Low-flow anesthesia and ancillary techniques

How to minimize inhaled anesthetic agent waste

This document is intended to provide information to an international audience outside of the US.

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Abbreviations

AA	Anesthetic Agent
F_A or F_{ET}	Alveolar Fraction or End-Tidal Fraction, the concentration the patient exhales
F_D	Delivered Fraction The concentration you dial (“set”) on the flow meters (for O_2) or the vaporizer
FGF	Fresh Gas Flow
F_I	Inspired Fraction The concentration the patient inhales
fMAC	Fraction of the Minimum Alveolar Concentration
MV	Minute Ventilation
RBF	ReBreathing Fraction
VR	Volume Reflector
VR Indicator	Volume Reflector Indicator

An introduction to

Low-flow anesthesia

This manual provides the clinician guidelines to reduce anesthetic waste in a manner that smoothly integrates with the clinical workflow with the Flow Family devices.

1. Introduction

Rationale for low-flow anesthesia: economy and ecology

Inhaled anesthetics provide safe and reliable anesthetic conditions. Like any drug we use, they come with a cost, both financial and environmental. Inhaled anesthetics are greenhouse gases, thus good clinical practice requires minimizing their waste — one of many reasons to practice low-flow anesthesia. Reducing FGFs literally recycles administered inhaled anesthetic. Oxygen consumption of an average adult is 180 mL/min[1]. With a FGF of 180 mL/min of oxygen, the minimum amount of sevoflurane needed to maintain anesthesia (= closed circuit anesthesia) for 1 hour at an end-expired concentration of 2% is only 7 mL liquid sevoflurane[2]. In clinical practice, FGFs well above 1 L/min are often noticed to be used.

Low-flow anesthesia (the keystone) and ancillary techniques (the puzzle)

While low-flow anesthesia is the mainstay to reduce inhaled anesthetic waste, ancillary techniques help further reduce waste. These techniques are really the parts of a puzzle that, when all pieces are interlocked, reduces inhaled agent use to a few milliliters of liquid sevoflurane per hour.

These include:

- Slow wash-in (guided by the MAC Brain, processed EEG and projected wash-in display)
- Titrating 0.7 – 0.8 fMAC during maintenance (taking advantage of the synergetic effect of opioids)
- Coasting toward the end of the procedure (guided by MAC Brain, processed EEG and projected wash-out display)

Defining low-flow anesthesia

Closed-circuit anesthesia, minimal flow, low-flow, and high-flow anesthesia are all terms that have been used to refer to fresh gas flows used within the FGF spectrum. However, we prefer to back away from these terms and instead just refer to the specific FGF one is using. For clinicians, it is more important to master the tools and technology that enable them to work with the lowest FGF they feel comfortable with. This has been referred to as “lower flow anesthesia” i.e., use a FGF lower than what you are currently using (Samsun Lampotang, University of Florida, FL, USA). Referring to specific FGFs instead of the more vague and ever confusing terms referred to above makes also sense because what constitutes high FGF for a baby may not be high FGF for an adult patient. Throughout the text we will use the term “low flow anesthesia” to generically refer to the use of a FGF below 1 L/min.

Low-flow anesthesia

2. Low-flow anesthesia basics

F_D – F_I – F_{ET} (O_2, Volatile agent)

The key to understand low-flow anesthesia is to understand the meaning of the difference between the delivered (F_D), the inspired (F_I) and the end-expired (F_{ET}) concentration (or fraction) of the inhaled anesthetic agent (F_DAA, F_IAA and F_{ET}AA, respectively).

The delivered concentration is what you dial on the vaporizer. Note that the principles outlined here for the anesthetic agent also apply to O_2 (F_DO_2, F_IO_2 and $F_{ET}O_2$, respectively). For O_2, the F_DO_2 refers to the delivered O_2 concentration on the carrier gas flow meters or automated gas mixer.

The difference between the inspired and the end-expired concentration (F_IAA - F_{ET}AA) is caused by uptake by the patient. Because uptake decreases over time, this difference will decrease over time. For O_2 this difference is more or less constant because O_2 consumption is more stable.

The difference between the delivered and inspired concentration, (F_DAA - F_IAA) or (F_DO_2 - F_IO_2), depends on the fraction of rebreathing (see next topic).

