help to guide adjustments to fresh gas flow. Since the F_{I,O_2} changes slowly at low fresh gas flow, a low oxygen concentration alarm can be set above the minimum safe level to provide a notification if F_{I,O_2} is heading lower than desired.

Managing inspired oxygen concentration during low-flow anesthesia is relatively straightforward since oxygen consumption is fairly constant during a procedure. Managing inspired anesthetic agent concentration is a bit more challenging since the uptake of agent falls exponentially over time.

ENSURING ADEQUATE INSPIRED ANESTHETIC AGENT CONCENTRATION

As mentioned previously, safe anesthetic agent delivery requires that the patient have a sufficient concentration to be unaware, but not so much that physiologic stability is threatened. Similar to the case of oxygen, the expired concentration of anesthetic agent ($F_{E,Agent}$) will always be less than the inspired concentration of agent ($F_{I,Agent}$) due to uptake, except during emergence. Early in the procedure, when uptake of agent is high, the difference between $F_{E,Agent}$ and $F_{I,Agent}$ can be substantial. For that reason, it is more difficult to reduce flows during induction and maintain the desired anesthetic concentration compared with the maintenance phase of the anesthetic when uptake has slowed and $F_{E,Agent}$ approaches $F_{I,Agent}$.

Continuous monitoring of inspired and expired anesthetic agent concentration is essential to the safe and effective practice of low-flow anesthesia. The difference between inspired and expired anesthetic agent concentration indicates the rate of uptake. As the difference narrows, uptake is slowing and it is easier to reduce flows and maintain the desired anesthetic concentration in the circuit. While the Delivered agent concentration, $F_{D,Agent}$, is determined by the vaporizer setting, the $F_{I,Agent}$ indicates what is being inspired by the patient. As flows are reduced, it may be necessary to increase the vaporizer setting above the Minimum Alveolar Concentration (MAC) concentration desired in the patient to maintain the $F_{I,Agent}$ and $F_{E,Agent}$ at the desired levels. Like

oxygen delivery, setting the vaporizer is an estimate by the low-flow practitioner, and continuous agent concentration monitoring becomes essential to guiding vaporizer and fresh gas flow settings.

MANAGING FRESH GAS FLOW WHEN CHANGING OXYGEN AND AGENT CONCENTRATIONS

One major challenge to the practice of low-flow anesthesia is the rate of change of oxygen and agent concentrations in the circuit. The time constant for the rate of change is the internal volume of the anesthesia machine and breathing circuit in liters divided by the fresh gas flow in L/min. The internal volume can be 5 liters or more so that a fresh gas flow of 1 L/min could result in a time constant of 5 minutes, and it can take four-time constants to get close to equilibrium.

As fresh gas flow is reduced, concentrations of oxygen and anesthetic will change more slowly to reach a new equilibrium. As a result, the practitioner may change the gas mixture or vaporizer setting, but the ultimate impact on concentrations in the circuit will not be apparent for several minutes. This is another reason for continuous monitoring of oxygen and agent concentrations in the circuit as well as the use of high and low alarm limits to draw attention to slow changes that might otherwise go unnoticed. Indeed, it may be necessary to increase the total fresh gas flow to ensure that oxygen and agent concentrations change more quickly if needed.

DOES SEVOFLURANE HAVE A MINIMUM SAFE FRESH GAS FLOW?

The package insert for sevoflurane indicates that sevoflurane is safe when fresh gas flow is not less than 1 L/min for up to 2 MAC-Hours or not less than 2 L/min for longer procedures.⁵ This recommendation is neither scientifically sound nor consistent with a modern practice of low-flow anesthesia. Nevertheless, given the FDA labelling, practitioners may be understandably reluctant to reduce flows to less than these recommendations and deliver sevoflurane “off-label.” In another article in the *APSF Newsletter* (Off-label low-flow sevoflurane: Regulatory red herring or liability landmine?. *APSF Newsletter*. 2022;372):57–58, Brian Thomas JD, vice-president for Risk Management, Preferred Physicians Medical, provides some guidance on the actual medico-legal concerns associated with off-label medication administration. This article will briefly review the science that clearly indicates a lower flow limit for sevoflurane is unnecessary.

