Fuzzy Logic Control of Blood Pressure during Anesthesia

R. Meier, J. Nieuwland, A.M. Zbinden and S.S. Hacisalihzade

This article describes research on a fuzzy logic controller which controls mean arterial pressure (MAP) which was taken as a parameter for depth of anesthesia. The controller was designed and implemented on a personal computer. The design process was iterative and the reference points of the membership functions as well as the linguistic rules were determined by trial and error. The control rules made use of the error between the desired and the actual values of MAP as well as the integral of the error. The controller was tested in 11 different surgical operations and it was observed that the anesthetists supervising the controller never had to intervene or override it. Moreover, measures of the quality of keeping the MAP constant show the fuzzy controller to be superior to an ordinary human controller. Such a fuzzy logic controller has the potential for use during anesthesia with an agent like isoflurane. However, further clinical studies are needed before it becomes routine practice to use such a fuzzy logic controller for the control of anesthesia.

Controlling Depth of Anesthesia

One of the main tasks of the anesthetist during surgery is to control the depth of anesthesia. However, the depth of anesthesia is not readily measurable. In clinical practice, the depth of anesthesia is evaluated by measuring blood pressure, heart rate, and clinical signs such as pupil size, motor activity, etc. Control of depth of anesthesia has become more difficult today than at the times of ether as the classical signs of depth of anesthesia defined by Guedel are no more used. Cullen [1] showed a good correlation of blood pressure to the anesthetic dose given. EEG signals have been used by Schwilden [2] for the dosage of Propofol. However, in clinical routine EEG is difficult to use due to artifacts and large intra- and interindividual variations partly caused by differing anesthetic agents. Continuous electromyographic recording of spontaneous activity of the upper facial muscles has been used [3] but results in unpredictable values when the patient receives muscle relaxants. Evoked responses have been used [4] for various agents; they, too, show an agent-dependent effect.

None of the above-mentioned methods has been established on a routine basis. Anesthesiologists still use blood pressure as the most reliable guide for dosing inhaled anesthetics. An argument heard frequently against this practice is that blood pressure depends on many other factors such as blood volume and cardiovascular function. This is true, of course, but anesthesiologists, when unable to treat rapidly enough the primary cause of hypotension (hypovolemia and
hypervolemia, cardiac failure, etc.) will always adjust the concentration of the inhaled anesthetic to rapidly bring blood pressure to normal ranges. Thus, control of blood pressure still appears as the most appropriate way of controlling depth of anesthesia.

To obtain adequate depth of anesthesia, MAP has to lie within a predefined range. The main reason for automating the control of depth of anesthesia is to release the anesthetist so that she can devote her/his attention to other tasks — such as controlling the fluid balance, ventilation, and drug application — which cannot yet be adequately automated, thus increasing the patient’s safety.

Depth of anesthesia is controlled by using a mixture of drugs which are injected intravenously or inhaled as gases. Most of these agents decrease MAP. Among the inhaled gases isoflurane is widely used, most often in a mixture of 0–2% by volume of isoflurane in oxygen and/or nitrous oxide. The isoflurane concentration in the inspired air is adjusted by the anesthetist depending on the patient’s physiological condition, surgery, MAP, and other clinically relevant parameters. To deliver the anesthetic agent to the patient, a semi-closed circle breathing system is used that allows the reuse of the exhaled anesthetic gases (see Fig. 1).

The isoflurane concentration at the end of each expiratory cycle is called endexpiratory or endtidal concentration. It mirrors the arterial concentration and correlates with the brain concentration of the anesthetic agent. The semi-closed circuit makes the inspired concentration more difficult to control, because of an additional delay and a variable dilution of the inflowing gas by the exhaled gas. Thus, a variable gradient exists between the inflowing, inspired, and expired isoflurane concentrations.

First experiments in the automatic control of the depth of anesthesia started in the 1960s with constant gain PID-controllers [5]. Then came controllers like fuzzy controllers which are suitable for the control of time varying parameters. These facts suggest the use of rule-based controllers like fuzzy controllers which are suitable for the control of such systems.

