CASE STUDY

Sevoflurane consumption in manual vs automatic modes

AGC technology permits safe and convenient reduction of anesthetic waste by up to 58%

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Anesthesia | Automatic Gas Control

Sevoflurane consumption in manual vs automatic modes

Minimizing sevoflurane wastage by sensible use of automated gas control technology in the Flow-i workstation: an economic and ecological assessment

Alain F. Kalmar[1,2] · Nicky Van Der Vekens[3] · Fréderic De Rydt[3,5] · Silvie Allaert[3] · Marc Van De Velde[4,5] · Jan Mulier[1,2,6]

Abstract

Both ecological and economic considerations dictate minimising wastage of volatile anesthetics. To reconcile apparent opposing stakes between ecological/ economical concerns and stability of anesthetic delivery, new workstations feature automated software that continually optimizes the Fresh Gas Flow (FGF) to reliably obtain the requested gas mixture with minimal volatile anesthetic waste. The aim of this study is to analyse the kinetics and consumption pattern of different approaches of sevoflurane delivery with the same 2% end-tidal goal in all patients. The consumption patterns of sevoflurane of a Flow-i were retrospectively studied in cases with a target end-tidal sevoflurane concentration (Et_{sevo}) of 2%. For each setting, 25 cases were included in the analysis. In Automatic Gas Control (AGC) V4.4, a speed setting 6 was observed, with software V4.7, speed settings 2 were observed, and a group with a fixed 2 L/min FGF. In 45 min, an average of 14.5 mL was consumed in the 2L-FGF group, 7.1 mL in the $AGC_{4.4}$ group and 6.0 mL in the $AGC_{4.7}$ group. The more recent $AGC_{4.7}$ algorithm was more efficient than the older $AGC_{4.4}$ algorithm.

This study indicates that the AGC technology permits very significant economic and ecological benefits, combined with excellent stability and convenience, over conventional FGF settings and should be favoured. Routine clinical practice using what historically is called "low flow anesthesia" (e.g. 2 L/min FGF) should be abandoned, and all anesthesia machines should be upgraded as soon as possible with automatic delivery technology to minimize atmospheric pollution with volatile anesthetics.

(1) Department of Anesthesiology, Reanimation and Intensive Care, AZ Sint Jan Brugge-Oostende, Brugge, Belgium. (2) Department of Anesthesia, Ghent University, Gent, Belgium. (3) Departmen of Anesthesia and Critical Care Medicine, Maria Middelares Hospital, Gent, Belgium. (4) Department of Cardiovascular Sciences, KULeuven, Leuven, Belgium. (5) Department of Anesthesiology, UZLeuven, Leuven, Belgium. (6) Department of Anesthesiology, KULeuven - University of Leuven, Leuven, Belgium

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Introduction

Volatile anesthetics are widely used hypnotics with desirable pharmacological properties. A major drawback, however, is that these gases are eventually discarded into the atmosphere where they contribute significantly to the greenhouse effect. Global emissions of fluorinated volatile anesthetics in 2014 equaled three million tons of CO_2 [1]. As the climate emergency becomes ever more apparent, threatening to decimate complete ecosystems and triggering vast medical and societal emergencies [2], it is everyone's duty to minimize their personal ecological impact. Given the strong heat-trapping potency of volatile anesthetics, anesthetists have an important responsibility in this regard [3]. Remarkably simple choices made by the anesthetist can reduce the climate impact by orders of magnitude without negatively impacting the quality of care. As far as volatile anesthetics still being desirable, a minimal understanding of their climatic effects dictates that the most important steps should be to choose volatile agent and carrier gas with care, and to make optimal use of modern technology to minimize fresh gas flow [4]. In addition to environmental benefits, reducing the wasteful use of volatile anesthetics can provide significant financial savings.

» all anesthesia machines should be upgraded as soon as possible with automatic delivery technology to minimize atmospheric pollution with volatile anesthetics. «

Resulting from the complexities of the atmospheric physics and chemistry, which is extensively described elsewhere, sevoflurane has a global heating effect which is 349 times worse than CO_2 [3]. Because volatile anesthetics are widely and often con-tinuously used in operating theatres, the total consumption of volatile anesthetics in conventional low-flow settings may easily amount to 40 L of sevoflurane per anesthesia workstation per year. This amounts to a financial cost of well in excess of 16,000€ per year of volatile anesthetics, and a greenhouse gas equivalent of 21 metric tons of CO_2 for sevoflurane [3, 5]. As such, a reduction in volatile anesthetic waste would lead to significant financial savings – easily covering the additional cost of modern equipment – and a huge reduction in atmospheric pollution. As a reference, one roundtrip intercontinental flight Brussels-New York in economy class results in 2 metric tons of CO_2 emissions per person.