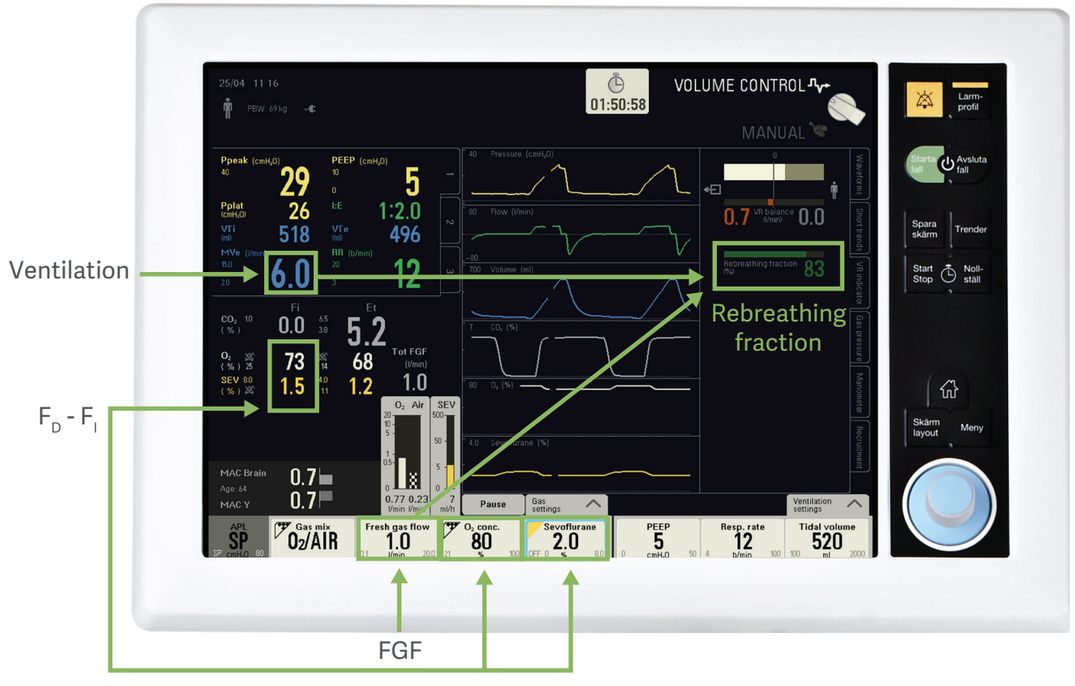
Ventilation

Low-flow anesthesia

The ReBreathing Fraction (RBF)

To maintain normocapnia, a certain minute ventilation is required. As long as the FGF (i.e., the combined flow of O_2 and air you dial, also called "carrier gas") is higher than minute ventilation, the lungs will be filled with fresh gas only. For example, if minute ventilation is 6 L/min and total fresh gas flow of O_2 and air is 6 L/min or higher, the composition of the inspired mixture will match the delivered one, and the difference between the delivered and inspired concentration, ($F_DAA - F_IAA$) or ($F_DO_2 - F_IO_2$), is zero. But once the fresh gas flow is reduced below minute ventilation, previously exhaled gas will make up for the deficit to ensure adequate ventilation: rebreathing occurs.