The control loop studied has the structure shown in Fig. 2. There are two different kinds of disturbances: a) System noise due to pain caused by surgery, cardiovascular disease, concomitantly applied drugs, etc. (for example, a skin incision can lead to rapid changes in blood pressure of more than 10 mmHg), b) Measurement noise in the blood pressure and artifacts caused by calibration, electrocautery, etc.

**Controller Design and Simulations**

The controller should mimic the control actions of the anesthetist (and not act, for instance, like a “bang bang” controller). This way a supervising anesthetist can easily ensure proper functioning of the controller. Furthermore, modeling a biological process like anesthesia is very complex, because it has a nonlinear, time-varying structure with time varying parameters. These facts suggest the use of rule-based controllers like fuzzy controllers which are suitable for the control of such systems.

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**Fig. 2. The block diagram of the control loop for the control of depth of anesthesia.**

For simulation and controller design purposes the relationship between inflow concentration of isoflurane \( v(t) \) and the resulting blood pressure \( y(t) \) is modelled as the sum of two first order terms each with a pure time delay (the model includes the patient and also the semi-closed circuit). The step response \( h(t) \) corresponding to a unit step input can be written as follows where \( K_1 = -3, K_2 = -7.3, \tau_1 = 23 \text{[s]}, \tau_2 = 101 \text{[s]}, \alpha_1 = 0.01, \alpha_2 = 0.006 \):

\[
h(t) = f_1(t) + f_2(t)
\]

\[
f_1(t) = \left\{\begin{array}{ll}
0 & \text{for } t \leq \tau_1 \\
K_1 \left(1 - \exp(-\alpha_1(t - \tau_1))\right) & \text{for } t > \tau_1
\end{array}\right.
\]

\[
f_2(t) = \left\{\begin{array}{ll}
0 & \text{for } t \leq \tau_2 \\
K_2 \left(1 - \exp(-\alpha_2(t - \tau_2))\right) & \text{for } t > \tau_2
\end{array}\right.
\]

For the purpose of this analysis it is assumed that \( \tau_1 \) and \( \tau_2 \) are integral multiples of the sampling period \( T \) such that \( \tau_1 = c_1T \) and \( \tau_2 = c_2T \). The z-transform of the transfer function of the step response in (1) can be expressed as shown where \( Y(z) \) and \( U(z) \) are z-transforms of the output blood pressure and input isoflurane concentration, respectively:

\[
Y(z) = \sum_{i=2}^{2} K_i \alpha_i \left[1 - z^{-1} \exp(-\alpha_i T)\right]^{-1} z^{-c_i} U(z)
\]

\[
b_1 z^{-c_1} + b_2 z^{-2} + c_1 z^{-1} + b_2 z^{-2} + c_1 z^{-1} + c_2 \right) U(z)
\]

\[
1 + a_1 z^{-1} + a_2 z^{-2}
\]

**Fig. 1. Flow and signal diagram of the configuration used during anesthesia.**

- **Inflowing isoflurane concentration,** \( F_{in} \)
- **Inspired isoflurane concentration,** \( F_{ins} \)
- **Endtidal isoflurane concentration,** \( F_{end} \)

\[\text{Anesthetist} \quad \rightarrow \quad \text{Vaporizer} \quad \rightarrow \quad \text{Patient}\]

\[\text{ISO} \quad \rightarrow \quad \text{CO}_{2} \text{ absorber} \quad \rightarrow \quad \text{Valve} \quad \rightarrow \quad \text{Ventilator}\]

\[\text{MAP} \quad \rightarrow \quad \text{Setting} \quad \rightarrow \quad \text{Anesthetist} \]
where
\[ b_1 = K_1 a_1 \]
\[ b_2 = K_1 a_1 \exp(-a_2 T) \]
\[ b_3 = K_2 a_2 \]
\[ b_4 = -K_2 a_2 \exp(-a_2 T) \]
\[ a_1 = -\exp(-a_1 T) \exp(-a_2 T) \]
\[ a_2 = \exp(-a_1 T) \exp(-a_2 T) \]

