Student Conference Proceedings
Vol 2, No 1, 2026, Article ID 2687, 4 Pages

Student Conference Lübeck

Proceedings Article

Performance evaluation of an anesthetic feedback control loop and uptake assessment of an oil filled lung simulator

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Received 11 February 2026; Accepted 15 June 2026; Published online 02 July 2026

Abstract

Feedback control systems in anesthesia consist of advanced algorithms that contribute to less workload of the anesthesiologist, ensures precise concentration adjustments and reduces anesthetic gas consumption. This research paper examines the uptake behavior of isoflurane utilizing the AGC (Automatic Gas Control) algorithm using MAQUET Flow-i 4.7 together with a two-compartment mechanical lung simulator. The motivation is to analyze the performance of automatic gas control with different speed settings because it is crucial for medical staff that operate anesthetic machines to understand which effects the automated regulation of volatile anesthetic agents and oxygen have on humans. MAQUET's AGC mode allows to control inspired oxygen- (FiO2) and the end-tidal anesthetic (EtAA) concentrations during ventilation. A comparison between different speed modes of the AGC settings shows that higher speed leads to a quicker response and lower settling time of EtAA. But on the other hand results in higher overshoot.

I. Introduction

During the discovery of carbon dioxide, oxygen and nitrous oxide, the therapautic possibilities of using these gases were explored in the late 1700s. The inhalation effect of nitrous oxide was described in 1799 by Humphrey Davy where the two major effects were euphoria and analgesia which is the relief of pain. The use of inhaled gases to perform anesthesia was not exploited until a breakthrough on 16. October 1846 where ether vapor was used during the removal of a tumor from Gilbert Abbott's neck without signs of pain [1]. Today any surgery on humans or animals that requires the patient to be motionless and without consciousness uses anesthesia delivery systems for drug administration. These delivery systems are operated manually by professionals, but have been increasingly automated in the last few decades. Introducing closed loop anesthesia with feedback control saves anesthesiologists of workload, ensures precise adjustments of anesthetic concentration based on real time measurements, and reduces the overall consumption of anesthetic agent [2]. This paper investigates the uptake pattern of isoflurane using the MAQUET Flow-i software version 4.7 with a mechanical lung simulator. First a complete description of the system setup is being presented. Then MAQUET's AGC system is being used to run step responses with isoflurane as anesthetic agent and a performance evaluation of the results with different speed settings is shown in Chapter III.

10.18416/SCP.2026.2687

II. Methods and materials

II.I. Experimental setup

The physical experiment setup is presented in Fig. 1 and can be described with three main parts: MAQUET Flow-i 4.7, LUSIAN lung simulator and an external gas analyzer system.

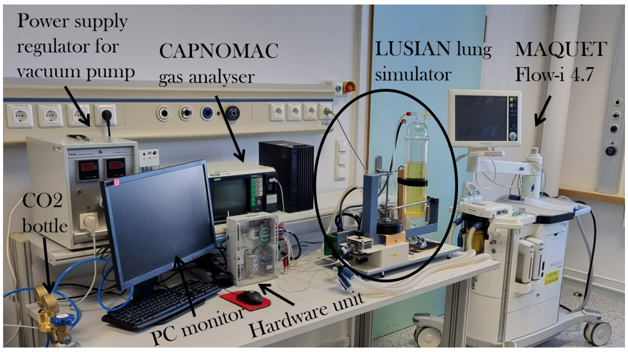

Figure 1: Experiment setup

II.II. MAQUET Flow-i 4.7

The MAQUET anesthetic machine is connected to LUSIAN lung simulator described in section II.III with a Y-piece connector where an internal sampling line directs inhaled and exhaled gases to be analyzed and displayed on a monitor.