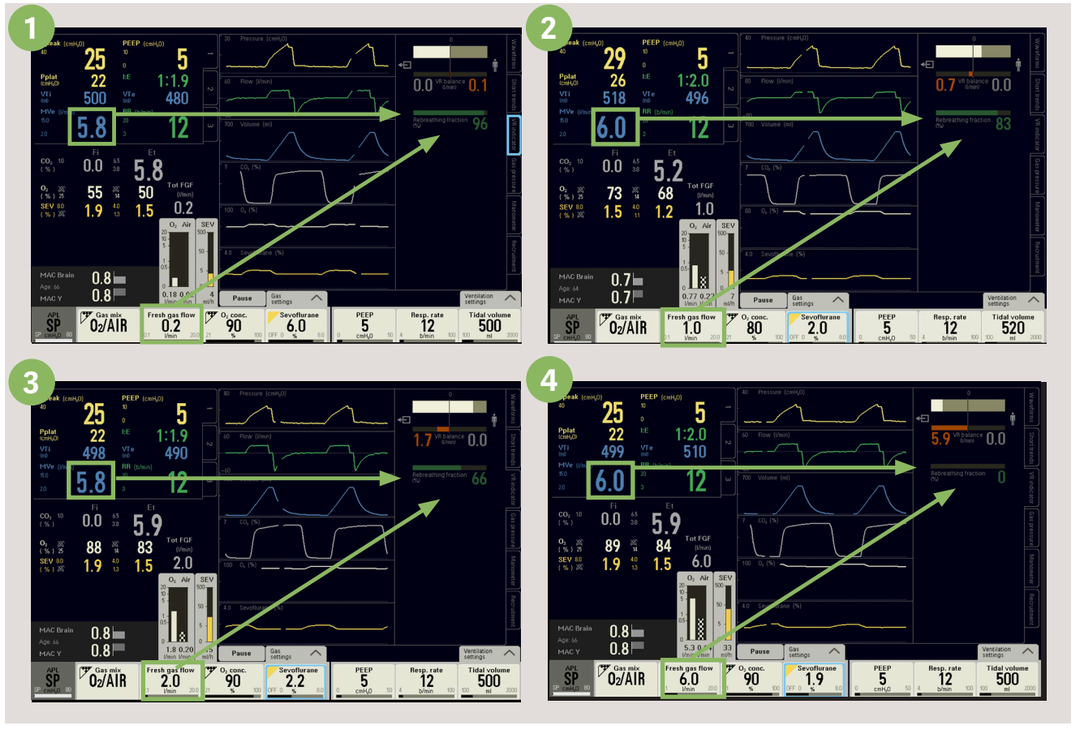
For example, with a FGF of 1 L/min and a minute ventilation of 6 L/min, the fresh gas is 5 L/min short of the 6 L/min minute ventilation, thus 5 L/min exhaled gas will have to be rebreathed. Because this 5 L makes up 5/6 or 83% of the required 6L/min minute ventilation, the RBF is 83%: 100 * (1 - [1 L/min FGF/6 L/min minute ventilation]). This has consequences because the concentration of sevoflurane in the exhaled gas is lower than in the inspired gas due to uptake by the patient. The inspired sevoflurane concentration will become lower than the delivered concentration (dilution effect), resulting in an increased difference between the delivered and inspired concentration.



The image below displays the change of RBF with different FGF. The minute ventilation is approximately 6 L/min. See examples below.

The Rebreathing Fraction (RBF)

1. FGF 0,2 L/min — RBF 96%
2. FGF 1,0 L/min — RBF 83%
3. FGF 2,0 L/min — RBF 66%
4. FGF 6,0 L/min — RBF 0%



Low-flow anesthesia

The Volume Reflector (VR)

From the wall outlets, carrier gases (O_2, air, and N_2O) pass through pressure regulators on entrance of the anesthesia machine. Their flow into the breathing circuit is controlled by gas modules. During spontaneous or assisted ventilation in manual mode, excess gas is vented via the APL valve. The graph depicts the workstation in the inspiratory phase of a mechanical breath, where the green arrows indicate the flow of fresh gas generated by the three gas modules, and the red arrows indicate the flow of rebreathed gas from the volume reflector driven by O_2 from the reflector gas module. During the inspiratory phase, the PEEP/APL valve is excluded from the circle system, the inspiratory valve is open, and the expiratory valve closed.[3]