It is convenient to write the z-transform notation in the recursive form as shown with \( T = 10s, a_1 = -1.331, a_2 = 0.335, b_1 = 0.030, b_2 = -0.048, b_3 = 0.017, \) and \( b_4 = -0.041: \)
\[ y(kT) = a_1 y((k-1)T) - a_2 y((k-2)T) + b_1 u((k-c_1)T) + b_2 u((k-c_2)T) + b_3 u((k-c_3)T) + b_4 u((k-c_4)T) \]  

(2)

The parameters used in the controller design process were identified off-line recursively from MAP data collected during surgery after step changes in the inflow concentration of isoflurane. A single patient was used for the identification of these parameters. At first, this might sound insufficient. However, sensitivity analysis during the design phase where all or a combination of these parameters were changed greatly showed no major effect in the simulated controller performance. Actually, this very robustness makes a fuzzy controller the appropriate choice for the task at hand. For the simulation study a random noise signal was added to \( y. \) The artifacts and the low frequency noise were not included in the model.

The first simple linguistic rules that describe the anesthetist’s actions were tested and systematically extended in several simulation runs. During the first design phase the error \( e(t) \), the change of error \( ce(t) \) and the integral of error \( ie(t) \) were used for the computation of the control variable \( u(t) \). The reason for using the integral part was to eliminate the steady state error; the point in using the derivative part was to speed up the controller. The membership functions and the reference points were chosen by using the data recorded during an actual operation where MAP was controlled by an anesthetist. The bell shaped membership functions used can be described by the following exponential equation where \( \xi \) is the input value and \( \lambda \) is the shifting of the function in relation to zero:
\[ \eta = \exp[-K(\xi-\lambda)^2] \]  

(3)

The factor \( K \) determines the “width” of the bell. The evaluation of the linguistic rules was performed using the max-min composition and the center of gravity method [14].

The control characteristics and behavior under different disturbances were tested in simulations with different noise amplitudes and parameters. The best results were achieved with the linguistic rules and parameters of the membership functions shown in Table I and Fig. 3. The controlled variable was the absolute amount of inflow concentration of isoflurane, not the incremental value. There are three stabilized situations considered, according to Table I(b) (rules 5, 6 and 7), i.e., a stable output is limited by any combination of \( ps, pm, \) and \( pb. \) To stabilize at a value different than 2% there must be an integral error (i.e., it forces a certain trajectory). On the other hand, there will not be an inflow concentration higher than 4% (safety measure). Therefore, rules 3 and 8 are only for transients. Fig. 4 depicts a simulation run with the reference points and linguistic rules shown in Table I.

Some conclusions drawn from the simulation study are: a) More rules do not necessarily result in better control characteristics. Conflicting rules can even lead to unstable behavior. Furthermore, computational requirements increase with an increasing number of rules; b) The

### Table I(a)
The Reference Points Of The Membership Functions

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>e [mmHg]</td>
<td>ie [mmHg]</td>
</tr>
<tr>
<td>nb</td>
<td>-10</td>
</tr>
<tr>
<td>ns</td>
<td>-5</td>
</tr>
<tr>
<td>ze</td>
<td>0</td>
</tr>
<tr>
<td>ps</td>
<td>5</td>
</tr>
<tr>
<td>pb</td>
<td>10</td>
</tr>
</tbody>
</table>

### Table I(b)
The Linguistic Rules which Result in the Best Control and Noise Rejection Characteristics

<table>
<thead>
<tr>
<th>Rule #</th>
<th>INPUTS</th>
<th>OUTPUT</th>
</tr>
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<tbody>
<tr>
<td>e</td>
<td>ie</td>
<td>u</td>
</tr>
<tr>
<td>1</td>
<td>ns</td>
<td>-</td>
</tr>
<tr>
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<td>nb</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>pb</td>
</tr>
</tbody>
</table>

For instance, Rule 7 says “if the error is around 0 (ze) and if the integral of the error is around -90 (ns), then set the inflow concentration of isoflurane about 3% (pb).”

