

Automated control of end-tidal inhalation anaesthetic concentration using the GE Aisys Carestation™[†]

S. Singaravelu and P. Barclay*

Tom Bryson Department of Anaesthesia, Liverpool Women's Hospital, Liverpool L8 7SS, UK

* Corresponding author. E-mail: philip.barclay@lwh.nhs.uk

Editor's key points

- New anaesthetic machines can automatically control the concentrations of volatile agents and fresh gas flow.
- This study compared the EtControl™ with manual adjustment of fresh gas flow by the anaesthetist in clinical practice.
- Time spent at low gas flows was significantly greater and volatile agent usage and costs were lower when using the automated system.
- Further studies are needed to confirm these findings.

Background. Automated control of end-tidal inhalation anaesthetic concentration is now possible. The EtControl™ module of an Aisys Carestation Anaesthetic machine digitally adjusts fresh gas flow and plenum vaporizer output to achieve a target end-tidal concentration.

Methods. We evaluated EtControl in clinical practice by measuring volatile agent consumption and the need for user input. We compared these values with contemporaneous controls using manual control of fresh gas flow rates.

Results. A total of 321 patients were anaesthetized with EtControl and 168 with manual control of fresh gas flow. The mean [95% confidence interval (CI)] sevoflurane usage for cases of 20–40 min duration was 14 (13–16) ml h⁻¹ with EtControl and 30 (26–35) ml h⁻¹ with manual control. For cases of the same duration, the mean (95% CI) desflurane consumption was 27 (21–33) ml h⁻¹ with EtControl and 45 (29–62) ml h⁻¹ with manual control. The average number of keypresses per case was 6.5 with EtControl and 13.6 during manual control of fresh gas flow.

Conclusions. Automatic implementation of low-flow anaesthesia using EtControl allows the user to set and maintain a desired end-tidal volatile concentration while using less volatile agent.

Keywords: anaesthesia, inhalation/economics; anaesthesia, inhalation/instrumentation; drug costs; drug utilization; humans

Accepted for publication: 2 October 2012

Demands for increased efficiency in health expenditure have led to a renewed interest in promoting low-flow anaesthetic techniques to reduce the quantity of inhalation anaesthetic agents used. Such techniques require repeated adjustment of the concentration of volatile vapour added to the fresh gas flow as flow rates are reduced, with the anaesthetist acting as a controller in a negative feedback loop, comparing information from end-tidal gas monitoring with the desired value. This process has been automated by adding servomotors to adjust both the analogue rotameter and vaporizer controls simultaneously,¹ but this has never been developed commercially. The Zeus anaesthesia machine (Draeger Medical, Lubeck, Germany) was the first anaesthetic machine to offer automated control of volatile delivery, using a system of direct vapour injection into the breathing circuit, combined with a turbine-driven ventilation circuit.²

The FELIX AInOC anaesthetic station (Air Liquide Medical Systems, Brescia, Italy) uses a conventional Selectatec vaporizer turned to the maximum output, with automated delivery of volatile controlled using an electronic mixing system.³ The GE Aisys Carestation™ (GE Healthcare, Madison, WI, USA) has digital control of both fresh gas flow and plenum vaporizer output together with a compact breathing circuit to reduce the time to equilibration. In April 2010, an optional EtControl™ module was introduced which automatically adjusts gas flow and vaporizer output to achieve the target end-tidal concentration. A multiplexing system diverts gas monitoring to sample machine output every 3 min to confirm that fresh gas and vapour concentrations agree with values set by the software.

The aim of our study was to evaluate the EtControl module in clinical practice by measuring inhalation

[†]Presented in part at Euroanaesthesia, Amsterdam, June 2011.

anaesthetic usage and the need for user intervention and comparing this with contemporaneous cases undertaken using manual control of fresh gas flow.