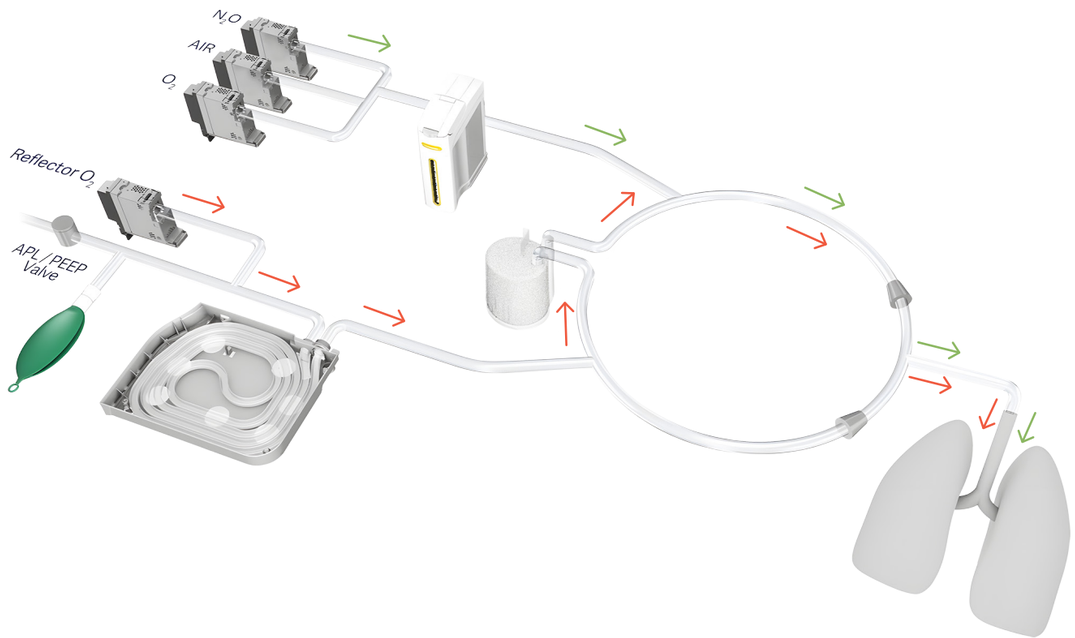
Fresh gas is delivered via three gas modules, one for each gas (O_2, air, N_2O), and vapor is added from a vaporizer by injecting liquid agent into the heated chamber of the vaporizer. Note: it is not directly injected in the circuit. Exhaled gas is temporarily stored in a long piece of tubing called the VR, which directs or "reflects" a volume of exhaled gas back to the circle system. The inspired tidal volume consists of gas from the VR pushed out by the reflector gas module (which uses 100% O_2) and fresh gas from the three fresh gas modules with agent added by the vaporizer. The lower the FGF, the more exhaled gas will be pushed back into the circle system.

If the anesthesia provider dials a FGF that is higher than minute ventilation during any ventilatory controlled mode, the workstation will automatically cap off the FGF at a value equaling minute ventilation because the three carrier gas modules serve both as the FGF source and ventilator. This feature eliminates excessively high FGF. The dialed flow is depicted in the tab at the bottom of the Flow Family unit display, while the actual delivered FGF is displayed in the flow meters depicted above the dialed FGF.

This is not the case in spontaneous manual mode; under these conditions, the delivered FGF does match the dialed FGF.

Gas mixing within the VR is minimal.

The APL/PEEP valve is physically the same valve and electronically controlled.



The Volume Reflector Indicator (VRI)

The VR Indicator is an indicator of the adequacy of "supply and demand" of carrier gas.

In the upper part, a white bar moves to the right during inspiration ("person" symbol) and to the left during expiration (symbol "exhaust"). The position at end-expiration relative to the vertical black line in the middle gives an indication of waste: if the white bar stops at the line, there is full rebreathing, and if it stops all the way to the left, there is no rebreathing.

The numbers in the second bar "VR balance" indicate how much of the minute ventilation (L/min) is leaving via the pop-off valve, which equals the FGF minus the sum of uptake and any leaks. As long as this balance is positive (i.e., gas is wasted via the pop-off valve), the VR balance (displayed in red) ends to the left of the vertical bar. Once the FGF becomes lower than the sum of uptake and any leaks, O_2 is added from the second O_2 gas module (reflector gas module). The VR balance under these conditions is "negative": the VR balance (still displayed in red) ends to the right of the vertical bar. This display can be used to help the clinician guide FGF management during low-flow.

The lower bar indicates the fraction of rebreathing (also see RBF section) which is the part of minute ventilation made up of rebreathed gas (formula RBF = 100*(MV-FGF)/MV relative to total minute ventilation.

Low-flow anesthesia

3. Titrating inhaled agents

Besides reducing FGFs, other steps can be taken to minimize the impact of inhaled anesthetics.