![Fig. 3. The membership functions μe for the error e and μie for the inflow concentration u and their reference points. nb: negative big, ns: negative small, ze: zero, ps: positive small, pb: positive big; pm: positive medium; pv: positive very big. The value of K in (3) was chosen as 5 for all membership functions.](image-url)
The derivative part shows a lot of switching of the control variable. The controller is robust with respect to variations in process parameters. Relatively fast changes still remain in the signal. Thus, the contribution of the derivative part is minor. Even after smoothing, relatively fast changes still remain in the signal. Therefore, a controller using the derivative part shows a lot of switching of the control variable without improving the quality of control (just as in classical control). The controller is robust with respect to variations in process parameters.

The results of the simulations encouraged us to apply the controller during surgery under "real life" operating room conditions.

Ensuring the patient's safety during surgery has the highest priority. In addition, the following points are important for the anesthetist: the patient's hemodynamics (MAP, heart rate, etc.) remain stable and that the patient remains sufficiently anesthetized. Moreover, she has to recognize malfunctioning of monitors and other devices. The safety concept of an automatic depth of anesthesia control should also fulfill these requirements. Therefore, the implemented safety concept supervises both the MAP and the endtidal concentration.

The data for monitoring were collected separately from the data used for the control of MAP. An audible alarm is sounded if the difference between the desired and the actual value exceeds 10 mmHg although the controller keeps on working normally (the alarm is suppressed during 3 minutes after a change of the set-value). If the endtidal concentration sinks below 0.4% (danger of awakening), the inflow concentration is increased by 0.1% and held there for 3 min. If the endtidal concentration is still under 0.4% the process is repeated. If the endtidal concentration exceeds 2.5% (toxic limit), it is also signaled by an acoustic alarm, the inflow concentration is decreased by 0.2% and the controller is switched off. When the endtidal concentration returns to a level between 0.4% and 2.5%, the controller is switched on again. Also, the anesthetist can either override or switch the controller off at any time without having to worry about any adverse consequences.

**Implementation**

An IBM compatible personal computer (Toshiba T5100) was used for collection, display, control and storage of data as well as feedback control. The analog input and output data were converted to/from digital data by using a Burr-Brown PCI-20041C-A carrier board in connection with the analog input module PCI-20019M-1A and the analog output module PCI-20003M. Additional digital communication was done via the RS232 serial port. The desired inflow isoflurane concentration was obtained using a Dräger Vapor 19.3 vaporizer driven by an external servo-motor (the servo-motor was driven by a PID-controller-amplifier, which in turn was controlled by a conventional electronic interface). The servo-motor had a switch enabling toggling between manual and automatic control at any time. After determining the curve relating the D/A-output voltage (0...10 V) to the resulting isoflurane concentration (0...5% by volume), the computer software calculated the D/A-gain required for a specified inflow isoflurane concentration, taking into account the actual ambient temperature and barometric pressure. The precise concentration was reassured by a Dräger Irina infrared gas analyzer with an analog output voltage for the A/D-converter. A Dräger Sulla ventilator with an 8-ISO circle system was used for ventilation. The fresh gas flow was set to a constant 3 l/min oxygen.

Automatic control was not started before an acceptably deep anesthesia was achieved. A catheter was inserted into a radial artery and connected to a transducer. The obtained electrical signal was then preamplified and displayed by a Hellige Servomed monitor. Its analog output voltage was transmitted to the A/D-converter to measure MAP. The gas concentrations (O2, CO2 and isoflurane) were measured at the mouthpiece of the patient by a Datex Capnomac gas analyzer. It transformed the gas concentrations to a data string that was sent to the RS232 serial port of the computer. Update rate of the data was 0.1 Hz.