While technological innovations, like pulse oximetry and continuous gas analysis have made conventional manual minimal flow anesthesia safe, it still demands expertise and continuous attention [6, 7]. The addition of automated low-flow software finally enables optimized carrier gas flows and volatile agent administration to precisely secure the delivery of the desired gas mixture while effortlessly minimizing waste [8, 9]. The Flow-i anesthesia machine (Getinge, Goteborg, Sweden), for instance, can be supplied with AGC (Automated Gas Control). This permits the anesthetist to set the appropriate speed—on a numeric scale from 1 (slow) to 8 (fast)—to reach the selected end-tidal concentrations of volatile anesthetics. The AGC algorithm gradually reduces the FGF to a minimal rate depending on the patient's oxygen consumption, resulting in environmental and economic advantages. [10, 11] Automated software obviates frequent manual adjustment of the settings during minimal flow anesthesia and optimizes the stability of the administered anesthetics and inspiratory oxygen fraction (F_iO_2) [12]. Except for rare situations, such as carbon monoxide poisoning, there are no contraindications to perform minimal flow anesthesia [6]. In addition, the increased cost due to elevated CO_2 absorbent consumption at minimal flow does not outweigh the volatile anesthetics economised [13]. The current study aims to compare the rate of sevoflurane consumption in conventional low flow anesthesia (2 L/min FGF) and AGC verion 4.7.

Methods

After institutional ethical approval (MMS.2021.004), the data of the digital charting system (ICCA, Philips, Amsterdam, Netherlands) were analysed. These records include all intraoperative data at 15 s interval, in addition to any anesthetic intervention such as provided airway and administered drugs. All Flow-i workstations were equipped with either AGC version 4.4 or version 4.7. The cumulative amount of sevoflurane consumption reported by the Flow-i is automatically recorded with a precision of 0.1 mL.

Data from all cases after 01/10/2019 were evaluated and the first 25 subsequent cases in each of the following groups meeting the inclusion criteria were extracted and analyzed: AGC version 4.4 in speed 6; AGC version 4.7 in speed 2, or a fixed 2 L/min fresh gas flow (2LFGF). In AGC the FGF was automatically reduced to a minimal rate of 300 mL/min. In all cases, an F_iO_2 of 80%, and a target Et_{Sevo} of 2% was pursued. The primary outcome variable of interest was the cumulative consumption of sevoflurane after 45 min.

Data registration and analysis

All anesthetic data were extracted and subsequently imported into Microsoft Excel 2010 (Microsoft, Redmond, USA) for analysis. Assuming a normal distribution of the consumption data, we considered a mean difference of 1 mL after 45 min between AGC and minimal flow to be relevant (estimated SD of 1.1 mL, based on pilot data). To detect this difference with an α-error of 0.05 and a power of 0.95, a total of 25 records was needed in each group [14]. Normality was tested with the Kolmogorov–Smirnov test. Continuous data are expressed as mean (SD). For statistical analysis and visualization, the individual records were synchronized at the moment (T0) after initiation of ventilation that Et_{Sevo} exceeded 0.2%. Recordings with at least 55 min sevoflurane administration were included in the analysis.

For comprehensive comparison of the different groups, the average values were shown in Figs. 1, 2, 3. The rate of sevoflurane consumption at a certain minute (Rm, expressed as mL/hour) was calculated as the increase in cumulative consumption over the coming minute: $Rm = (C(m+1) - Cm)*60$. The average (SD) values of the analysed variables were determined at 5, 15, 30 and 45 min. ANOVA followed by an Unpaired T-test was used to determine differences between groups. Significance was set at $P < 0.05$.