Agent selection

The choice of anesthetic gas and reduction of fresh gas flow rates are important measures to mitigate environmental impact. According to the Intergovernmental Panel on Climate Change, IPCC's report from 2021, desflurane has a significantly higher climate impact than sevoflurane. Compared to sevoflurane, desflurane's GWP20 is 10 times higher, and its climate impact per hour at comparable doses and flow rates is 25-26 times higher.[4]

End-expired concentration (F_{ET}) versus fMAC

The end-expired concentration required to attain a certain fMAC (fraction of the MAC) is age dependent.[5] It is therefore important to enter the patients age in the Flow Family device. It will calculate the age corrected MAC, ensuring you do not overdose or underdose the patient while at the same time attenuating environmental impact.

0.7 fMAC [+/- muscle relaxants], drug interactions

The lower the fMAC, the less agent will be used and wasted. 0.7 fMAC (1.5% end-expired sevoflurane in a 40-year-old patient) suffices to ensure unconsciousness.[6] For most patients, 0.7 fMAC also suffices to ensure immobility without muscle relaxants with a 90% probability if opioids are properly as well as adequate autonomic suppression on most patients. While it is up to the anesthesia provider to adjust dosing in the individual patient, the use of the fMAC concept combined with proper opioid dosing (and muscle relaxants, if required) provides a powerful additional tool to help reduce agent overdosing and thus cost and waste.

See figure 1 below.

Target 0.7 MAC (40 year old patient)

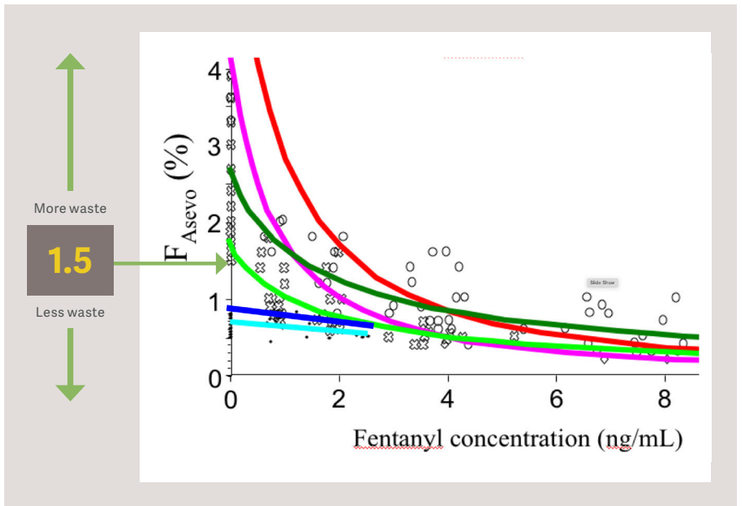


Figure 1 (image modified)

Hendrickx JFA, De Wolf AM, Van Zundert AAJ. Inhalational anesthetics. In: Oxford Textbook of Anaesthesia. Edited by Jonathan G Hardman, Philip M Hopkins, and Michel M.R.F Struys. *Oxford University Press*, Published June 2017 Fig. 14.9 Copyright © Jan Hendrickx and Andre De Wolf 2015.

Wash-in hysteresis

The manner in which an inhaled anesthetic is washed in is important when it comes to minimizing waste. For example, with a sevoflurane vaporizer dial setting (F_D) of 4% and a FGF of 8 L/min for three min, 960 mL vapor or 5.3 mL liquid is used. This is the same (or more) as the total amount needed for wash-in and maintenance during target control delivery with the Flow Family device at 1.5% end-expired sevoflurane for 1 hour.

A golden rule is to never administer inhaled agents before the airway is secured with a laryngeal mask or endotracheal tube. Use propofol to deepen anesthesia if needed prior to securing the airway.

After securing the airway, there is no need to rapidly go to a high end-expired concentration because:

- This requires a combination of high fresh gas flows and high vaporizer settings which is extremely wasteful;
- The serum concentrations of propofol and opioid are still so high that a rapid wash-in would lead to overdosing (resulting e.g. in postinduction hypotension); and
- The patient rarely needs more than 0.7 fMAC anyhow.

Monitoring the wash-in process: MAC Brain, processed EEG, predictive display (AGC only).

