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ORIGINAL RESEARCH

Automated gas control with the Maquet FLOW-i

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Abstract The FLOW-i anesthesia machine (Maquet, Solna, Sweden) can be equipped with automated gas control (AGC), an automated low flow tool with target control of the inspired oxygen concentration (F_IO_2) and end-expired concentration (F_A) of a potent inhaled anesthetic. We examined the performance and quantitative aspects of the AGC. After IRB approval and individual informed consent, anesthesia in 24 ASA I–II patients undergoing abdominal or gynecological surgery was maintained with sevoflurane in O_2/air with a target F_IO_2 of 40 % and a target sevoflurane F_A ($F_A$sevo) of 2.0 %. The AGC tool also allows the user to select 1 out of 9 different speeds with which the target $F_A$sevo can be reached (with 9 being the fastest speed). Eight patients each were randomly assigned to speed 2, 4, and 6 (= group 2, group 4, and group 6, respectively); these three speeds were chosen arbitrarily. AGC was activated immediately after securing the airway, which defined the start of the study, and the study ended 60 min later. The following parameters were compared among the three groups: age, height, weight, F_IO_2, $F_A$sevo, BIS values, heart rate, mean arterial blood pressure, fresh gas flow, and sevoflurane usage. Agent usage as reported by the FLOW-i was compared among the three groups. Patient demographics and maintenance FGF did not differ among groups. A very short-lived very high FGF ($\approx$20 L min^{-1} for 8–12 s) ensured that the target F_IO_2 was attained within 1–2 min in all patients. $F_A$sevo was 1.8 % after 15, 10, and 6 min, and 1.9 % after 30, 20 and 15 min in groups 2, 4, and 6, respectively. Blood pressure, heart rate, and BIS values did not differ among the three groups. BIS values remained acceptable in all patients, even with the slowest speed. Cumulative agent usage differed among all three groups between 2 and 30 min (lower with the lower speed), and between group 2 and 6 between 35 and 60 min. AGC combines an exponentially decreasing FGF pattern with a choice of ramp functions for the end-expired target concentration of the inhaled anesthetic. Consequently, both FGF *and* the choice of speed become factors that influence agent usage. After 15 min, a 300 mL min^{-1} maintenance FGF reduces agent usage to near closed-circuit conditions. This new addition to our automated low flow armamentarium helps to reduce anesthetic waste, cost, and pollution, while minimizing the ergonomic burden of low flow anesthesia.

Keywords Target control · Automated low flow · Closed loop · Equipment · Anesthesia machine

1 Background

While the use of low fresh gas flows (FGFs) with a circle breathing system decreases anesthetic waste and thus costs and pollution, most anesthesia providers intuitively use a 1.5–2 L min^{-1} FGF [1]. The routine use of FGF well below 1 L min^{-1} is avoided for a variety of reasons. First, rebreathing will cause the concentration inhaled by the patient to differ from that dialed by the anesthesia provider, which may be perceived as lack of control: the dialed concentration of O_2, N_2, N_2O and/or the inhaled agent will no longer match what the anesthesia provider has

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selected [2]. Second, more frequent vaporizer and rotameter adjustments are needed, and these can be tedious or distracting, especially during the busy induction phase. Third, vaporizer dial setting variability increases, making it more difficult to predict the vaporizer setting required for the individual patient. Automated target control allows the user to directly target the end-expired partial pressure (F_A) of the anesthetic agent. This will eliminate the above mentioned disadvantages associated with the use of low FGFs, and it will help reduce the incidence of under-dosing: in a large prospective study designed to maintain MAC above 0.7 MAC, anesthesia providers failed to do so in more than 15 % of the time when they were controlling FGF and vaporizer settings themselves [3]. Automated target control helps the clinician to use low flows more consistently [4, 5].

Even more important, directly targeting the inspired oxygen concentration (F_IO_2) will make low flow safer by preventing inspired hypoxic mixture formation [6, 7]. During conventional, non-automated low flow with O_2/N_2O or O_2/air mixtures, inspired hypoxic mixtures can form during despite the presence of a hypoxic guard system [6, 7].

The Zeus (Dräger, Lübeck, Germany) and the Aisys (GE, Madison, WI) offer target controlled automated closed circuit and minimal flow anesthesia, respectively. Recently, the FLOW-i® (Maquet, Solna, Sweden) has also been equipped with a target controlled automated low flow anesthesia feature, called AGC® (automated gas control). The aim of this study was to examine the clinical performance of the first released AGC software version (4.0.0).