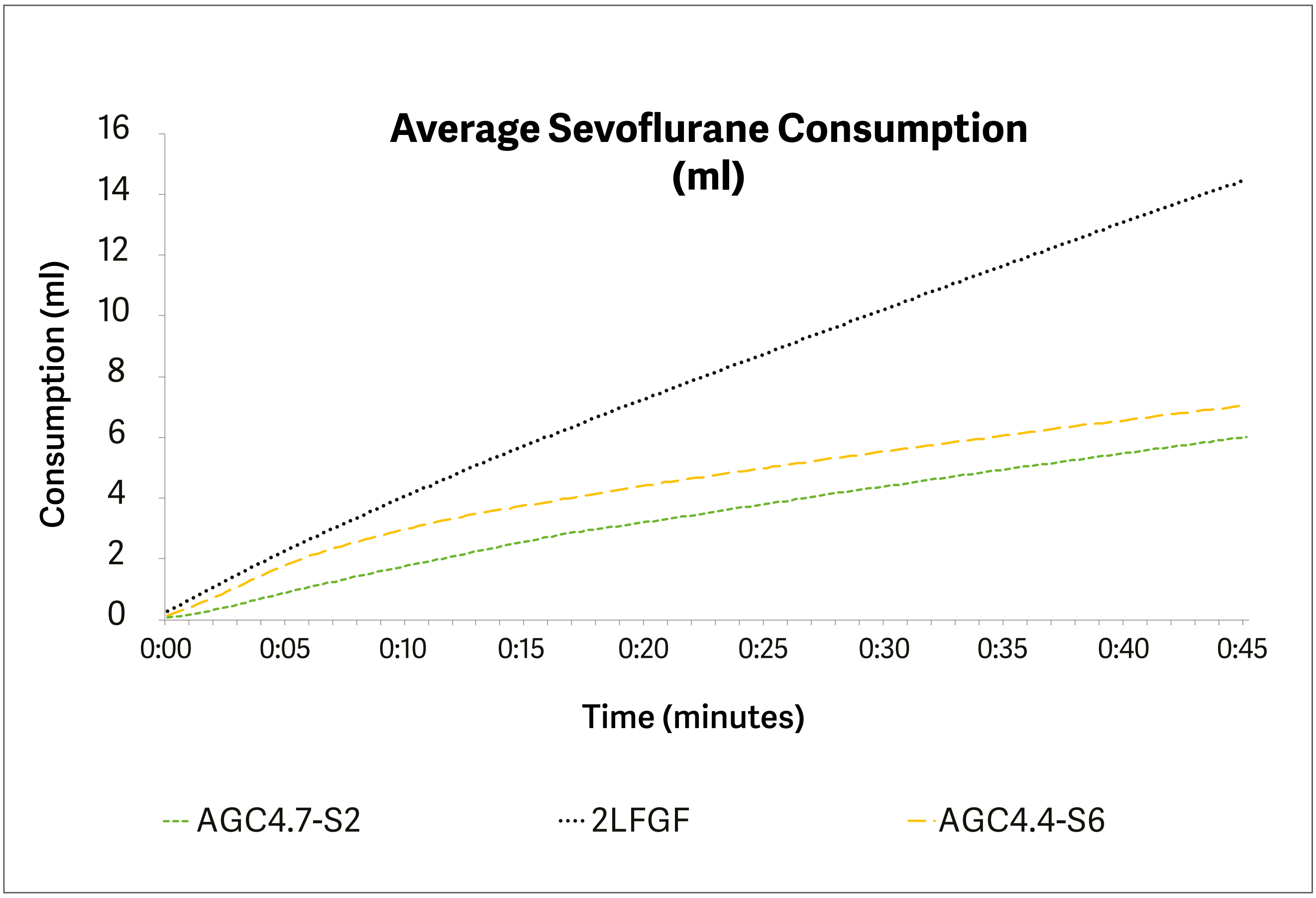

Figure 1: **Average cumulative sevoflurane consumption in different modes of sevoflurane administration in the Flow-i ventilator. AGC speed 6 with the AGC4.4 algorithm, AGC speed 2 with the newer AGC4.7 algorithm, and constant 2 L/min FGF (2L FGF)**