We routinely measure the end-expired agent concentration, which is then converted into an age corrected fMAC value. fMAC is a reflection of how likely it is that the patient is unresponsive to verbal command. For example, at an end-expired agent concentration of 0.7 fMAC unconsciousness is virtually assured. But this is only the case when the fMAC in the end-expired gas and the central nervous system are the same ("in equilibrium"), typically during maintenance phase. After a change in delivered concentration (as is the case during wash-in and wash-out), the concentration in the brain will lag behind that in the end-expired gas due to the transport delay between the lungs and the brain. This delay is called hysteresis. This renders fMAC less useful whenever the end-expired gas is changed rapidly because it will tend to overestimate the MAC in the central nervous system (=MAC Brain) during wash-in and the fMAC will underestimate MAC Brain during (fast) wash-out. Fortunately, this delay can be taken into account based on well-known physiological parameters, allowing MAC Brain to be derived from the fMAC calculated from the end-expired concentration. On the Flow Family workstation display, fMAC derived from end-expired gas sampled from the Y-piece is labeled "MAC Y", and the hysteresis corrected fMAC as MAC Brain.

The hysteresis concept is illustrated in figure 2, see below. Part A displays the MAC-Y (dark blue) and MAC Brain (light blue) during wash-in (t1) and wash out (t2); in both instances the MAC Brain trails the MAC Y. The same MAC Y values during wash-in and wash-out do not reflect the same MAC Brain, and thus represent not the same likelihood of unconsciousness (compare part B and C). The clinically relevant value is MAC Brain.[6]

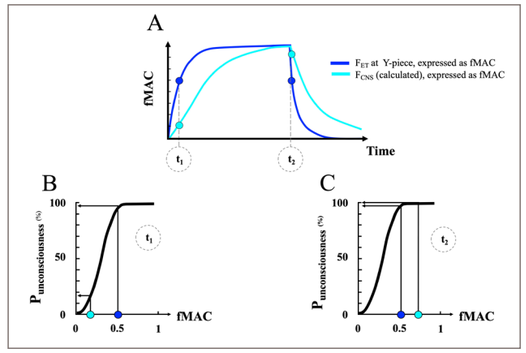


Figure 2

6. Hendrickx JFA, De Wolf AM. End-tidal anesthetic concentration: monitoring, interpretation, and clinical application. Clinical Focus Review. *Anesthesiology*. 2022;136:985-996

