P.Grant, Ol.Naesh

THE APPLICATION OF FUZZY LOGIC SCIENCE TO ANAESTHETICS

Department of Anaesthetics
Timaru Hospital
South Canterbury, New Zealand

Summary: How do we make decisions? Decision-making is central to the role of the Anaesthetist who supports and controls the unconscious patient. The processes of 'Fuzzy Logic' are explored and its' multiple applications to the field of Anaesthetics are assessed. It offers greater benefits and efficiency than existing techniques and also has important implications for future practice .

Introduction

Anaesthesia can be described as the control of the continuum between consciousness and unconsciousness, pain and analgesia, muscle activity and relaxation, 'The inhibition of activation and the enhancement of inhibition' (1). The decision making behind this balancing act is the core of anaesthetics and in this paper we discuss this process and how the use of Fuzzy Logic is revolutionising the practice of anaesthesia.

The Feedback Circuit

During an operation, an anaesthetised patient is part of a 'feedback circuit'.. There is a system in place whereby changes in the patients condition e.g. blood pressure or respiratory rate, are monitored and adjustments made accordingly to stabilise the patient (via ventilation control and drugs) (2).

The anaesthetist is the controller and decision-maker in this loop. As such, there will be varying thresholds for action between different anaesthetists, in response to ever changing variables such as; low blood pressure, tachypnoea or decreasing oxygen saturation. It is these imprecisely defined patterns of thinking that play such an important role in human behaviour and this is why the emergence of fuzzy logic is so important to the art and science of anaesthetics.

What is Fuzzy Logic?

How do you define statements like, "turn up the induction agent a little" or "move the patient down the table a fraction". Fuzzy logic (FL) is simply a conclusion reached by a computer which recognises that all values are not absolutes such as yes or no or black and white. FL makes calculations considering varying degrees between absolutes. For example, it may recognise black and white, yet make an evaluation based on a shade of grey which is somewhere in between.

It provides a simple way to arrive at a definite conclusion based upon vague, ambiguous and imprecise data. In essence the approach is to solve problems by mimicking how a person would make decisions, only much faster.

Consider what happens when you get into a shower and the temperature is too cold, you'll make the water comfortable very quickly with little trouble. FL mimics this kind of behaviour. It is a simple, rule-based system and is empirically based (eg. If X and Y then Z). FL can be used to monitor biological systems that would be difficult or impossible to model with simple, linear mathematics. It opens the door for control systems that would normally be deemed unfeasible for automation.

This is achieved through the use of adaptive controllers, which use a simplified form of human 'fuzzy' thinking. An adaptive controller is any control system with adjustable inputs and outputs and a mechanism for altering them. It contains two loops, a control loop and a parameter adjustment loop. In practice any kind of automatic system can be set up so long as your goals are defined. An example would be blood pressure control during surgery. A fuzzy control device can monitor the patient's BP, if it is too low, then the IV fluids will be run in faster, until a satisfactory BP value is achieved.

Applications in Anaesthetics

Already much work has been done in the field of anaesthetics to apply the benefits of FL control (2,3). The following examples indicate the inherent reliability and stability of FL in the world of complex, dynamic systems.

Fuzzy Logic Control of Mechanical Ventilation

Artificial ventilation of the lungs represents a continuous process during which optimal values of arterial O2 and CO2 partial pressures must be achieved, whilst ensuring careful handling of the lung, avoiding cardiac failure and fatigue of the respiratory muscles.

In one particular study by Schaublin (4) a fuzzy logic programme was used to monitor SpO2 and end tidal CO2 in a series of ventilated patients and made automatic alterations in ventilatory frequency and tidal volume in order to achieve and maintain the end tidal CO2 at a desired level. The system was successful in its goal and when compared to the anaesthetist's standard control under similar conditions; accuracy, stability and breathing pattern did not differ significantly between the two.

Similarly, there is no universally agreed approach to weaning patients with respiratory insufficiency from ventilation. FL control systems have been applied to the management of pressure support ventilation e.g. BIPAP, in intensive care units, using measurements of heart rate, tidal volume, breathing frequency and oxygen saturation. In a study by Nemoto (5) the FL system agreed 88% of the time with it's anaesthetist counterparts concerning pressure adjustments and was found to be somewhat less aggressive in reducing support levels of ventilation from the ongoing measurements of a patients vital signs. Whether this is safer is an interesting question.

Control of Inspired Anaesthetics & Blood Pressure

Studies on the performance of FL control of inspired oxygen and volatile anaesthetic agents such as Isoflurane have shown that it can achieve and maintain very accurately the desired gas concentrations in comparison with anaesthetist control (6). This is managed through the alteration of gas flow rates to achieve the best range of oxygen concentration and MAC (mean alveolar concentration of isoflurane).