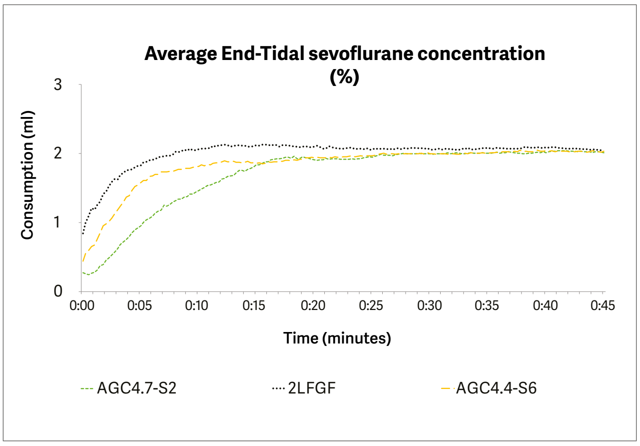

Figure 2: **Average end-tidal sevoflurane concentration in different modes of sevoflurane administration in the Flow-i ventilator. AGC speed 6 with the AGC4.4 algorithm, AGC speed 2 with the newer AGC4.7 algorithm, and constant 2 L/min FGF (2L FGF).**

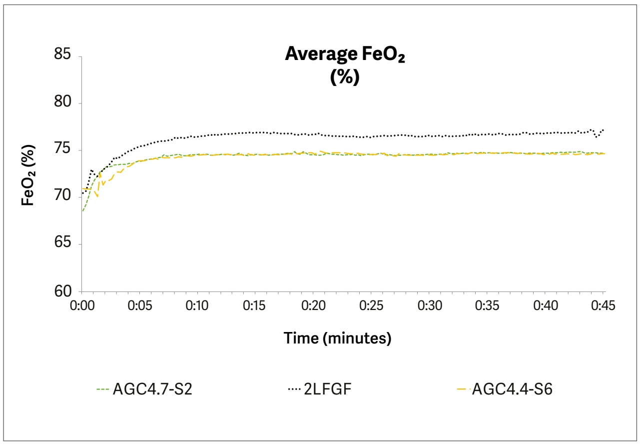

Figure 3: **Average end-tidal O_2 concentration in different modes of sevoflurane administration in the Flow-i ventilator. AGC speed 6 with the AGC4.4 algorithm, AGC speed 2 with the newer AGC4.7 algorithm, and constant 2 L/min FGF (2L FGF).**

Results

Patient characteristics and cumulative consumption of each group at 5, 15, 30 and 45 min are shown in Table 1. Figures 1, 2, and 3 show the cumulative consumption of sevoflurane (mL), the average Et_{sevo} (%) and the expiratory O_2 concentration (%) in each group, respectively. In the 2L-FGF group, the rate of sevoflurane consumption remains high during the entire 45 min, whereas in the AGC groups there is a significant drop after three minutes. In all groups, except the 2L-FGF group, although initial consumption rates vary significantly, after 10 min the rate of consumption becomes comparable. Sevoflurane consumption with the new algorithm – AGC 4.7 – initially had an equal consumption compared to the old algorithm – AGC 4.4 – but thereafter, the newest algorithm spent significantly (P = 0.027) less sevoflurane to maintain its target.

» Cumulative volatile anesthetic consumption – and therefore pollution – can be significantly reduced by using AGC, compared to the traditionally called “low flow” anesthesia. «

Table 1: **Patient characteristics and cumulative consumption:**

	AGC $_{4.7}$ Speed 2	AGC $_{4.4}$ Speed 6	2LFGF	P value
Age	51 (16)	55 (18)	59 (15)	0.444
Weight	80 (22)	82 (21)	72 (12)	0.310
Gender (M/F)	14/11	11/14	14/11	
Cumulative consumption				
At 5 min	0.9 (0.2)*	1.8 (0.4)*	2.3 (0.3)*	< 0.001
At 15 min	2.6 (0.3)*	3.8 (0.9)*	5.8 (0.6)*	< 0.001
At 30 min	4.4 (0.7)	5.5 (1.2)*	10.2 (0.8)*	< 0.001
At 45 min	6.0 (1.2)	7.1 (1.4)*	14.5 (1.2)*	< 0.001

Average(SD) Age, Weight and cumulative sevoflurane consumption, gender distribution (Male/Female) in the different groups. Twenty-five patients were included in each group
*Significant difference between adjacent columns

Discussion

Scientists have a moral obligation to clearly warn humanity of any catastrophic threat. On this basis, supported by overwhelming evidence, Scientific American declared we are living in a climate emergency [15]. As the adverse effects of climate change are much more severe than expected and now threaten both the biosphere and humanity, every effort must be made to reduce emissions of greenhouse gasses. While this call is resonating increasingly loudly, many anesthesiologists are insufficiently aware of the extent to which their daily choices have an impact thereon, and how minimal adjustments in daily practice can dramatically reduce the environmental impact of anesthesia without compromising anesthetic end-tidal concentration corresponding to anesthetic depth.