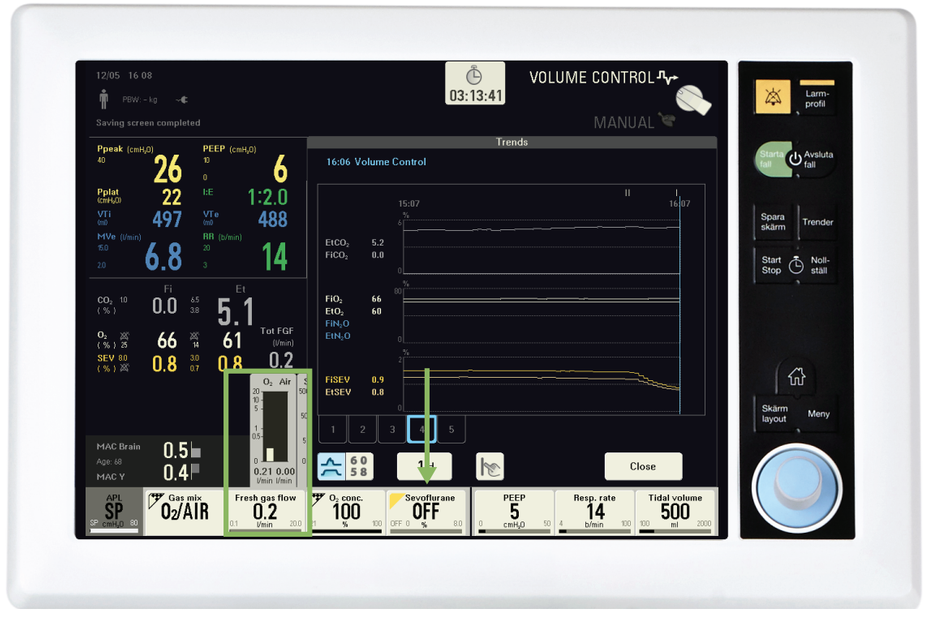
Low-flow anesthesia

By allowing the end-expired agent to rise slowly, we can reduce waste because it obviates the need for high FGFs combined with high vaporizer settings. Instead, agent is washed in slowly with the combination of a low fresh gas flow and a high (up to maximum) vaporizer dial setting (during manual control of the vaporizer) or by using the speed feature (when using AGC, the user can choose one out of 8 wash-in speeds). MAC Brain then becomes useful in two ways. First, MAC Brain does not have to exceed 0.7 because 0.7 fMAC suffices to ensure unconscious, especially while waiting for surgical incision. Second, there is no need to reach 0.7 fMAC Brain rapidly because the intravenous propofol and opioid concentrations are still high. On the other hand, MAC Brain is also useful to ensure wash-in to 0.7 fMAC is not too slow, especially when using muscle relaxants. To monitor crossover from IV to inhaled agent induced unconsciousness, processed EEG may also be useful. Finally, the predictive display of the end-expired agent concentration (displayed during AGC) can also help guide agent wash-in, but because it does not take hysteresis into account, it is best used in combination with fMAC Brain.

Fast versus slow alveolar wash-out (coasting)

Coasting in Manual Gas Control (MGC)
As surgery proceeds, more and more anesthetic agent will be stored in the tissues. The longer the case, the more tissues will be filled up with anesthetic agent. The amount of agent stored in the tissues can be used to maintain anesthesia for a while if FGF is kept low after stopping the delivery of agents. This technique is called coasting and helps save some additional agent at the end of the case. The longer the procedure prior to stopping delivery, the higher the end-expired agent concentration used during maintenance, and the lower the FGF used after switching off agent delivery, the longer coasting will be possible, i.e. the longer the end-expired agent will remain at clinically useful concentrations.

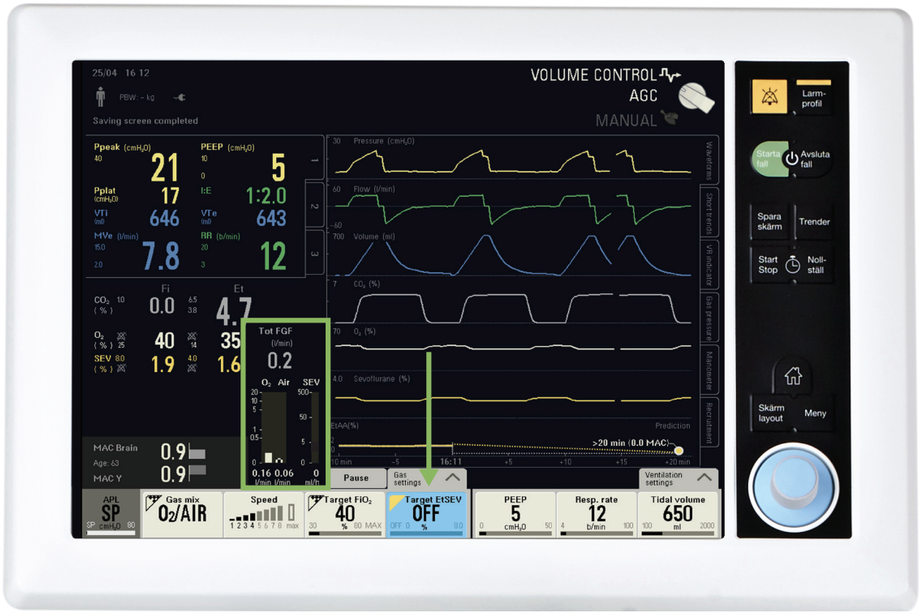
During manually controlled low-flow, coasting is started by switching the vaporizer off while maintaining low FGFs.



Low-flow anesthesia

Coasting in Automatic Gas Control (AGC)
During AGC, the target is set in the "OFF" position, which instructs the Flow Family device to stop agent delivery but to continue the use of low-flow (as long as the Target FiO_2 remains unchanged). Tools that can be used to guide this process are the MAC Brain and the predictive display of the end-expired agent during AGC. A MAC Brain of 0.7 fMAC continues to ensure unconsciousness, and the opioids given for postoperative pain management will help prevent patient movement.