Methods

End-tidal control (EtControl) hardware and software was fitted to five GE Aisys machines in the Gynaecology Theatres of the Liverpool Women's Hospital in April 2010. In the fresh gas control mode, anaesthetists use three controls to manually set the oxygen mixture, fresh gas flow, and percentage volatile output as required throughout the case. Where the EtControl mode is used, anaesthetists set targets for end-tidal oxygen concentration, minimum flow rate, and end-tidal volatile concentration. The system uses an algorithm to adjust both fresh gas flow and vaporizer to achieve the set values via a negative feedback control system, although the precise details of the algorithm are uncertain. Fresh gas flow automatically reduces down to the minimum set value, although this can be increased during the case to compensate for system leaks.

We performed a service evaluation between June 2010 and October 2010 to observe fresh gas flow rates and inhalation anaesthetic usage in clinical practice where the anaesthetist had used either EtControl or fresh gas control. The project was approved by the Trust audit committee.

No patient identification information was collected during the audit. All information was collected from the log files stored within the Aisys anaesthetic machine. EtControl data were analysed from the files generated for each case that store breath-by-breath information about 114 variables derived from raw and processed data obtained from the Aisys machine, with an average time interval of 5.0 s. Data log files were obtained from each of the machines by our senior Biomedical Engineer using a Compact Flash card. Information from each log file was imported into a Microsoft Excel 2010 spreadsheet template [Microsoft (2010), Redmond, WA, USA], which contained formulae described in the Appendix, to calculate each of the variables described in the Results. The accuracy of control and bias were measured during conditions of steady state, defined as >300 s after a change in target concentration.

Fewer data were available for patients who received anaesthesia using fresh gas control as the Aisys software does not currently output data about flow rates or vaporizer settings. Instead, the keypress logfile was analysed, to determine user settings of fresh gas flow and vaporizer output during each case.

All patients received sevoflurane or desflurane. Patients with a duration of anaesthesia of <10 min were excluded, as there were insufficient data to perform a full analysis of the system performance in the maintenance phase of anaesthesia.

For comparison, Dr Ross Kennedy (Department of Anaesthesia, Parkside, Christchurch Hospital, University of Otago, Christchurch, New Zealand) kindly supplied us with original

data from his 2006 and 2009 studies of the changing patterns of fresh gas flow rates.⁴

Data were analysed with Graphpad Prism version 5.01 for Windows (GraphPad Software, San Diego, CA, USA, www.graphpad.com) using the Spearman correlation and *t*-tests.

Results

During the evaluation period, we observed routine anaesthetic practice, leaving the choice of inhalation anaesthetic, fresh gas flow rate, and method of flow rate adjustment to the discretion of the individual anaesthetist. A total of 321 patients were anaesthetized using EtControl of fresh gas flow, 181 receiving sevoflurane and 140 receiving desflurane. Data were also obtained from 168 patients who had manual control of fresh gas flow during the same time period; of whom, 143 received sevoflurane and 25 received desflurane.

The time spent at each gas flow rate during the first 10 min of anaesthesia is shown in Figure 1. The gas flow profile for the total duration of anaesthesia is shown in Figure 2, together with data from Kennedy and French.⁴ The average fresh gas flow during EtControl decreased significantly with increased duration of anaesthesia (Spearman $r = -0.88$, $P = 0.0016$). The average fresh gas flow and rate of liquid volatile agent usage, categorized by duration of anaesthesia, is shown in Table 1. The cost of anaesthesia in £ h^{-1} is shown in Figure 3, using prices from the BNF.⁵