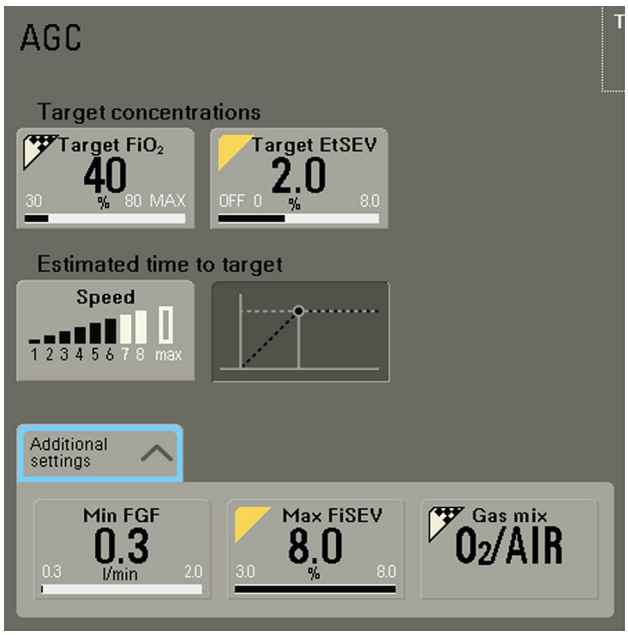

Fig. 1 AGC (automated gas control) settings. The AGC tool allows the user to select the target inspired O_2 concentration (target F_IO_2) and target end-expired agent concentration (target EtSEV) as well as the rate of rise (speed) of the end-expired sevoflurane concentration towards target EtSEV. The speed pertains only to the rate of rise of the end-expired agent concentration, NOT to the F_IO_2 (which always takes priority). Speed ranges from 1 to 8 up to "max", the latter being the fastest rate of rise. In the "additional settings" tab, and from left to right, the lowest acceptable maintenance fresh gas flow, the maximum inspired agent concentration, and carrier gas composition can be selected. At the time of writing, 0.3 L min^{-1} is the default fresh gas setting as well as the lowest maintenance fresh gas flow that can be selected

2 Materials and methods

After obtaining IRB approval and informed consent from all individual participants (OLV study number 2013/058, Belgian Registration number B126201317885), 24 ASA I–II patients were enrolled. Patients were undergoing abdominal or gynecological surgery that was expected to last at least 1 h. Premedication consisted of oral alprazolam (0.5 mg) 1 h prior to surgery. In addition to routine monitors, BIS monitoring (Covidien, Dublin, Ireland) was used to help assess the impact of the rate of rise of the end-expired sevoflurane concentration on the hypnotic component of anesthesia (see below).

With the machine still in standby mode, the agent (sevoflurane) and the AGC parameters were "preselected" (= entered before activating any carrier gas flow) (Fig. 1): carrier gas = O_2/air; FGF = 300 mL min^{-1} (= maintenance FGF, with the current default and lowest possible FGF being 300 mL min^{-1}); and target F_IO_2 = 40 %, target F_A sevoflurane ($F_A$sevo) = 2.0 %. The AGC tool also allows the user to select 1 out of 9 different speeds with which the target $F_A$sevo can be reached (1 = slowest, 9 = fastest). Out of a choice of 9 different speeds, we arbitrarily decided to study the effects of using speeds 2, 4, or 6. Using Excel's random function, eight patients were randomly assigned to speed 2, 4 or 6 (= group 2, group 4, and group 6, respectively). After closing the AGC pop-up screen, the "start case" knob was activated, causing the FLOW-i to deliver 6 L min^{-1} of 80 % O_2 in air, facilitating preoxygenation of the patient. After anesthesia had been induced with intravenous sufentanil (0.1–0.15 μg/kg) and propofol (2–3 mg/kg), the trachea was intubated, facilitated with rocuronium (0.6 mg/kg).

After securing the airway (confirmed by the presence of end-expired CO_2), mechanical ventilation was activated by twisting a knob that simultaneously activated AGC. This defined the start of the study. Additional sufentanil and rocuronium were administered as deemed necessary by the attending anesthesiologist. Controlled mechanical ventilation was adjusted to maintain normocapnia. Data collection ended 60 min after activating the AGC mode.