Volume control - continuous mandatory ventilation mode (VC-CMV) is used as ventilation mode, and allows the user to enter the tidal volume of the patient. In manual mode without activation of the AGC algorithm, the operator can adjust anesthetic agent (AA) and O_2 concentration by changing the values on the MAQUET's user interface. AGC mode can be switched on together with VC-CMV and is an automated control function that uses setpoints of FiO_2 and EtAA which means inspiratory O_2- and expiratory AA (which is a surrogate parameter for the alveolar AA) concentration. The AGC mode can be used with different speeds from 1-8 and 9 (max) where high speed setting is designed to reach setpoint concentrations faster. When the setpoint value is reached, fresh gas flow (FGF) is decreased to a minimal flow of $0.3 l/min$.

II.III. LUSIAN lung simulator

The LUSIAN mechanical lung simulator was built by Dräger and has been modified to incorporate a CO2-gas flow to ensure that AGC can be used. A pneumatic diagram of the system is shown in Fig. 2.

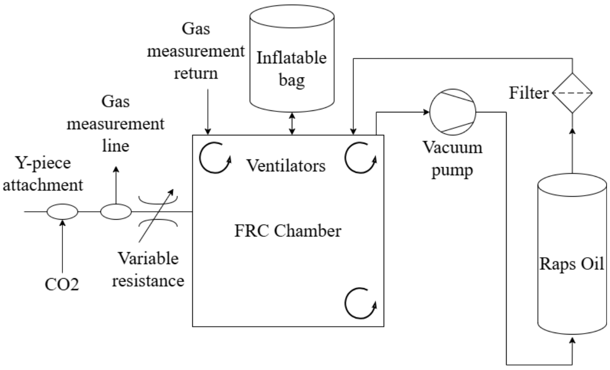

Figure 2: Pneumatic diagram of the LUSIAN: FRC: Functional residual capacity, Inflatable bag: represents the lung tidal volume, Vacuum pump: representing cardiac flow. Raps oil: representation of a tissue

The CO_2 flow is directly led into the Y-piece attachment to simulate a human breathing cycle where exhaled air contains approximately $5.2 Vol. - \%$ of CO_2 after gas exchange in the alveoli [3]. Due to safety reasons, the detection of an exhaled CO_2 concentration is necessary for the MAQUET anesthetic machine to use AGC mode. The CO_2 flow is regulated by a PI-controller with a proportional valve and flow sensor. This ensures a stable and controlled flow. The CO_2 concentration is measured by the MAQUET's gas sampling line when delivered into the Y-piece attachment shown in Fig. 3. Experimenting with different CO_2 flow values during ventilation, it was found that a flow of 30 ml/min resulted in FiCO_2 $= 0.02\%$ and EtCO_2 between $4.8 - 9.2\%$ depending on the FGF which was acceptable with using AGC mode.

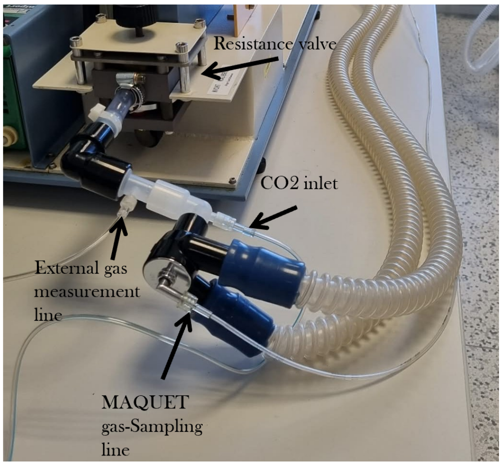

Figure 3: Detailed view of the Y-piece attachment

The external gas measurement line directs the gas mix to a CAPNOMAC Ultima gas analyzer from Datex

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and then returned into the LUSIAN FRC-chamber ensuring a closed breathing system. The gas analyzer measures the volume concentrations of O_2, CO_2, N_2O and anesthetic concentrations. The gas measurements are extracted from the CAPNOMAC and converted to digital signals with a hardware unit with a timestamp of 100ms. The data is then displayed on a PC where it can be saved as .csv files.

