Fuzzy control of neuromuscular block during general anesthesia – system design, development and implementation

MILAN ADAMUS,
University Hospital, Olomouc, Czech Republic

RADIM BELOHLAVEK,
Palacky University, Olomouc, Czech Republic

Abstract

We present a system for fuzzy control of neuromuscular block during general anesthesia. The system (Relax 2005) was clinically used in 50 patients undergoing neurosurgical intervention. From the medical point of view, the benefit of using this system is twofold. First, the workload of the anesthetist is reduced. Second, the efficacy of muscle relaxant administration is improved. As far as medical costs are concerned, using the system decreases the expenditure on muscle relaxants. We describe the design, development, and implementation of the system as well as the results of clinical tests.

1. Introduction

Several interesting applications of fuzzy systems in medicine have been reported by Barro and Marin (2001). Medicine seems to be a particularly suitable area for fuzzy systems mainly due to the fact that fuzziness abounds in medicine. Put succinctly, reasoning of a medical doctor is a typical example of approximate reasoning. Symptoms, diagnoses, treatments of diseases are all, more often than not, described by doctors in a natural language. It is these descriptions on which the judgment and decision of a medical doctor are based. Since natural language is fuzzy by its very nature, and medical language is no exception, fuzziness is an inherent aspect of medical procedures.

Anesthesiology is a promising area for fuzzy systems (Asbury and Tzabar, 1995), and for applications of fuzzy control in particular. During general anesthesia, muscle relaxants are often administered to the patient in order to keep the depth of a neuromuscular block at a desirable level. The depth of a neuromuscular block can be monitored by measuring a muscle response to an electric stimulation. The entire process of general anesthesia can be seen as a sum of closed-loop procedures, muscle relaxation being no exception. Traditionally, this process is controlled by an expert anesthetist. The expert, when requested to describe his way of muscle relaxants administration, provides us with a couple of linguistically described rules containing a verbal description of the variables involved. These rules are typical fuzzy if-then rules (Dubois and Prade, 1980, Klir and Yuan, 1995, Zadeh, 1975). It is therefore a natural and challenging goal to develop a system for automatic delivery of muscle relaxants operated by a fuzzy controller which is based on the rules provided by an expert anesthetist. Such a development is important from several points of view. First, from the point of view of fuzzy control, anesthesiology and medicine in general are recent areas of application of fuzzy control and new experience in this field is valuable (Curatolo et al., 1996, Edwards et al., 1998, Schaublin et al., 1996) for related approaches. Second, from medical point of view, automatic delivery of muscle relaxants can improve medical care. Third, one can expect a reduction of costs due to enhanced effectiveness.

This paper describes an application of fuzzy logic in medicine. We present a system of automatic control of neuromuscular block during general anesthesia. The system is based on Mamdani-type fuzzy controller (Babuska, 1998, Driankov et al., 1993, Yager and Filev, 1994). We describe the design, development, and implementation of both the hardware and software parts of the system. In addition to that, the results achieved during clinical testing are summarized and discussed. The system was tested in the Department of Anesthesiology and Intensive Care Medicine, University Hospital, Olomouc, Czech Republic, during general anesthesia of 50 patients. Our results indicate that automatic control of neuromuscular block results in more effective muscle relaxant delivery and enables the patient to receive a minimum amount of drug. In addition to that, the workload of the anesthetist in the operating room is markedly reduced. Both of these

findings are important in a context of clinical anesthesiology. As far as the overall costs are concerned, using of the system reduces the expenditure on muscle relaxants.

In Section 2, basics of general anesthesia are surveyed. Sections 3 and 4 present our approach to automatic control of neuromuscular block. We describe three parts of the developed system: hardware, software, and the control algorithm. In Section 5, the clinical tests results are summarized. Section 6 contains conclusions and an outline of future research and development of the system.

2. The concept of modern general anesthesia

Modern general anesthetic technique must guarantee that its three essential parts, i.e. narcosis, analgesia and muscle relaxation, be adequately covered. In simple terms, during general anesthesia, the patient must sleep deeply enough, must not suffer pain, and has to be adequately relaxed. With selective drugs, it is possible to vary just one component of this triad without affecting the others. While this principle can be advantageous (total amount of all drugs can be reduced), when improperly used, it may create a situation that is dangerous and potentially harmful to the patient. During poorly balanced general anesthesia, it is possible for example to have the patient totally paralyzed (he/she cannot breathe or move at all) without providing adequate level of unconsciousness. That is why exact information about all of the general anesthesia modalities is of utmost importance.