Besides patient demographic data (age, height, weight and gender), the following data were collected every minute: F_IO_2, $F_A$sevo, BIS values, heart rate, (noninvasive) mean arterial blood pressure, FGF, and sevoflurane usage reported by the FLOW-i. The amount of sevoflurane usage reported by the cumulative agent display of the FLOW-i was previously found to closely reflect the amount that had disappeared from the injector as measured by weighing the injector before and after use [8]. ANOVA followed by the Holm–Sidak test was used to compare all data among the three groups, with $p < 0.05$ denoting statistical significance.

3 Results

Patient demographics did not differ among groups (Table 1). The FGFs were the same in all three groups (Fig. 2). A very short-lived very high FGF ($\approx$20 L min^{-1}) for 8–12 s (Fig. 2) ensured the target F_IO_2 was attained within 1–2 min in all groups (Fig. 3). After 2 min, the F_IO_2, presented as average (SD), were 40 (1), 40 (1), and 41 (1) % with speed 2, 4, and 6, respectively. $F_A$sevo was 1.8 % after 15, 10, and 6 min and 1.9 % after 30, 20 and 15 min in groups 2, 4, and 6, respectively (Fig. 4). Blood pressure and heart rate did not differ among groups (Fig. 5a, b). BIS values did not differ among the three groups, and remained acceptable in all patients: the highest BIS value (63) was found in a patient from the slowest speed (group 2), and lasted only 1 min (Fig. 6a, b, c).

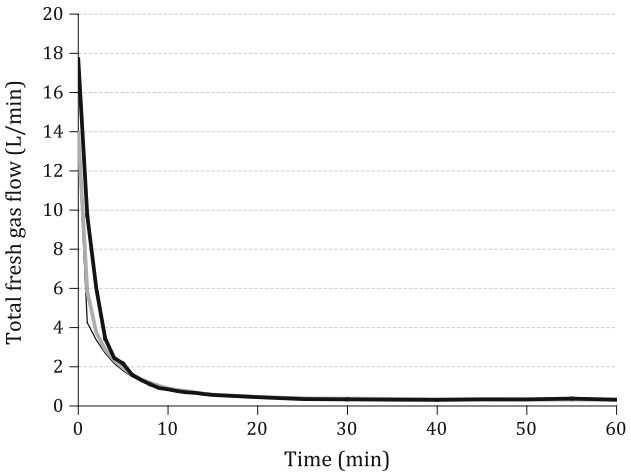

Fig. 2 Fresh gas flow (FGF) course. The FGFs were the same in all three groups. For clarity, only the average FGF is presented. *Thin line* speed 2; *thick grey line* speed 4; *thick black line* speed 6. Standard deviations have been omitted for clarity

Cumulative agents usage differed among all three groups between 2 and 30 min (lower with the lower speed), and between groups 2 and 6 between 35 and 60 min (Table 1; Fig. 7). The use of speed 2 instead of speed 6 reduces cumulative agent usage by 45 % (from 4 to 2.2 mL) after 10 min, and by 35 % (from 4.9 to 3.2 mL) after 15 min (Table 1). Cumulative agent usage during the last 45 min (when FGF was reduced to 300 mL min^{-1}) did not differ among the three groups (Fig. 7).

Table 1 Demographics and cumulative agent usage

	Speed			Statistical analysis	
	Speed 2	Speed 4	Speed 6	*p* value	Between group differences
Patient demographics					
n	8	8	8		
Female/male	5/3	4/4	6/2		
Age (year)	66 (7)	62 (14)	60 (9)	0.506	
Height (cm)	167 (8)	170 (10)	165 (5)	0.528	
Weight (kg)	70 (13)	71 (14)	75 (16)	0.744	
Cumulative liquid sevoflurane (mL)					
Time (min)					
5′	1.1 (0.1)	1.7 (0.2)	2.5 (0.2)	<0.001	All groups differ
10′	2.2 (0.2)	3.2 (0.3)	4 (0.4)	<0.001	All groups differ
15′	3.2 (0.3)	4 (0.4)	4.9 (0.5)	<0.001	All groups differ
30′	5.0 (0.5)	6.1 (0.8)	7.0 (0.9)	<0.001	All groups differ
35′	5.6 (0.5)	6.7 (1.0)	7.5 (1.2)	<0.002	Speed 2 and 6 differ
60′	8.1 (1.0)	9.2 (1.4)	10.5 (1.4)	<0.008	Speed 2 and 6 differ
15′–60′	5 (0.9)	5.2 (1.1)	5.6 (1)	0.476	