Following initial clinical administration, volatile anesthetics can be reused after their passage through the carbon dioxide absorber. When low fresh gas flow is applied, less gas must be vented to the exhaust system and consequently less sevoflurane must be added into the breathing system. An increased consumption of CO_2 adsorbents is seen but does not have a global negative impact on the financial price tag [13]. With the modified formulations in the current CO_2 absorbents in the last decades, compound A formation and toxicity in humans at low flows is no longer a concern [16, 17] and apart from rare conditions such as CO intoxication, there is no reason to avoid minimal gas flow [6]. Still, at lower FGF, there will be an increased consumption of absorbents, with consequently also the pollution associated with their production and destruction. Even though neither the plastic package nor the soda lime are ecotoxic when landfilled, an amount of CO_2 is released during production and incineration.

A large sodalime canister contains 1200 g sodalime and 200 g plastic, the production and incineration of which results in CO_2 emissions of around 1.3 kg, corresponding with 2.4 mL of sevoflurane [5, 18, 19]. As such, it is striking that the pollution owing to even only the excess sevoflurane consumption when using 2 L/min FGF instead of AGC speed 2 in the first 12 min of anesthesia in only one average patient equals the pollution attributable to the production and incineration of a large sodalime canister.

Our results confirm that cumulative volatile anesthetic consumption – and therefore pollution – can be significantly reduced by using AGC, compared even to the traditionally called "low flow" (2 L/min FGF) anaesthesia.

While it is often important to quickly reach this target concentration, in most clinical cases, a period of minimal patient stimulation occurs after intubation while the

induction dose of propofol still provides a strong hypnotic effect. As such, swiftly attaining an Et_{sevo} of 2% would in most cases result in an unnecessarily high dose of hypnotics often with adverse hemodynamic effects, in addition to needless waste and pollution.

Figure 1 shows that the sevoflurane consumption is highest in the 2L-FGF group, compared to all other groups. Figure 3 shows that in AGC, the algorithm manages to stabilize the expiratory O_2(FeO_2). The higher FGF required to stabilize FeO_2 probably resulted in somewhat higher consumption of sevoflurane. This observation suggests that a lower target F_iO_2 when using AGC will result in lower consumption of volatile anesthetics.

Comparison with reports on the first AGC software version shows a steady trend of continuous improvement. Carette et al. reported for version 4.0 at speeds 2 and 6 a cumulative consumption after 30 min of 5.0 mL, and 7.0 mL sevoflurane, respectively [9]. Our results for the same speed settings show a consumption of 4.4 mL, and 4.9 mL after 30 min. This emphasizes that even an update to the most recent software version easily results in an annual saving of 2500 mL of sevoflurane and an equivalent of 1326 kg of CO_2 in emissions. Likewise, since even conventional "low flow" anesthesia at 2 L/min FGF results in a consumption of 240% compared to AGC speed 2, institutions lacking automated gas delivery technology should be encouraged to invest in more modern equipment. Simply replacing routine 2 L/min FGF by AGC, at 250 working days/year, 8 h/day, implementation of AGC would result in annual savings of 17,000 mL of sevoflurane for each machine, equalling 9 metric tons of CO_2 and costing circa 6000€. Since the AGC software costs approximately 5000€, this investment would be paid back in less than a year. If completely new workstations are required, a purchase price, including the most advanced software of, generously estimated, 45,000€ is recovered in less than 8 years. If a higher FGF than 2 L/min is often applied, the purchase price is obviously recovered much faster. Analogously, proper investment in training and raising awareness of the anesthesiologists to make maximal and conscious use of this new technology would be highly beneficial to maximise the economic and ecologic benefits. On a societal level, it is appropriate to consider the social cost of CO_2 as well. Since anthropogenic climate change will cause excess mortality due to heat stress, this mortality cost is estimated at 37$ to 258$ per ton of emitted CO_2 equivalents, depending on model assumptions [20]. This difference in societal cost resulting from climate change between 2L/min FGF and AGC would thus amount to annually between 337$ and 2353$ when using sevoflurane per workstation [3, 20].