Neuromuscular blockers are drugs used during general anesthesia to produce muscle relaxation (paralysis) of striated muscles; they neither have analgesic nor hypnotic properties. During anesthesia, the degree of neuromuscular block (NMB) must be sufficient to provide adequate surgical conditions but not as excessive as to make it difficult to antagonize at the end of surgery. Neuromuscular blockers are usually administered intravenously as repetitive bolus doses. This method necessarily results in both over- and undershooting of the effect. Furthermore, there is a wide interindividual variation in dose response and dose requirements may also vary during long procedures.

While a continuous relaxant infusion is an appropriate technique for long-lasting operations, infusion rates need to be adjusted repeatedly to maintain a given level of neuromuscular blockade and a manual control of pump speed is time-consuming. If this adjustment is performed automatically, the anesthetist is freed to attend to other aspects of patient care.

Traditionally, the degree of neuromuscular block during anesthesia is seldom monitored. Usually, the anesthetists assess the level of block just on the basis of clinical signs. This estimation is very imprecise and can be confusing, that is why the neuromuscular monitoring introduces considerable improvement in anesthetic care. The principle of *neuromuscular transmission* (NMT) monitoring is fairly simple. A peripheral nerve stimulator delivers an electric current of variable frequency and pattern to a pair of electrodes placed over a peripheral motor nerve (usually at patient's distal forearm). The evoked mechanical or electrical response of the innervated muscle is observed. As a result of the administration of neuromuscular blocker which acts on the neuromuscular junction, the transmission through these synapses is impaired, resulting in a decrease of the evoked muscle response. Because the degree of neuromuscular block can be measured reliably and practically continuously, this information can be used for a closed-loop controller of muscle relaxant administration.

3. Fuzzy control of muscle relaxants delivery

The rationale of our system for automatic control of NMB during general anesthesia originates from the following prerequisites. Due to state-of-the-art instruments, a reliable and precise monitoring of neuromuscular transmission is available. An expert anesthetist is able to provide us with a control strategy of muscle relaxants delivery. This strategy is described in a natural language in the form of if-then rules. The rules refer to the variables measured during the monitoring (if-part) and to the variables describing the amount of relaxants to be administered to the patient (then-part). This set of rules can be translated into a set of fuzzy if-then rules of a fuzzy controller. The whole system can be implemented in a way which fulfils the safety requirements necessary for clinical

practice. In addition to that, a continuous anesthetist's supervision makes it possible to override the automatic control instantly whenever he/she considers it necessary. This is important for controller testing and tuning. As a result, the system can be tuned even while clinical testing.

Neuromuscular transmission can be monitored in several ways but the principle is the same. Namely, we evaluate a muscle response to an electric stimulation of a peripheral nerve. The most common stimulation patterns are single twitch stimulation (TW), tetanic stimulation (TET), train-of-four stimulation (TOF), double burst stimulation (DBS), and post-tetanic count (PTC), see Miller (1994). The evoked muscle response can be quantified using various physical principles, the most common ones being mechanomyography (MMG), electromyography (EMG), accelerometry (ACC), and phonomyography (PhMG). In our approach, we used T_1 value in TOF stimulation pattern because it reflects the desired target level of neuromuscular block. For evaluation of muscle response, we employed electromyography since it is fairly resistant to motion artifacts.

In the rest of this section, we describe an algorithm for automatic delivery of muscle relaxants. The algorithm is based on the anesthetist's expertise. We describe a general idea of the algorithm and, in particular, the part where fuzzy control plays its role. We present a control strategy of the anesthetist in terms of "points" describing the state of the variables. The "points" represent a natural way to describe the strategy for the expert anesthetist. For the sake of illustration, we also list the default values which, in fact, represent the parameters of the control strategy.