Patient demographics did not differ between groups. Up until 30 min cumulative sevoflurane usage (mL liquid agent) differed between all groups; after 35 min, for the remainder of the study, it only differed between speeds 2 and 6

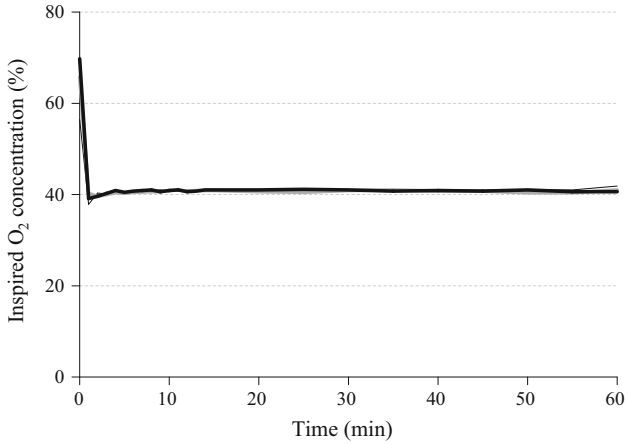

Fig. 3 Course of the inspired O_2 concentration (F_IO_2). The target F_IO_2 was attained within 1–2 min in all groups, and did not differ between the groups. *Thin line* speed 2; *thick grey line* speed 4; *thick black line* speed 6. Standard deviations have been omitted for clarity

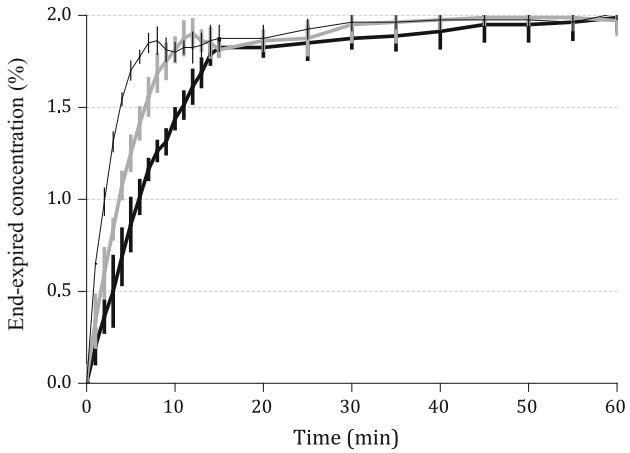

Fig. 4 Course of the end-expired sevoflurane concentration. $F_A$sevo was 1.8 % after 15, 10, and 6 min and 1.9 % after 30, 20 and 15 min in groups 2, 4, and 6, respectively. *Thin line* speed 2; *thick grey line* speed 4; *thick black line* speed 6. *Bars* represents standard deviations

4 Discussion

The AGC feature of the FLOW-i allows the user to select a target F_IO_2 as well as a target F_A and the ramp speed of the inhaled agent. The speed feature does not apply to F_IO_2: the target F_IO_2 is attained within 1–2 min by the use of a very short lived (about 10 s) very high FGF ($\approx$20 L min^{-1}).

Next, the FGF is exponentially reduced from 20 to 0.3 L min^{-1} over the course of 15 min. The rate of rise and predicted time to target of the anesthetic agent can be followed on the monitor screen, and is continually updated during wash-in (Fig. 8). The fresh gas controller acts, at present and by design, the same irrespective of the selected speed. But despite FGF being the same in all groups, agent usage is lower when a slower speed is used: the use of speed 2 instead of speed 6 reduces cumulative agent usage by 45 % (from 4 to 2.2 mL) after 10 min, and by 35 % (from 4.9 to 3.2 mL) after 15 min. These differences are due solely to the difference in injection rate of liquid agent.