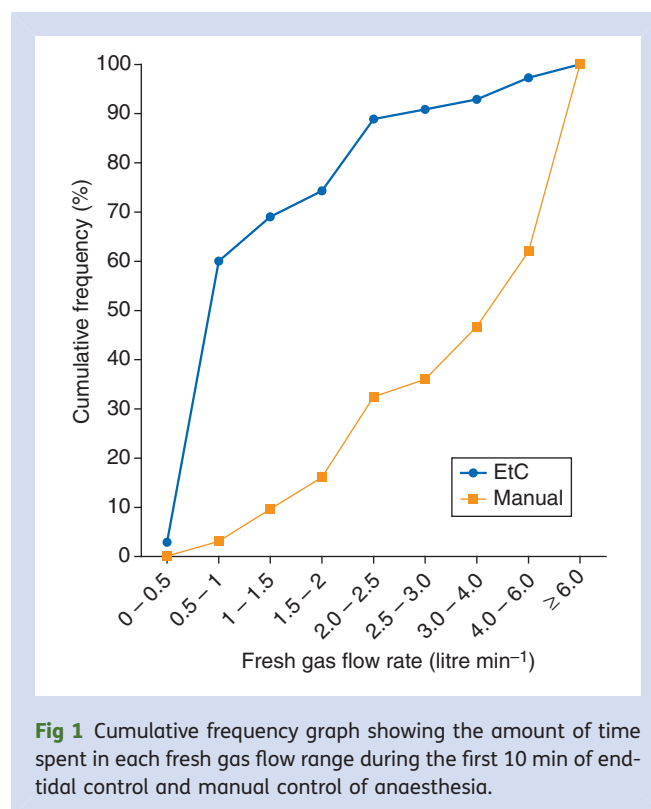


Fig 1 Cumulative frequency graph showing the amount of time spent in each fresh gas flow range during the first 10 min of end-tidal control and manual control of anaesthesia.

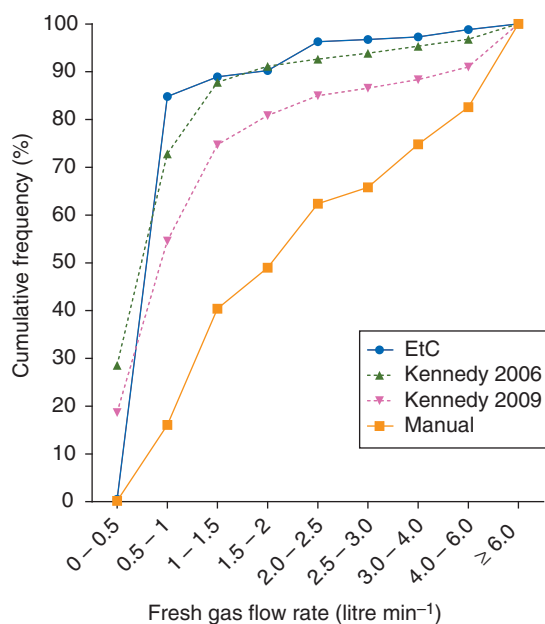


Fig 2 Cumulative frequency graph showing the quantity of time spent at each flow rate during end-tidal control and manual control of anaesthesia, together with data provided by Kennedy from his 2006 and 2009 studies.⁴⁻⁶

Table 1 Fresh gas flow and liquid volatile anaesthetic usage, categorized by duration of anaesthetic. Data are presented as mean (95% CI), with duration of anaesthesia categories in minutes

Duration	Et Control		Manual control	
	Mean (95% CI)	n	Mean (95% CI)	n
Fresh gas flow (litre min ⁻¹)				
<20	1.4 (1.1-1.7)	41	3.6 (3.3-3.9)	86
20-40	1.2 (1.1-1.4)	76	3.1 (2.7-3.5)	42
40-60	0.9 (0.8-1)	87	1.9 (1.7-2.1)	20
>60	0.7 (0.7-0.8)	117	1.5 (1.3-1.7)	20
Liquid sevoflurane usage (ml h ⁻¹)				
<20	15 (12-17)	31	33 (30-37)	79
20-40	14 (13-16)	55	30 (26-35)	34
40-60	11 (10-12)	52	20 (14-27)	14
>60	9 (8-9)	43	14 (12-17)	16
Liquid desflurane usage (ml h ⁻¹)				
<20	32 (25-39)	10	75 (50-100)	7
20-40	27 (21-33)	21	45 (29-62)	8
40-60	19 (17-20)	35	33 (30-35)	6
>60	17 (15-18)	74	33 (23-43)	4