After the induction of general anesthesia but before the administration of muscle relaxant, the NMT monitor determines the amplitude of a supramaximal impulse and the intensity T_{ref} of the corresponding muscle response. The main aim then is to deliver a muscle relaxant in order to keep the value of T_1 (muscle response) at a desirable level, compared to T_{ref}. This level, called a target level, corresponds to the desirable muscle relaxation. Typically, T_1 is set to 10 % of the T_{ref} value (default value). After the determination of

T_{ref}, a bolus dose of rocuronium (Esmeron®, Zemuron®, Organon) (0.6 mg . kg^{-1} by default) is administered at a bolus speed (1200 ml . hr^{-1}). In order for the automatic control to start, the T_1 value needs to drop below point X (default value 5%). If this does not happen within 5 minutes, another bolus dose is administered (supplementary bolus, default 0.15 mg . kg^{-1}) at bolus speed and the system waits another 5 minutes. The repetition of supplementary bolus is limited (two times by default). If T_1 does not drop below point X, the automatic control stops and a manual intervention is requested. If T_1 drops below point X, automatic control continues by setting the speed of the infusion pump to zero (since the patient is deeply relaxed below point X). Then, a "hunt" for a target level of T_1 begins. The "hunt" is described in terms of points Z, A, B, C, and D.

- Point Z is reached when the value of T_1 exceeds a predefined value (default 20 % of T_{ref}). In such a case, a bolus dose (0.2 mg . kg^{-1} by default) is administered at a bolus speed.
- Point A is reached when the value of T_1 increases (ΔT_1 positive) and comes close to the target level (around 9.5% of T_{ref} by default). In this case, the pump speed is set to "low speed" (0.2 mg . kg^{-1} . hr^{-1} by default).
- Point B is reached when the value of T_1 increases (ΔT_1 positive) and departs from the target level (around 10.5% of T_{ref} by default). In this case, the pump speed is set to "high speed" (1.0 mg . kg^{-1} . hr^{-1} by default).
- Point C is reached when the value of T_1 is decreasing (ΔT_1 negative) and approaches the target level (around 10.5% of T_{ref} by default). In this case, the pump speed is set to "low speed."
- Point D is reached when the value of T_1 is decreasing (ΔT_1 negative) and departs the target level (around 10.5% of T_{ref} by default). In this case, the pump speed is instructed to stop ("zero speed").

This strategy can be converted into a look-up table shown in Tab. I.

TABLE I TO BE PLACED HERE

The rows of the look-up table correspond to the values of T_1 which are, in fact, used by the anesthetist when describing his strategy: Z means "approximately point Z or more" (i.e. approximately 20 % of T_{ref} or more by default); TL means "approximately the target level" (i.e., approximately 10 % of by T_{ref} default), TL+ means "approximately the upper boundary of target level" (i.e., approximately 10.5 % of T_{ref} default), TL- means "approximately the lower boundary of target level" (i.e., approximately 9.5% of T_{ref} default), ATL means "between the upper boundary and Z" (i.e. between approximately 10.5 % and 20 % of T_{ref} by default), BTL means "below the lower boundary" (i.e. below approximately 9.5 % of T_{ref} by default). The columns of the look-up table correspond to the values of ΔT_1 used in the strategy: POS means "positive or zero", NEG means "negative." The table entries contain values of the infusion pump speed: BOLUS means the administration of bolus dose (rocuronium, 0.2 mg . kg^{-1} by default) at bolus speed (1200 ml . hr^{-1}); LOW means "low speed" (rocuronium, 0.2 mg . kg^{-1} . hr^{-1} by default), HIGH means "high speed" (rocuronium, 1.0 mg . kg^{-1} . hr^{-1} by default), STOP means "zero speed."

The look-up table, in fact, encodes a set of if-then rules (if T_1 is TL+ and ΔT_1 is POS then speed is HIGH, etc.). Therefore, a fuzzy controller can be employed with this set of if-then rules as its rule base provided the fuzzy sets corresponding to Z, ATL, ..., BTL, POS, NEG, HIGH, LOW, STOP will be specified. For fuzzy sets describing the values of T_1, we used triangular and trapezoidal fuzzy sets determined by the default values (these can be set prior to starting the algorithm). For fuzzy sets describing the values of ΔT_1, we use crisp sets corresponding to "positive or zero" and "negative". For the values of pump speed, we use singletons determined by the default values. Applying then a Mamdani-type inference with a mean of maxima defuzzification gives us the simplest algorithm for hunting for the target level.

Note that the basic algorithm allows for obvious modifications – refinements due to distinguishing more states of the involved variables. For instance, the basic algorithm

distinguishes only “positive or zero” and “negative” and except for BOLUS and STOP, we distinguish only two values of pump speed. It is interesting to note that even this simple version of “hunting for target level” yields satisfactory results, see Sec. 5.