After 15 min, FGF is decreased to the default (and currently lowest) maintenance FGF of 0.3 L min^{-1} (it is possible to select a higher default maintenance FGF if desired so). As a result, cumulative agent usage during the *last* 45 min of the study period did not differ among the three groups. Therefore, any differences in cumulative agent usage at 60 min were caused by differences in agent delivery during the first 15 min. These findings corroborate our earlier findings that the manner in which anesthetic agent target concentration is reached during initial wash-in has a pronounced effect on cumulative agent usage at the end of a procedure [9]. The 0.3 L min^{-1} maintenance FGF is 100–120 mL min^{-1} above O_2 uptake by the adult patient [10]. Reducing FGF by another 100 mL min^{-1} would have reduced sevoflurane agent usage by 0.66 mL liquid sevoflurane per hour (calculated assuming the waste gas would contain 2 % sevoflurane). It has to be noted that

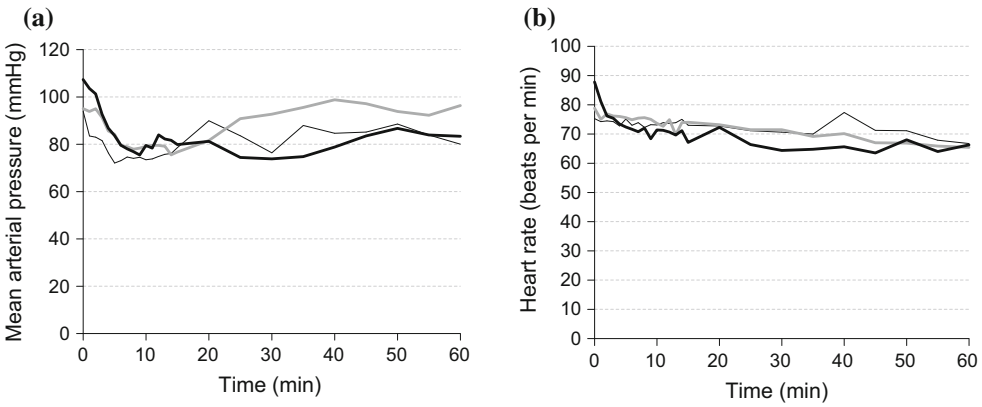

Fig. 5 Mean arterial blood pressure (*left*, **a**) and heart rate (*right*, **b**). For clarity, only the average FGF is presented. Blood pressure and heart rate did not differ between groups. *Thin line* speed 2; *thick grey line* speed 4; *thick black line* speed 6. Standard deviations have been omitted for clarity

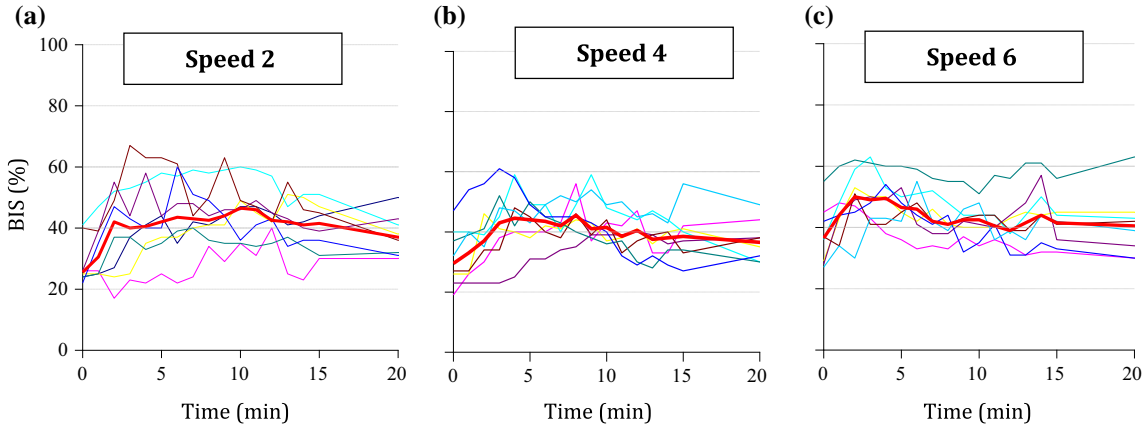

Fig. 6 BIS values. BIS values did not differ between the three groups. *Thick red line* median, *thin colored lines* values of individual patients