Computer programs (modules) written in Modula-2 were developed to perform the tasks of data acquisition, display, control and storage. The main program can be started at any instance. The anesthetist is first asked to enter the desired MAP. An internal clock and the variables are then initialized. Thereafter, the controller starts working. During automatic control a loop, consisting of MAP-updating (A/D-conversion), filtering, control calculations, control signal (i.e., isoflurane concentration) updating (D/A-conversion), data display and data storage on file is repeated every 10 s. The computer displays the actual and the desired blood pressure, as well as the inspiratory and endtidal isoflurane concentrations. The desired MAP may be changed at any time without interrupting automatic control. A filtering procedure for MAP was developed, in order both to smooth the incoming signal and to detect disturbances during data acquisition. Therefore, the incoming MAP signal is processed by a median-filter with a moving window size of 21 samples. The advantage of the median-filter is its good performance in the presence of disturbances having a wide probability density function. Then, the signal is checked for consistency, i.e., it is compared with a number of conditions that have to be satisfied if the data acquisition works properly. Otherwise the MAP data are not updated and, if the malfunction continues, a warning is displayed. All data of interest are stored in files for later examination.

**Results**

The controller was first tested during surgery in the so called "consultative mode," which means that the controller suggested a value for the inflow concentration and the anesthetist could then decide to set this value or not. This way the patient's safety was assured even in the very early stage of development and the controller could be tested under realistic operating room circumstances. Subsequent analysis of data collected during surgery showed that the inflow concentration suggested by the controller was always very close to the actual concentration set by the anesthetist. Therefore, a fully automatic run was completed during which the controller actually set the inflow concentration administered to the patient. Fig. 5 shows the results of that operation.

In a further operation, MAP was first controlled by a decision based controller (this will not be discussed any further in this article), then by
the fuzzy controller and finally by an experienced anesthetist. Fig. 6 shows the resulting MAP. It can be seen (with a "trained eye!") that the fuzzy controller does a better job of keeping the blood pressure of the patient within a tight range of the set value. This point is quantified in Fig. 7. With the fuzzy controller, the blood pressure was within 5 mmHg of the set value (85 mmHg) 69% of the time and within 15 mmHg of the set value all the time. When the anesthetist controlled the blood pressure, these numbers were 47% and 92% respectively and 8% of the time the patient’s blood pressure deviated more than 15 mmHg from its desired value. The $L_1$ norm of the difference between the desired and the actual blood pressure during manual control is 40% more than during fuzzy control. For the $L_2$ norm this number is 35%. The $L_p$ norm of the error $e(t)$ is defined as the following integral:

$$L_p = \frac{1}{T} \left[ \int_0^T |e(t)|^p dt \right]^{\frac{1}{p}}$$

The results in Fig. 7 relate to a typical patient. However, in all cases, the fuzzy controller also proved to be superior or at least equivalent to the human controller. The results of a controlled study will be published in the medical literature.

**Fuzzy Control of Mean Arterial Pressure**

A proportional-integral fuzzy controller which controls the MAP during anesthesia with isoflurane was designed and implemented on a personal computer. The controller was tested in 11 surgical cases (all abdominal surgery with patients in the 20-55 years age group and within the American Society of Anesthesiologists (ASA) risk class I). The anesthetists supervising the controller never had to intervene or override it. Furthermore, the quality of control achieved by the fuzzy controller proved to be superior to manual control. Therefore, it is concluded that such a controller can be routinely used during anesthesia with an agent like isoflurane. It is, however, necessary to test the controller in many more operations with a wider range of patients and types of operations to see its limitations. Also, the controller has to be enhanced to account for the use of more than one anesthetic agent and variable gas flow which necessitates multivariable control [15].

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References


1992 CDC

The IEEE Conference on Decision and Control (CDC) is the annual meeting of the IEEE Control Systems Society. It is conducted in cooperation with the Society for Industrial and Applied Mathematics (SIAM) and the Operations Research Society of America (ORSA). The thirty-first CDC will be held on December 16-18, 1992, at the Westin La Paloma, Tucson, Arizona. The General Chair of the Conference is Tamer Basar of the University of Illinois at Urbana-Champaign. The Program Chair is Sergio Verdú of Princeton University. The conference will include both contributed and invited sessions in all aspects of the theory and application of systems involving decision, control, optimization and adaptation.

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