4. Relax 2005: a system of automatic fuzzy control during general anesthesia

In this section, we describe Relax 2005–the system we developed during our study. The system consists of its hardware part and its software part, which involves the fuzzy control algorithm. The basic scheme of the system is depicted in Fig. 1.

FIGURE 1 TO BE PLACED HERE

4.1 Hardware

The hardware part of Relax 2005 consists of mutually interconnected devices (NMT monitor, infusion pump, MOXA server for serial communication via Ethernet network, 3COM wireless access point, laptop, 3COM Wi-Fi PCMCIA card for laptop, NMT signal simulator Datex, and interconnection cables). The patient is attached to the NMT monitor via cable and to the infusion pump via intravenous line. In what follows we describe the components of the hardware part.

- NMT monitor (Datex Ohmeda S/5™) is a modular device for patient monitoring during anesthesia. The NMT is measured in 10 sec intervals and the data is sent to MOXA server through a serial port.
- Infusion pump (Pilot Anaesthesia 2, Fresenius Vial) is a medical device for intravenous administration of drugs. It is connected to MOXA server and controlled by commands sent from the laptop by a running program which takes care of the automatic control of neuromuscular block (see Sec. 4.2).

- MOXA (NPort 5410) is a server for serial communication via Ethernet (10/100 Mbps) and provides an interface between the medical devices (NMT monitor and infusion pump) and the wireless access point.
- 3COM Wireless access point makes possible a wireless communication (Wi-Fi signal) between MOXA server and a laptop. For this purpose, the laptop is equipped with a 3COM Wi-Fi PCMCIA card.
- Laptop is a standard Windows-based PC. Relax 2005 software is installed on the laptop.
- In addition to the above-described devices, we used an NMT signal simulator (Datex-Ohmeda 871251). The simulator was used during testing and tuning Relax 2005 system in laboratory settings.

4.2 Software

The software part of Relax 2005 is a computer program installed on a laptop. Software (SW) Relax 2005 serves two main purposes.

1. The software enables us to monitor, collect, and display data during anesthesia. The data is used by the expert anesthetist both for supervision of the patient's state during the operation (the data is displayed on the laptop screen) and for subsequent analysis after the surgery has finished (data is stored on hard disk).
2. The software makes it possible to design a rule based fuzzy controller and to run the control algorithm for automatic administration of the muscle relaxant during anesthesia.

SW Relax 2005 (Hropko and Ludma, 2006) was written in C# programming language for MS Windows platform. A modular structure makes it possible to extend the software by further functions. An important feature of the software is its configurability by a user via configuration dialogues. For instance, a user can configure the user interface (i.e., the outlook of the display). This is important since the anesthetist needs to have the data displayed so that the basic data can be read quickly and immediately, and additional relevant data can be accessed by a minimum number of keyboard presses. The software

offers a number of predefined visualization components that can be used for displaying the data and for the control of infusion pump with muscle relaxant. The components can be arranged in a modular way to meet the particular needs of the anesthetist. In what follows, we describe the software capabilities by describing a typical session. This gives an impression of how Relax 2005 is being used in the operating room.

After the start, the program runs in the operating memory of a computer (laptop). All data related to Relax 2005 is continuously stored on hard disk. The system stores data of medical relevance (the value of supramaximal impulse, value of T_1, TOF-ratio, speed of infusion pump, amount of relaxant administered, etc.) and technical data (system log).

At the beginning, a window appears with three cards. The first card (Input data) contains data related to the patient, data related to the muscle relaxant, parameters of the bolus dose, and parameters used by the algorithm of control. This information needs to be entered at the start of the program. The second card (Device test) enables us to test if the communication between the computer, the NMT monitor, and the infusion pump works properly. A test of the devices and of the communication follows automatically entering the input data by a user. The third card (Main screen) provides a user with the information about the actual state of the whole system as well as about the history since Relax 2005 start.

A correct functioning of the devices and of the communication is tested continuously during the whole run-time of the program. In addition to that, the software detects suspicious values of the observed variables. This enables the software to detect artifacts like disturbance of the signals by noisy environment, by mechanical intervention, motion artifacts, etc. A user is informed via a multilevel control mechanisms, warnings, and alarms. The warnings and alarms are organized according to their priorities. The alarms with highest priority immediately stop the infusion pump and warn the anesthetist acoustically as well as by a flashing display.