The LUSIAN's FRC chamber has a volume of $3l$ which is around the same for a healthy human [4]. Equipped with three ventilators the gases are mixed and simultaneously inflates/deflates the tidal volume bag as the LUSIAN is ventilated shown in the pneumatic diagram in Fig. 2. From the FRC chamber a vacuum pump at a constant flow rate of $2l/min$ is pumping the mixed gases through an oil-filled cylinder, and the air is filtered when returning to the FRC. The purpose of the oil is to simulate absorption of anesthetic gas, where the oil represents a tissue group in the compartmental model of the body. This makes LUSIAN a two-compartment model; the lung and oil compartment [5].

II.IV. Patient parameters and controller settings

Table 1 shows the ventilation parameters which are being set in the MAQUET which are typical values for an adult patient.

Table 1: Ventilation settings

Tidal volume	$0.5l$
RR	$12/min$
Patient age	40y
MAC_{40} for isoflurane	1.15% [6]

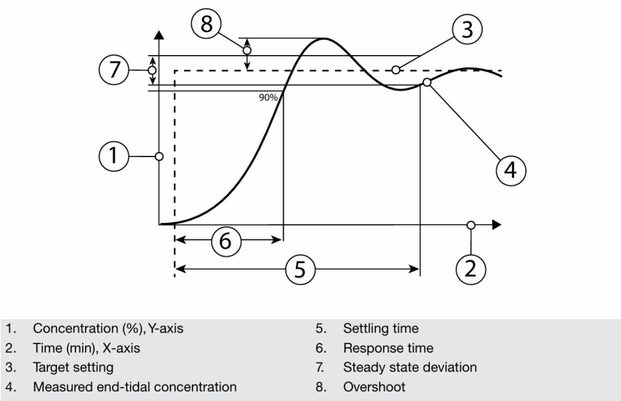

Figure 4: Second order system response

A typical AGC performance during wash in of AA is shown in Fig. 4, taken from MAQUET Flow-i manual [6]. The system response and settling times are measured after the "dead time", which represents hoses where the transport of gases form one location to another takes place but no mixing of gases is present. Response time is the time it takes for the output to reach 90% of the target setting. Settling time is defined as the time it takes for the system to stabilize at the setpoint within a defined deviation. A deviation of 10% is being assumed in this paper for calculation of the settling time because of the absolute measurement deviation error of the CAPNOMAC gas analyzer of $\pm 0.2 Vol.-\%$ [7]. This corresponds to $\pm 0.05 Vol.-\%$ when using an EtAA setpoint of $0.5 Vol.-\%$, equivalent to 8.7% of MAC_{40} for isoflurane (see Table 1).

III. Results and discussion

Fig. 5 shows the time course of anesthetic concentration with an AGC speed setting 8. The horizontal red line highlights the overshoot, purple and green lines show the response- and settling-times measured after the "dead time" respectively.

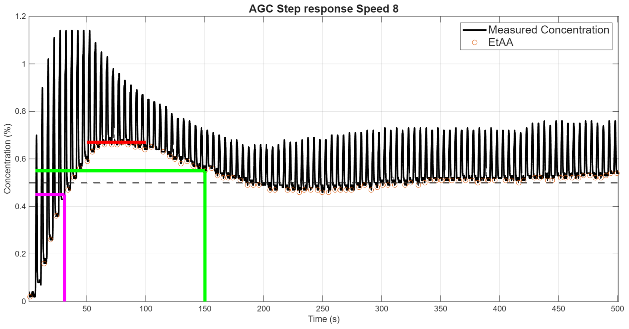

Figure 5: Anesthetic concentration over time with speed 8

Response-, settling time and overshoot percentage for different speed settings is presented in Table 2.