With EtControl, the measured end-tidal concentration was within 10% of the set target for 98.0% of the total time spent in steady state, allowing 5 min for equilibration after each change in the set target. The mean [95% confidence interval (CI)] bias was +1.47 (1.29-1.66)% of the target. The mean

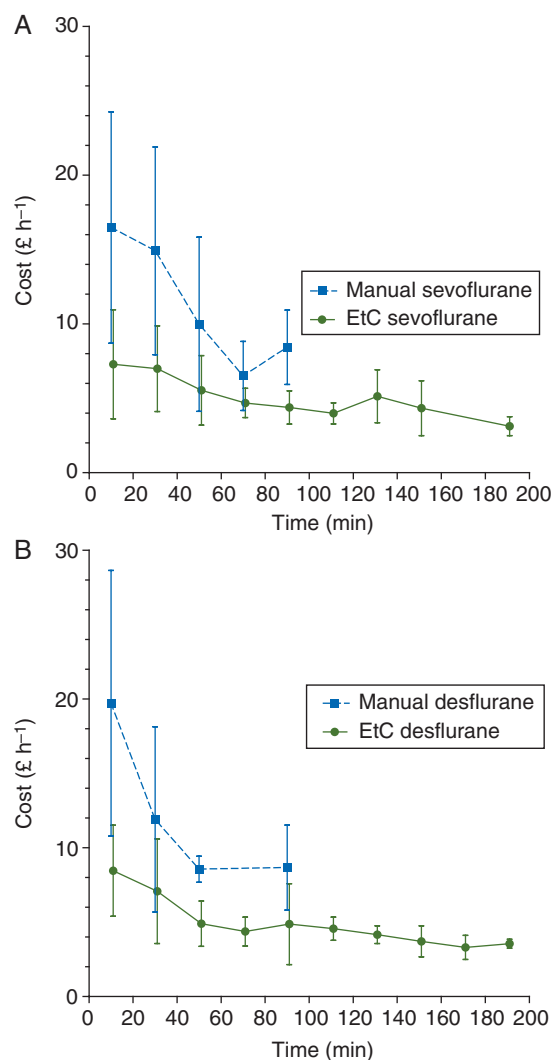


Fig 3 Mean cost of volatile liquid per hour of anaesthesia (£ h⁻¹) by duration of anaesthetic, using EtControl and manual control with (A) sevoflurane and (B) desflurane.

(95% CI) number of keypresses required was 6.5 (6.0-7.0) during EtControl and 13.6 (12.8-14.4) during manual control.

Discussion

The current economic climate requires that anaesthetists use low-flow anaesthetic techniques to reduce the cost of modern volatile agents. Many studies have been carried out to determine optimal flow patterns to maximize efficiency at low flows.⁶⁻⁹ However, moving from research demonstrating best practice algorithms into routine clinical practice has proved to be more difficult as the careful application of low-flow techniques often decreases down the priority of clinical tasks at the onset of anaesthesia and surgery. Education programmes have been shown to have an impact on the usage of low flow, reducing the average fresh gas flow from 2.4 to 1.8,¹⁰ 4 to 2.6,¹¹ and 3 to 1-2 litre min⁻¹.¹²

It is difficult to audit compliance with low-flow techniques where anaesthetic machines have analogue controls. Digital control of flow enables data to be gathered accurately and unobtrusively for an entire department so that the proportion of time spent in each flow rate 'bin' can be determined.⁴ Kennedy and French used these data to provide individual feedback to clinicians together with education about low flow. He was able to demonstrate a significant shift in the curve, increasing the amount of time that was spent at flow rates of <1 litre min^{-1} from $<30\%$ in 2001 to more than 70% in 2006. However, regression to patterns of higher flow occurred when repeated measurements were taken in 2009 after the education programme ended (Fig. 2).