Relax 2005 system can operate in three modes:

- Automatic mode (Bolus + Regulation): The system administers a bolus dose and then continues with automated delivery of muscle relaxant according to the control algorithm.
- Semiautomatic mode (Regulation only): The same as the automatic mode except for the application of the initial bolus dose which is skipped in this mode.
- Mode with no regulation (Data collection): The system just collects and stores data without controlling the infusion pump. This mode is useful for testing of farmacodynamic profiles of muscle relaxants.

5. Results of clinical tests

5.1 Method

A clinical testing of Relax 2005 system was approved by the Medical Ethics Committee of the University Hospital of Olomouc and the Faculty of Medicine of the Palacky University of Olomouc. 50 patients undergoing neurosurgical intracranial intervention with tracheal intubation were enrolled in the study. We obtained a written informed consent from each patient (declaring his/her awareness of the risk related to use of this system). Exclusion criteria were patients of ASA classes > 3 (American Society of Anesthesiologists risk classification), those less than 18 years old, those with disorders known to interfere with neuromuscular function and those where surgery was expected to last less than 2 hours. Anesthetic management was standardized. We used total intravenous anesthesia (TIVA) with target-controlled infusion (TCI) of propofol (TCI sec. Schnider 2.0 μg . ml^{-1}) and sufentanil (TCI sec. Gepts 1.8 ng . ml^{-1}). After the induction of anesthesia, Relax 2005 system was started in Bolus + Regulation mode. Neuromuscular transmission was determined with NMT module of Datex-Ohmeda S/5™ Anaesthesia Monitor (stimulation pattern = TOF, input parameter of regulation = T_1, impulse width = 200 μsec, TOF repetition interval = 10 sec, impulse intensity = supramaximal, nerve stimulated = ulnar n., evaluation method = electromyography,

muscle monitored = adductor pollicis or interosseus dorsalis I. m., electrodes = skin surface Ag/AgCl). Infusion line of Pilot Anaesthesia 2 infusion pump (Fresenius Vial) was attached to the patient.

The efficacy of regulation was assessed by data collected during a regulation phase. This phase started with the first infusion pump run-up following the pause after initial bolus dose and its end was represented by stopping the system by anesthetist. For every T_1 reading obtained during regulation phase, the real error from the target level was computed. These errors were analyzed with SPSS software package (SPSS for Windows, 12.0.1): mean, standard deviation, range, root mean square deviation (RMSD), point count (PC). RMSD gives an index of the extent of spread of values about the target, irrespective of whether they were below or above the target. Point count (PC) is a number of values above the target expressed as a percentage of all measured values and indicates if the block achieved tended to lie above or below the target. For each consecutive patient, the rocuronium consumption was computed either as the mean dose rate during the regulation phase or together with the initial bolus dose.

5.2 Results

Relax 2005 system was used in 50 patients (23 males, 27 females) during general anesthesia for neurosurgical operations with an expected duration of more than 2 hours. Demographic data of the patients are summarized in Tab. II.

TABLE II TO BE PLACED HERE

For every patient, a reliable neuromuscular monitoring was set up with correct determination of supramaximal impulse and reference T_1 value. After system start, an initial bolus dose for facilitation of tracheal intubation was automatically administered. After partial recovery from this deep blockade, the regulation phase ensued. Never during this phase was it necessary to administer a rescue bolus dose (i.e., initiated by the program) nor a manual bolus dose (i.e., requested by the anesthetist). The average operating time of the system (per 1 patient) was 162.2 minutes (with the span from 32.8 to 618.5 minutes). The total operating period (sum over all patients) exceeded 135 hours

with the total of more than 45,000 of NMT measurements and corresponding changes of pump speed (control actions). The results are given in Tab. III.

TABLE III TO BE PLACED HERE

5.3 Discussion of the results

Relax 2005 system was able to maintain a stable level of neuromuscular block during prolonged neurosurgical operations. During the regulation phase, the curves showed outstanding stability with very small T_1 fluctuations around the target level. After switching the automatic system off, the neuromuscular block subsided rapidly (typically within 15 minutes) or it could have been antagonized easily.

Both mean T_1 error (-0.27 %) and mean PC (41 %) indicate that the resulting neuromuscular block was kept a little below the target level. A change of the regulation algorithm could probably decrease this imperfection, but this is of no clinical relevance. An important point to stress is that the precision of Relax 2005 system is superior by approximately one order of magnitude to that one which can be achieved by manual control of the infusion pump speed. Moreover, from the practical point of view, one can hardly imagine the anesthetist observing the NMT monitor every 10 seconds and making accordingly corrections of the pump speed in the same intervals. A PC-controlled closed-loop regulation fulfils this task with ease – the quality of regulation remains constant during the whole anesthetic course.