» minimal adjustments in daily practice can dramatically reduce the environmental impact of anesthesia «

» AGC improved stability and arguably additionally improves safety, and should therefore be advocated also from a clinical perspective. «

While practicing manual minimal flow anesthesia with the Flow-i is reliable, the stability of Et_{sevo} when using AGC-technology is significantly better without the need of any adjustments of the vaporizer or fresh gas flow settings. On top of an increased convenience for the anesthetist, AGC improved stability and arguably additionally improves safety, and should therefore be advocated also from a clinical perspective. As such, while manual minimal flow may yield lower consumption in the first few minutes, we regard this primarily a directional message to the software developers, but as a clinical recommendation we would encourage systematically using AGC mode.

Compared to other studies, focused on the pharmacokinetics, it is noteworthy that the speed to reach 90% of target in our findings is slightly faster than in software version 4.0. Carette et al. showed that 90% of target was reached in speed 2, and 6 after 15, and 6 min, respectively. In our observations in version 4.7 we reached 90% of target with the same speed settings after 13:45, and 05:00 min:sec, respectively [9]. Likewise, De Medts et al. reported that when using desflurane, 90% of target was reached after 16:00, and 06:45 min:sec [21].

The most important limitation of this study, is its retrospective nature. While in all patients an end-tidal concentration of 2% was pursued, some bias that might affect the results cannot be excluded. Nevertheless, analysis of the individual curves suggests reliable consumption rates and analysis of the patient characteristics (Table 1) indicates comparable patients in each group. Secondly, at the moment of the data recordings, the software was set to a lowest FGF in AGC mode of 0.3 L/min, while it also permits presetting a lower limit of 0.1 L/min, which would likely further improve the economics of AGC. Thirdly, by institutions protocol, an F_iO_2 of 80% was always used in AGC. The recent consensus recommendations, however, prescribe an F_iO_2 of ≥ 40%, which may reduce the fresh gas flow, thereby decreasing the consumption in the first minutes in AGC [22].

Still, our results demonstrate that future software upgrades may yield further improvements. Fourth, to enable correct comparison between groups, this analysis was limited to cases where the target concentration was set after induction of anesthesia and not adjusted thereafter. We may expect that frequent changes of the target concentration during the procedure will have a varying influence on the consumption figures in the different AGC settings. Fifth, regarding the calculations on greenhouse gas release, the ultimate impact is approximately 10% worse, since the waste emissions during industrial manufacturing of the sevoflurane releases roughly 10% of the CO_2 equivalents that are released during use, depending on the production methods [23]. Finally, the potential reduction in N_2O emissions was not investigated in this study, because the use of N_2O in the hospital was already phased out years ago for ecological reasons.

Conclusion

Implementation of AGC technology results in significant economic and ecological savings. Even compared to conventional "low flow anesthesia" of 2 L/min FGF, AGC is much more efficient. The excellent stability of AGC requiring minimal operator interventions represents a major advantage for AGC in terms of waste reduction, workload and patient safety. Implementation of automatic gas control technology permits safe and convenient reduction of anesthetic waste of easily 50%; this technology would therefore result for each machine in an annual financial saving well over 5000€ and an equivalent of 11 tons of CO_2 emission when using sevoflurane.

» On an ecological level, it should be emphasized that the patient receives the same level of anaesthesia, with even increased safety, but with a lower cost for both society and the biosphere. «

The financial savings resulting from the implementation of AGC in most cases suffices comfortably to finance the adoption of advanced anesthesia workstations. These financial considerations may vary depending on the region, because different business models and processes may be used for who is paying for medication versus the technical equipment. It is, however, abundantly clear that on a hospital or society level the investment in automated systems generously pays off. On an ecological level, it should be emphasized that the patient receives the same level of anesthesia, with even increased safety, but with a lower cost for both society and the biosphere.
Our results also demonstrate that there may still be room for significant improvement of the AGC algorithms to match the excellent stability with a further improved efficiency, particularly in the early wash-in period. Our results show that (even) what historically is called "low flow anesthesia" should be abandoned, and all anesthesia workstations should be upgraded as soon as possible in order to benefit from automated gas delivery.

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