We used a similar method to evaluate the impact of introducing the Et Control mode to our Aisys anaesthetic machines. A limitation of the study is that anaesthetics administered with EtControl had a longer average duration of anaesthesia, making a direct comparison of the two data sets invalid. Our evaluation was restricted to a measurement of machine performance data and we did not measure the individual anaesthetist's reason for the choice of manual or Et Control mode. It is possible that some clinicians may have chosen not to use the system for short cases, although in due course, as they acquire experience, this may change. However, when comparing anaesthetics of the same duration, the average volatile anaesthetic usage was consistently reduced by $40\text{--}55\%$ in the Et Control group. For cases of $20\text{--}40$ min duration, the average cost of volatile agent per hour was reduced from $\pounds 14.92$ to $\pounds 6.98$ with sevoflurane and from $\pounds 11.91$ to $\pounds 7.08$ with desflurane.

It is evident from Figure 1 that most anaesthetists using manual control kept flow rates moderately high during the first 10 min of anaesthesia and used similar flow rates for the entire case (Fig. 2). The flow rate profile was markedly different when using Et Control, which showed a greater proportion of time at low flow than Kennedy described in 2006. The anaesthetist's workload was also shown to be reduced as, despite having a longer average duration of anaesthesia, cases with Et Control required half the number of keypresses.

These results are comparable with *in vitro*¹³ and subsequent clinical studies² using the Zeus anaesthesia machine, which showed that desflurane consumption was reduced by 65% and anaesthesia workload was similarly lowered when using Target Control Anaesthesia[®] in place of manual control of fresh gas flow.

Sulbaek and colleagues¹⁴ showed that halogenated anaesthetic agents and nitrous oxide have a far greater effect on global warming per kilogram than an equivalent mass of carbon dioxide, due to their greater stability within the atmosphere. A reduction in volatile agent consumption with automated control of fresh gas flow will therefore benefit the environment and economic advantages.

A recent MDA¹⁵ alert highlighted the problem of unexpected low vapour output from conventional vaporizers mounted on a back bar putting the patient at risk of awareness. This is a particular problem when using low flows as vapour recirculation may lead to a delay in diagnosis.

EtControl solves this problem by continuously monitoring vaporizer output to confirm that a safe and accurate quantity of vapour is administered.

Automated control of low-flow anaesthesia was only previously possible using research devices or using anaesthetic machines whose operating principles are different from conventional anaesthetic machines. Installation of End-tidal Control on to the Aisys Carestation now makes it possible for all the anaesthetic machines within a hospital to benefit from automated control of low-flow anaesthesia. This will reduce the cost of inhalation anaesthetic drugs to both the health economy and the ecosystem while simplifying the process of anaesthesia by reducing the number of required interventions throughout the case.

Acknowledgements

We thank Mr David Cordon, Senior Biomedical Engineer, Liverpool Women's Hospital, Liverpool, UK. We thank Professor Ross Kennedy, Department of Anaesthesia, Parkside, Christchurch Hospital and University of Otago, Christchurch, New Zealand, for kind permission to use his original data, received by e-mail on August 29, 2010.

Declaration of interest

GE Healthcare are aware of this study but have not approved the text. The GE software engineers provided an explanation of the codes used in the EtC log files, but the data collection, analysis and interpretation was performed entirely by the study authors. P.B. has received payment of travel expenses but has not received any honoraria from GE.

Funding

No external funding was obtained to perform this service evaluation. The GE Aisys Carestation[™] anaesthetic machines were purchased by the hospital. At the time of the evaluation process, P.B. asked GE Healthcare whether the digitally controlled Aisys could be made to adjust its flow rates automatically to achieve a desired set target. They informed him that this facility would be available in a future software update. This was then included as part of our tender documentation in November 2008. When EtControl[™] was released in 2010, GE Healthcare upgraded five of our machines to EtControl[™] without further charge.

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Appendix

Analysis was performed using the following calculations.

Duration of volatile anaesthesia was defined as the time from the start of end-tidal control ($t=0$) until the time when the vaporizer output was switched off at the end of the case ($t=end$).