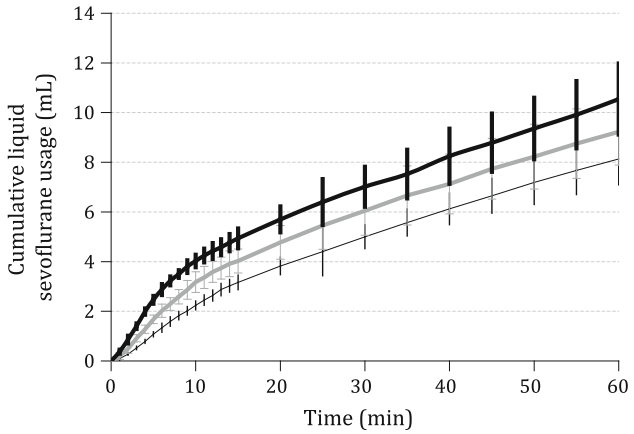

Fig. 7 Cumulative sevoflurane usage (mL liquid sevoflurane). Cumulative sevoflurane usage differed between all groups up until 30 min, and between speeds 2 and 6 up for the entire length of the study. Results are presented as average and standard deviation. *Thin line* speed 2; *thick grey line* speed 4; *thick black line* speed 6. *Bars* represents standard deviations

under the conditions of this study, no target F_IO_2 changes were made, which would have prompted the AGC to temporarily increase FGF again.

The automated low flow system decreases the FGF exponentially and rapidly over 15 min to attain the maintenance 300 mL min^{-1} FGF. Because it is the combination of FGF control and the ability to control the rate of rise and thus the injection rate that determines the system's behavior, "automated gas control" seems indeed the proper name to describe the target control algorithms.

How fast should the F_A of the anesthetic agent rise after intravenous agents have been administered to induce anesthesia [11]? Several factors need to be taken into account. First, the residual and waning effects of the intravenous induction agents (propofol, opioids) need to be taken in consideration, as well as the drug interactions between all these drugs [12, 13]. Second, the rate of rise has to be titrated not only towards the physiological reserve of the patient but also towards the anticipated time of incision. In the absence of a noxious stimulus, how slow can the F_A of the anesthetic agent be allowed to rise without risking awareness? The BIS data suggest that the hypnotic component of anesthesia remained adequate even with the lowest speed, but these results need to be confirmed in a larger patient population. On the other hand, if the agent concentration rises too fast, hypotension may ensue. Being able to (pre)select and adjust the rate of rise may help optimize anesthetic depth during the interval between securing the airway and surgical incision, but requires further clinical validation.

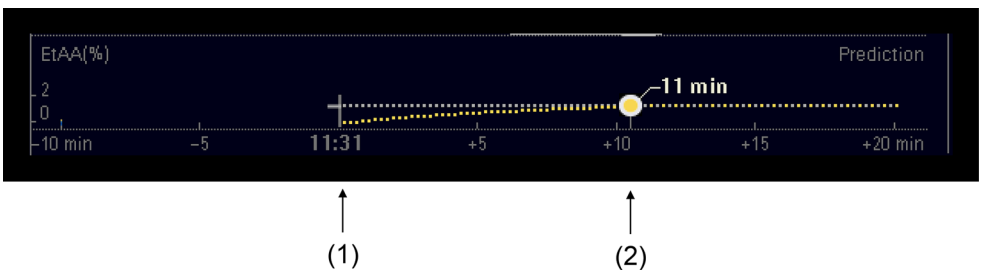

Fig. 8 Prediction tool. The prediction tool displays the past, current and predicted course of the end-expired sevoflurane concentration. EtAA (%) = end-expired agent concentration; (*1*) present time; (2) time when target EtAA is expected to be attained, marked by *yellow circle dot*

By reducing the number of interventions the anesthesia provider has to make, automated low flow machines make low flow more ergonomic [5]. Because the AGC allows the user to preselect anesthetic agent targets before inducing anesthesia, and because the same knob activates both the desired ventilation mode and AGC, a single twist of one knob may reduce the number of adjustments during the busy induction period to just one.

To summarize, the FLOW-i's AGC rapidly achieves the desired F_IO_2, and it combines an exponentially decreasing FGF pattern with a choice of ramp functions for the end-expired target concentration of the inhaled anesthetic during wash-in. The choice of ramp function has an effect on overall cumulative agent usage. The default 300 mL min^{-1} FGF reduces agent usage to near closed-circuit conditions during maintenance.

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Conflict of interest The authors declare that they have no conflict of interest.

Ethical standard The study has been approved by the IRB of the OLV hospital, Aalst, Belgium, part of OLV study number 2013/058, Belgian Registration number B126201317885.

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