One interesting development was the discovery that oxygen concentration was controlled more precisely by FL. Therefore during minimal flow anaesthesia, FL control of inspired gases (O2, N2O, volatile anaesthetics) has been shown to be reliable and as a bonus to reduce anaesthetic gas delivery and costs.

One of the most important measures in estimating the required dose of inhaled anaesthetics and the haemodynamic status of the patient is arterial blood pressure. This can be measured very easily and reacts rapidly, which makes it suitable as a variable for feedback when controlling the depth of anaesthesia. FL has been used in several studies of the control of the inhaled concentration of isoflurane during ventilation. FL control pressure values were found to be consistently close to the requisite mean arterial blood pressure values throughout (7,8). The same system can also be employed in reverse, ensuring a stable blood pressure during an operation, if this is the most important output to address.

Post Operative Pain Control

Patient controlled analgesia (PCA) has led to significant improvements in post operative pain control. Managed by the patient' own conscious feedback on a supply and demand basis. However it still has several drawbacks in that a patient may be drowsy or confused post operatively, pain may be too great to allow them to move, the PCA button may be misplaced, the patient may be too stoical to use pain relief medication or even unaware of the nature of the discomfort that they are feeling and the need for analgesia.

For these reasons, perfusion pumps containing analgesics have been developed which act under the guidance of FL control. The best example is the regulation of opiate infusions that react to the patient's physiological pain response (9). In practice such systems manage to maintain a patient's target analgesic values 77% of the time. These devices use adaptive controllers which monitor the objective markers of pain; changes in temperature, cardiac and respiratory rate, increases in catecholamines and altered pain fibre activity / evoked potentials (10). And then respond by increasing or decreasing infusions of opiates accordingly. If pain becomes severe then mini-boluses can be titrated to effect and the system is fitted with a safety mechanism which halts the infusion in case of desaturation, bradypnoea or significant pulse and BP variations.

Whilst not optimal, the implication is that FL can be used in the future to obtain adequate pain relief post operatively, working in concert with the patient's demands and ensuring that enough analgesia is being administered when required.

Neuromuscular Blockade during Surgery.

FL control of muscle relaxants is an emerging area. Patient responses to such medications exhibit a high degree of variability and patient dose requirements vary greatly intra-operatively. By monitoring the rate of drug delivery and analysing feedback from a sensor that measures muscle relaxation level, the amount of drug given can be adjusted to achieve the best results.

In recent studies the FL programme administers mini-boluses of non-depolarising muscle relaxants; atracurium (11), pancuronium (12) or rocuronium (13) and modulates the magnitude and time interval between the bolus doses to maintain a patients' muscle relaxation within an allowable range specified by the user. Before each new dose is given, the FL adaptation scheme uses the error between the predicted response and the measured response to learn and adapt the model. By monitoring neuromuscular excitability with a train–of-four stimulator the FL system responds with adjustments to drug infusion to maintain neuromuscular blockade. FL performed favourably with regard to both human and computational models of muscle relaxant drug delivery. FL control architecture can provide stable control of NM block despite considerable patient variation. Through the use of continuous infusion regulation rather than intermittent bolus injections of drug, FL produces less variability in the levels of achieved relaxation and in this way patients receive the minimum dosage of drug necessary to achieve adequate relaxation (14).

Discussion

The field of anaesthetics provides numerous opportunities for the applications of fuzzy logic and indeed the majority of research is application-driven. FL provides a simple but dynamic approach to sensitive, safety-critical problems by means of monitoring a patient's vital signs. Discrete adjustments are made to reach a desired output based on straightforward linguistic rules. In the majority of the above examples FL performed as well if not better than its' human counterparts.

The development of automated 'intelligent' systems has several benefits, they are more reliable than manual interventions because they are not prone to fatigue as are clinical staff in a busy, stressful environment, they can also reduce the clinical workload giving more time for staff to give direct patient related attention to critical events.

Advances in FL controlled drug delivery systems could serve as a valuable clinical research platform for the study of drug interactions and FL offers a fast, efficient and safe mechanism for supporting anaesthetised patients peri-operatively.

The drawbacks highlighted so far include occasions when FL systems do not match standard human performance and this often relates to inadequate programming (it still requires an expert anaesthetist to set the rules for how an expert system should behave). Also FL lacks innate intuition, humans are still good at acting beyond set rules. However, failure of FL systems are rare and they remain as good as their programmed goals. FL has the ability to learn and adapt, giving it far more potential than fixed Boolean computer algorithms (1,15).

Why Use Fuzzy Logic?

Biological systems cannot be modeled mathematically with great ease, they often behave erratically or with 'non-linearity', responses are constantly changing, so a fuzzy approach that imitates human thinking is often better to support them.

FL is a rule-based approach to problems meaning that it can efficiently represent an expert's knowledge about a situation. These rules are based on linguistics, which allow flexibility and are simpler to understand and implement than complex algorithms. This means that the output of any such systems will be a smooth function rather than a lurch between all or nothing.