When surgical closure starts, MAC Brain may be allowed to decrease to 0.5 fMAC, especially in the non-paralyzed patient. Once full surgical closure is imminent, agent can be washed out fast by increasing FGF during manual low-flow or by setting the target F_{ET} sevoflurane to 0%, which will prompt the workstation to increase its FGF. MAC Brain is useful to predict imminent wake up.



4. Replacing CO_2 absorbers

The only parameter that should prompt canister replacement is the inspired CO_2 concentration. The inspired CO_2 concentration should be allowed to increase to 0.5% or 4 mmHg. This value ensures optimal CO_2 absorbent use without affecting CO_2 homeostasis to any clinically significant extent. The resulting 0.5% or 4 mmHg increase in the end-expired CO_2 concentration is clinically acceptable in almost all patients.[7]

5. The special case of N_2O

The same principles that apply to O_2/air mixtures and to the use of sevoflurane in O_2/air apply when O_2/N_2O is used. A few issues deserve special attention. First, one has to use a brief period of high FGF (FGF ≥ minute ventilation) to wash-in N_2O because the circuit needs to be washed in and because there is a short-lived high uptake period of N_2O. This short 3-4 min high period also serves to remove nitrogen. Thereafter, FGF can be reduced to 1 L/min. Note that during AGC the decreasing FGF pattern used by the algorithm serves the same function (initial short-lived high FGF period to speed up wash-in and eliminate nitrogen).

Nitrogen will still accumulate slowly, and more so as FGF is lowered. This will be noticed by a decrease in end-expired O_2 and N_2O values. This can be tolerated — the small decrease in total MAC (the sum of sevoflurane and N_2O MAC) can easily be compensated by a small increase in the end-expired sevoflurane concentration. Alternatively, the circuit can be briefly flushed with a high FGF. This may also be warranted if the O_2 concentration has drifted down too much.

Second, during coasting, N_2O can be continued while sevoflurane administration is already discontinued. This will help to speed up initial recovery. When it is time to start washing out N_2O, do use a short period of a high FGF with high O_2 concentrations prior to emergence to avoid diffusion hypoxia due to the large amounts of N_2O coming back from the tissues. Do note that the use of N_2O will influence the total climate impact of the anesthetic because N_2O has a global warming potential (GWP20) of 264 and an atmospheric lifetime of about 120 years.[4]

6. Personal feedback

The Flow Family devices display the instantaneous use of the liquid agent during the case and cumulative agent use at the end of the case. This allows the individual practitioner to track their own agent use and monitor their own low-flow anesthesia learning curve.

Low-flow anesthesia

7. Summary

Low-flow anesthesia reduces the environmental impact of inhaled anesthetics. Understanding the effects of lowering FGF on the difference between the dialed and inspired agent concentration empowers the clinician to use lower FGF. It also provides the rationale for the further development and use of target controlled low-flow delivery. To maximally reduce agent use with automated target controlled low-flow delivery systems, one further has to consider the factors affecting target selection (patient age, opioid use) and hysteresis (slow wash-in, slow wash-out). The combined use of these factors will have a pronounced effect on agent use and waste. Lowering FGF is the most important action, but only one part of a larger puzzle to reduce the environmental impact of inhaled anesthetic agents.[8] These concepts are outlined in this manual.

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Authors

Author: Jan Hendrickx, M.D., Ph.D. Staff anesthesiologist, A-zorg Hospital, Aalst, Belgium
Professor, Dpt. of Basic and Applied Medical Sciences, Ghent University, Ghent, Belgium
Professor, Dpt. of Anesthesiology, UZLeuven & Cardiovascular Sciences, KULeuven, Louvain, Belgium

Co Author: Andre De Wolf, M.D. Professor Emeritus of Anesthesiology & Surgery
Feinberg School of Medicine, Northwestern University, Chicago, IL, USA

Content consultant: Patrik Norell, Global Clinical Marketing Manager, Getinge, Solna, Sweden

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Legal Manufacturer · Maquet Critical Care AB · Röntgenvägen 2 SE-171 54 Solna · Sweden · +46 (0)10 335 73 00

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