Total fresh gas and volatile usage values were obtained by summing the product of rate of usage by the duration of each time epoch.

$$\text{Total fresh gas (litre)} = \int_{t=0}^{t=end} \text{fresh as flow rate (litre min}^{-1}\text{)} dt$$

$$\text{Total volatile vapour (litre)} = \int_{t=0}^{t=end} \text{fresh gas flow (litre min}^{-1}\text{)} \times \text{vaporizer (\%)} dt$$

A conversion factor is derived from the quantity of vapour obtained from each ml of volatile liquid: 182 ml for sevoflurane and 209 ml for desflurane, derived from the following formula.¹⁶

$$\text{Conversion factor} = [\text{density of volatile liquid (g ml}^{-1}\text{)} \times \text{volume at room temperature and pressure (24 000 ml)] / \text{molecular weight (g)}$$

Total liquid (ml) =

$$\int_{t=0}^{t=end} \frac{\text{fresh gas flow (litre min}^{-1}\text{)} \times \text{vaporizer (\%)} \times 1000}{\text{conversion factor}} dt$$

The total volatile liquid used in the first 10 min of each cases was also calculated, by integrating from $t=0$ to $t=10$.

$$\text{Average fresh gas flow (litre min}^{-1}\text{)} = \frac{\text{total fresh gas used (litre)}}{\text{duration of volatile anaesthesia (min)}}$$

$$\text{Average volatile usage (ml h}^{-1}\text{)} = \frac{\text{total volatile liquid used (ml)}}{\text{duration of volatile anaesthesia (h)}}$$

Average volatile usage was also calculated for the first 10 min of each case.

Cost of volatile liquid

The current cost of inhalation anaesthetic liquids⁵ is as follows:

Sevoflurane: 250 ml bottle costs £123.00=£0.492 per ml.

Desflurane: 240 ml bottle costs £63.31=£0.264 per ml.

$$\text{Average cost of volatile (£ h}^{-1}\text{)} = \frac{\text{total cost of volatile liquid (£)}}{\text{duration of volatile anaesthesia (h)}}$$

Total volatile usage

Data bins were created at the following fresh gas flow rates: 0–0.5, 0.5–1, 1–1.5, 2–2.5, 2.5–3.0, 3.0–4.0, 4.0–6.0, and >6 litre min⁻¹.

The quantity of time spent at each flow rate was recorded for each individual case. This information was obtained for the entire operation and for the first 10 min. Time values for all cases were added together to give a sum for the entire case series. This method is comparable with that used by Kennedy, who has given kind permission for us to use his original previously published data from work using the GE ADU Carestation, which preceded the GE Aisys.

Accuracy of end-tidal control

The EtControl system uses the same method of measuring end-tidal volatile concentrations as the manual methods of controlling fresh gas. However, use of the algorithm in real-life clinical scenarios at low flows could result in a systematic discrepancy between measured and set concentrations (bias).

In addition, for the anaesthetist to remain in control of volatile concentrations, it is important that the measured value remains within a clinically acceptable range of the set value.

To determine the difference between measured values and set values, percentage difference was calculated for time epochs when the system was in steady state, defined as >300 s after a change in target concentration.

$$\text{Bias (\%)} = \frac{\sum_{t=0}^{t=\text{end}} (\text{measured Et[volatile]} - \text{set Et[volatile]}) / (\text{set Et[volatile]}) \times \text{duration (min)}}{\text{total duration of steady state (min)}}$$

Clinical precision was determined by calculating the percentage of time spent when the absolute percentage difference between measured and set concentrations exceeded 5% and 10% and when the absolute difference between measured and set exceeded 0.2%.

Number of keypresses

The number of setting changes required by the anaesthetist was measured for each case by inspecting the keylog file.

$$\begin{aligned} & \text{Number of keypresses per hour} \\ &= \frac{\text{total number of keypresses}}{\text{duration of volatile anaesthesia (h)}} \end{aligned}$$

Handling editor: J. P. Thompson