FL is considered to be an ideal tool for supplementing the work of the anaesthetist as it can work from approximate data, extract meaningful information and produce crisp solutions.

Complex processes such as maintenance of a patient's blood pressure can be controlled by a few relatively simple rules. This is part of the holy grail of FL in anaesthetics, an all-encompassing system which monitors and adjusts all the patient's vital signs; controlling ventilation, relaxation, haemodynamic status, analgesia and sedation interdependently.

Implications

The growth of FL does not mean to replace the anaesthetist per se, it is merely a control system to enhance their working. The equivalent benefits of say a computer over a typewriter. It is automatic and focused on patient safety, so the experience of the anaesthetist is complemented by a fast, continuous feedback circuit which makes subtle adjustments to keep an anaesthetised patient stable.

Possible future avenues for the use of FL in medicine include; in combination with tele-medicine and tele-surgery it is not unlikely that FL could be used for patient care where there is no fully trained anaesthetist available. Imagine a future of automated surgery and FL anaesthetic control. This means that one anaesthetist could be circulating through several theatres at any one time. Allowing multiple operations to proceed simultaneously with the anaesthetist on hand to deal with unpredictable events and emergencies. Anaesthetic support staff or nurses can connect IV lines and stabilise airways while the operation is monitored remotely. Fuzzy logic would work to a set of guidelines specific to the situation enabling the operation to continue and the responsive decision making position of the anaesthetist would be assumed by the automatic control of FL.

Currently the potential applications for fuzzy logic are limited only by our imagination.

References;

1.Grant, P. Naesh O. Medicine – A Non-Boolean Art? In Press.
2.Hayward G, Davidson V. Fuzzy logic applications. Analyst. 2003 Nov;128(11):1304-6.
3.Rau G, Becker K, Kaufmann R, Zimmermann HJ. Fuzzy logic and control: principal approach and potential applications in medicine. Artif Organs. 1995 Jan;19(1):105-12.
4.Schaublin J, Derighetti M, Feigenwinter P, Petersen-Felix S, Zbinden AM. Fuzzy logic control of mechanical ventilation during anaesthesia.Br J Anaesth. 1996 Nov;77(5):636-41.
5.Nemoto T, Hatzakis GE, Thorpe CW, Olivenstein R, Dial S, Bates JH. Automatic control of pressure support mechanical ventilation using fuzzy logic. Am J Respir Crit Care Med. 1999 Aug;160(2):550-6.
6.Sieber TJ, Frei CW, Derighetti M, Feigenwinter P, Leibundgut D, Zbinden AM. Model-based automatic feedback control versus human control of end-tidal isoflurane concentration using low-flow anaesthesia.Br J Anaesth. 2000 Dec;85(6):818-25.
7.Zbinden AM, Feigenwinter P, Petersen-Felix S, Hacisalihzade S. Arterial pressure control with isoflurane using fuzzy logic.Br J Anaesth. 1995 Jan;74(1):66-72.
8.Curatolo M, Derighetti M, Petersen-Felix S, Feigenwinter P, Fischer M, Zbinden AM. Fuzzy logic control of inspired isoflurane and oxygen concentrations using minimal flow anaesthesia.
Br J Anaesth. 1996 Feb;76(2):245-50.
9.Carregal A, Figueira A, Nunez M, Carollo A, Lorenzo A, Rey M, Gonzalez G. Fuzzy logic and postoperative pain Rev Esp Anestesiol Reanim. 1997 Jun-Jul;44(6):215-7.
10.Sharmann W. (1999) Physiological & ethological aspects of the assessment of pain, distress and suffering. In: Humane endpoints in animal experiments for biomedical research. London (United Kingdom): Royal Society of Medicine Press, 33-39.
11.Carregal A, Lorenzo A, Taboada JA, Barreiro JL. Intraoperative control of mean arterial pressure and heart rate with alfentanyl with fuzzy logic. Rev Esp Anestesiol Reanim. 2000 Mar;47(3):108-13.
12.Mason DG, Ross JJ, Edwards ND, Linkens DA, Reilly CS. Self-learning fuzzy control with temporal knowledge for atracurium-induced neuromuscular block during surgery. Comput Biomed Res. 1999 Jun;32(3):187-97.
13.Kern SE, Johnson JO, Westenskow DR. Fuzzy logic for model adaptation of a harmacokinetic-based closed loop delivery system for pancuronium. Artif Intell Med. 1997 Sep;11(1):9-31.
14.Shieh JS, Fan SZ, Chang LW, Liu CC. Hierarchical rule-based monitoring and fuzzy logic control for neuromuscular block. J Clin Monit Comput. 2000;16(8):583-92.
15. Mahfouf M, Abbod MF, Linkens DA. A survey of fuzzy logic monitoring and control utilisation in medicine. Artif Intell Med. 2001 Jan-Mar;21(1-3):27-42.

Paul Steven Grant
E-Mail: drpaul.grant@orange.net