Table 2: A comparison of response parameters for AGC

Speed	Response time	Settling time	Overshoot
2	354.3s	354.3s	-
4	228s	228s	-
6	63.5s	63.5s	8%
8	24.7s	143.8s	34%
9	14.9s	118.5s	38%

Settling- and performance times decreased with higher speeds meaning that the system reaches its EtAA setpoint value faster which corresponds to the expected result. Speed setting 2 and 4 respond with no overshoot, and the overshoot increases for higher values

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of the speed setting. Using the maximum speed setting 9 results in an overshoot of 38%. Speed setting 6 can be chosen as compromise to reach the target EtAA concentration fast while avoiding a high overshoot.

III.I. Washout of Isoflurane and oxygen concentrations

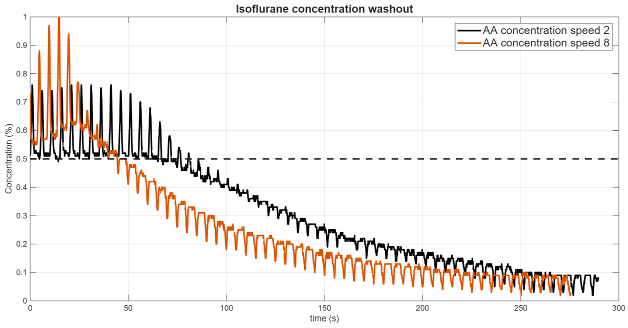

Figure 6: Isoflurane washout with speed 8 and 2

Using AGC speed 8 results in an overshoot of anesthetic concentration before declining when switching EtAA from $0.5Vol.-\%$ to $0Vol.-\%$ shown in Fig. 6. This is because the FGF increases more rapidly and aggressively with a higher speed setting, and at a maintenance FGF of $0.3l/min$ the isoflurane vaporizer delivers a higher concentration value into the breathing system of the anesthetic machine in order to maintain EtAA at $0.5Vol.-\%$. Washout with speed 2 results in no overshoot, but on the other hand increases washout time. Performing washout seems to be safer and more stable with low speed settings. When performing washout of isoflurane in a human patient the speed setting will determine whether there will be a concentration overshoot or a longer settling time.

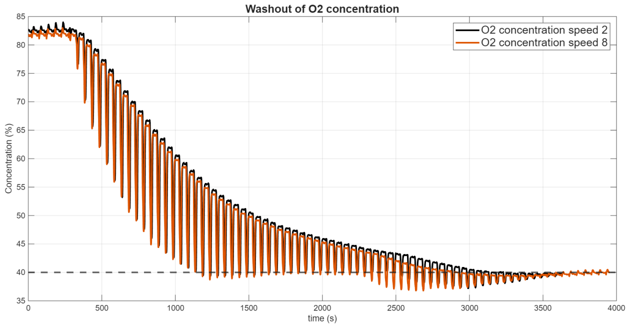

Figure 7: O_2 concentration step from $80Vol.-\%$ to $40Vol.-\%$ with speed 8 and 2

Washout of O_2 concentration from 80% to 40% was performed with speeds 2 and 8. It was observed that the concentration over time and settling times do not differ for different speed settings. This is important to know for an anesthesiologist during surgery.

IV. Conclusion

Using MAQUET's AGC function, the uptake of isoflurane has successfully been measured with different speeds and the performance of the anesthetic feedback controller in terms of overshoot, response time and settling time has been evaluated. This has been made possible because a CO_2 flow has been incorporated into the LUSIAN lung simulator. The results shows that high speed settings leads to a higher overshoot in terms of the concentration of the anesthetic agent, but on the other hand reaches the target EtAA value faster. Washout of isoflurane shows that overshoot and settling times varies with different speeds, where high speed modes causes overshoot in the anesthetic concentration. The time to perform washout of oxygen is observed to be independent of AGC speed setting.

Acknowledgements

The work has been carried out at Zentrum für Biomedizintechnik, Technische Hochschule Lübeck, Germany. Furthermore, we would like to thank B.Sc. Michelle Bromann for her contribution of ideas and equipment during the LAB experiments.

Author's statement

Conflict of interest: Authors have no conflict of interest.

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