A possible danger to the precision of NMT measurement is represented by diathermocoagulation used during surgery and by motion artifacts. As a result of these, the evoked electromyographic response may be distorted, giving thus inadequate input information about the depth of the blockade to the controller. During clinical tests we did not experience this difficulty. The NMT module used for measurements showed good resistance to the artifacts. The safety of the regulation process was further improved by software-based errors detection incorporated in Relax 2005 system.

The effect of muscle relaxant (neuromuscular block) does not follow immediately its intravenous administration. There is a lag interval between intravenous injection and measurable effect (i.e., deepening the blockade) that depends on several factors; only some of them can be influenced by the controller design. During a closed-loop automatic control, the interval between T_1 measurement and reaction of the system is negligible. This is, however, not true when considering the interval between the infusion speed change, transport of the muscle relaxant to the effect site, and producing the effect. Relaxant administration through the central venous line can reduce this delay; also important is priming the intravenous line with relaxant in concentration that is used in the syringe of the infusion pump. The quality of muscle relaxant the system uses is important, too. While in our previous closed-loop system (Adamus, 2001) we used atracurium (Tracrium®, Glaxo) nowadays we prefer rocuronium (Esmeron®, Zemuron®, Organon) because of its better farmacodynamic profile with rapid onset and good predictability of action (Adamus et al., 2005). With rocuronium, Relax 2005 system offers better flexibility and promptness compared to atracurium.

During general anesthesia, the consumption of muscle relaxant is influenced by many factors, type of anesthesia and simultaneous administration of volatile inhalational agents being the most important. An interaction with volatiles was avoided by using total intravenous anesthesia throughout our study. In spite of that, considerable differences in patients' sensitivity to rocuronium were demonstrated (reaching 500 % as judged by the rocuronium consumption). The average rocuronium consumption during regulation phase was 0.32 mg . kg^{-1}. hr^{-1} which is close to the lower limit recommended by the manufacturer (0.3 – 0.6 mg . kg^{-1}. hr^{-1}).

6. Conclusions

Our study demonstrates the potential of fuzzy systems in medicine and in anesthesiology in particular. The following conclusions summarize the main benefits of fuzzy control of neuromuscular block during general anesthesia which became apparent in our study. Relax 2005 system was able to maintain a stable level of neuromuscular blockade

throughout general anesthesia for long neurosurgical procedures. As no human intervention is needed during the regulation, the clinical workload of the anesthetist is reduced, allowing him/her to spend more time for other aspects of patient care. Controlling the depth of neuromuscular block in an automatic way improves the efficacy of muscle relaxant delivery and enables the patient to receive a minimum amount of drug. In addition to that, the automatic control prevents under- and overdosing on muscle relaxants. A considerable feature of our system is its flexibility: During regulation phase, the selected target level of neuromuscular block (T_1 = 10 %) is both deep enough for enabling surgery and not so excessive as to prolong the recovery from the block. Following the switching-off the infusion pump, full muscle strength either recovers spontaneously or this procedure can be accelerated with relaxant antidote (neostigmine). Typically, this strategy allows the anesthetist to terminate the neuromuscular blockade within 15 minutes irrespective of the regulation phase duration.

As far as the medical costs are concerned, using of the system cuts down the expenditure on muscle relaxants. For junior anesthetists, Relax 2005 system can be used as a "teacher" of or a "guide" to the muscle relaxant administration strategy. This relates to a broader aspect of using fuzzy logic in medicine. Namely, a fuzzy logic model reveals the structure of medical knowledge, makes it explicit but still close to understanding of a medical doctor. Nevertheless, the role of any system of automatic control of drug delivery is complementary. A continuous presence of anesthetist in the operating room remains a *conditio sine qua non* of safe general anesthesia.

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FIGURE 1
Caption:
Fig. 1. Hardware part of Relax 2005.