The major concern for reducing flows when using sevoflurane is the accumulation of Compound A in the circuit and the potential for renal toxicity. While there is no question that sevoflurane can interact with some absorbent formulations to produce Compound A, it has never been shown to result in renal toxicity in humans.⁶ Furthermore, subsequent to the FDA labelling of sevoflurane, it was clearly shown that Compound A results from the interaction of sevoflurane with absorbents that contain strong bases like potassium hydroxide (KOH) and sodium hydroxide (NaOH).⁷ It has also been shown that eliminating the KOH and limiting the NaOH to less than 2% yields an effective absorbent that does not produce Compound A.⁸ In short, while there is no substantiated concern for patient injury from Compound A, there is no risk of

See “Low-Flow Anesthesia,” Next Page

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Eliminating KOH and Limiting NaOH to Less than 2% Yields an Absorbent That Does Not Produce Compound A

From “Low-Flow Anesthesia,” Preceding Page

Compound A production when using one of the many carbon dioxide absorbents available that limit the strong base to NaOH <2%. Every absorbent has a safety data sheet that is readily available on the internet and indicates the chemical composition of the absorbent (Figure 2). Any fresh gas flow can be used safely when administering sevoflurane subject to the considerations for oxygen concentration noted previously.

CONCLUSION

The practice of safe and effective low-flow anesthesia is an art that requires the practitioner to understand the capabilities and limitations of the circle system, set fresh gas flow and vaporizer concentrations to estimate patient needs, and continuously monitor the concentrations that result in the circuit. Interested in reducing the waste and pollution in your practice of inhaled

anesthetic delivery? Look for the APSF-ASA course on low-flow anesthesia to be available on the APSF website in the fall of 2022.

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Dr. Feldman is a consultant for Medtronic, Becton-Dickinson, and Micropore. Dr. Lampotang has no conflicts of interest.

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Composition / Information on Ingredients

2.2 Chemical Characterization (Preparation):

Soda lime containing calcium dihydroxide, calcium chloride, sodium hydroxide, 14–18% water and the indicator ethylviolet.

CAS No.	Designation acc. to EC Directive	Content	Unit	Ident. Symbol	R-Phrases
1305-62-0	Calcium dihydroxide / Calcium hydroxide (Ca(OH) ₂) (EINECS-Nr. 215-137-3)	74–82	w/w per cent	X _i	R 41
10043-52-4	Calcium chloride	3–5	w/w per cent	X _i	R 36
1310-73-2	Sodium hydroxide	0.5–1	w/w per cent	C	R 35
2390-59-2	Ethyl Violet	<0.1	w/w per cent	X _n	R 22–41

2.3 Additional Information:

Dräger sorb® Free contents no ozone-depleting chemicals and no volatile organic chemicals (VOCs). During the manufacturing process for Dräger sorb® Free no ozone-depleting chemicals and no volatile organic chemicals (VOCs) were used.

Abbreviations: CAS No = unique identifier for all compounds published by the Chemical Abstracts Service; Compound names are Designation according to European Commission Directive; W/W = Weight by weight expressed as a percentage eg. 1% is 1 gram of the substance in 100g of the material; R-phrases = defined by the European Union Directive 67/548/EEC and describe special risks attributed to chemical preparations. (e.g., R-36 means irritating to the eyes)

Figure 2: Snapshot of medical safety data sheet for Dräger sorb Free. Note that the chemical composition is clearly noted, the sodium hydroxide concentration is 0.5-2%. From https://www.medline.com/media/catalog/Docs/MSDS/MSD_SDS71242.pdf. Accessed 4/4/2022. Similar safety data sheets can be found in the public domain for any commercially available CO₂ absorbent.