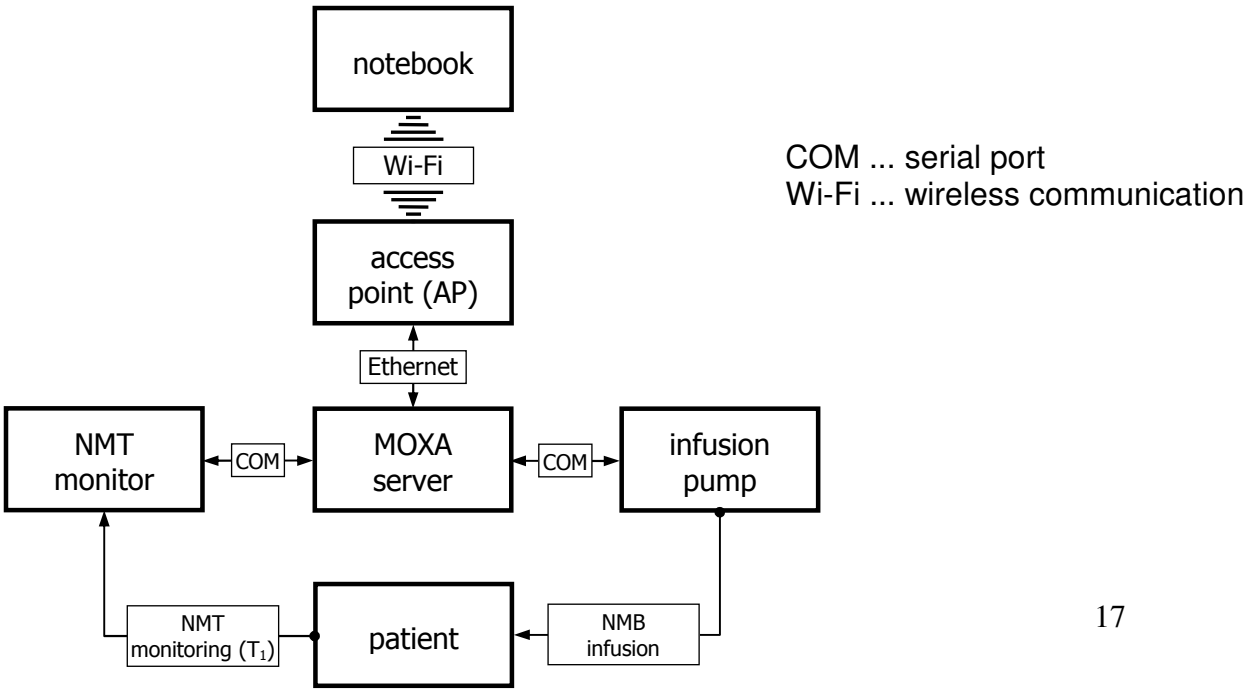

TABLE I

T_1 \ ΔT_1	POS	NEG
Z	BOLUS	BOLUS
ATL	HIGH	HIGH
TL+	HIGH	LOW
TL	LOW	LOW
TL-	LOW	STOP
BTL	STOP	STOP

TABLE II

	mean	SD	min	max
age (yr)	48.5	14.8	21	72
ASA	1.8	0.6	1	3
weight (kg)	74.2	13.9	47	100
height (cm)	170.1	8.8	153	186
BSA (m^2)	1.89	0.19	1.50	2.23
BMI ($kg \cdot m^{-2}$)	26.19	3.37	18.37	29.76
supramax (mA)	44.9	11.4	23	70

Table II Demographic data

ASA ... ASA (American Society of Anesthesiologists) classification, BSA ... body surface area, BMI ... body mass index, supramax ... supramaximal impulse, SD ... standard deviation, min ... minimum, max ... maximum

TABLE III

	mean	SD	min	max
duration of bolus dose (min)	24.8	9.6	14.0	48.4
duration of regulation phase (min)	122.8	71.1	18.2	584.6
operation time of Relax 2005 (min)	162.2	75.7	32.8	618.5
T_1 error during regulation (%)	-0.27	0.28	-1.44	0.69
variation of mean error T_1 (%)	1.24	0.37	0.24	2.31
RMSD (%)	1.08	0.53	0.18	2.14
PC (%)	41.0	10.2	18.2	66.3
rocuronium consumption (mg . kg^{-1}. hr^{-1})				
during regulation phase	0.32	0.22	0.08	0.54
total	0.54	0.32	0.16	0.81

Table III Parameters of regulation with Relax 2005 system

RMSD ... root mean square deviation, PC ... point count, SD ... standard deviation, min ... minimum, max ... maximum