Fuzzy logic and decision-making in anaesthetics

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The task of the anaesthetist is to control the continuum between consciousness and unconsciousness, pain and analgesia, muscle activity and relaxation—inhibition of activation and enhancement of inhibition.¹ During an operation, an anaesthetized patient is part of a 'feedback circuit' (Figure 1). Changes in variables such as blood pressure and respiratory rate are monitored and stability is restored by adjustments to ventilation and drug dosage.² The decision-maker and controller in this loop is the anaesthetist, who will make an individual judgment on how best to respond to, say, low blood pressure, tachypnoea or a decreasing oxygen saturation.

Computer programs employing 'fuzzy logic' are intended to imitate human thought processes in these complex circumstances but to function at greater speed. A simple computerized system might be based on the rule 'if *X* then do *Y*'. The drawback of such programs is that a large number of rules are needed to deal with every possible situation. In addition, if two or more indices are being measured the rule then becomes 'if *X* and *Y*, then *Z*' and the number of rules multiplies vastly. Fuzzy logic works by drastically reducing the number of rules and using proportionate amounts of each rule; and it can also 'learn' by assessing responses to changes in output. It thus opens the way to automation in circumstances that would be difficult or impossible to model with simple linear mathematics.

Figure 1. The control loop

APPLICATIONS

'Adaptive controller' is the name given to a system with adjustable inputs and outputs and a mechanism for altering them. It contains two loops—a control loop and a

parameter adjustment loop. The potential applications of such systems in medicine are very wide.^{1–3} The following examples illustrate the scope of fuzzy logic in the complex dynamic circumstances of anaesthesia.

Control of mechanical ventilation

Artificial ventilation of the lungs represents a continuous process during which arterial pO_2 and pCO_2 must be maintained at optimal levels consistent with avoidance of lung damage, cardiac failure and respiratory muscle fatigue. In a series of ventilated patients Schaublin and co-workers⁴ tested a fuzzy logic program that monitored pO_2 and end-tidal CO_2 and altered ventilatory frequency and tidal volume to keep end-tidal CO_2 at a desired level. The system was deemed to perform no less well than anaesthetists using conventional techniques under similar conditions.

Weaning from the ventilator, in a patient with respiratory insufficiency, is another procedure where there is no universally agreed approach. For determining the need for pressure support ventilation in intensive care, fuzzy logic systems have employed measurements of heart rate, tidal volume, breathing frequency and oxygen saturation. Nemoto *et al.*⁵ found that the computerized system agreed 88% of the time with its human counterparts concerning pressure adjustments and was somewhat less aggressive in reducing support levels of ventilation. Whether the patient is safer with this system remains to be determined.

Control of anaesthetic gases and blood pressure

When used to control dosage of volatile anaesthetic agents fuzzy logic systems have again performed almost as well as anaesthetists. For example, Sieber and colleagues⁶ reported accurate control of mean alveolar concentration of isoflurane by a system that altered the gas flow rates. In one study, during minimal flow anaesthesia, fuzzy-logic control of inspired oxygen, nitrous oxide and inspired isoflurane was actually superior⁷—an observation that might lead to economies in the use of this expensive agent.

One of the most important measurements for estimating the required dose of inhaled anaesthetics and judging the haemodynamic status of the patient is arterial blood

pressure. The ease of measurement and the speed at which it reacts to change make it suitable for feedback in systems that control the depth of anaesthesia. Zbinden *et al.*⁸ employed a system that regulated the inspired isoflurane concentration in response to changes in blood pressure, alternating this with manual techniques. At skin incision the fuzzy logic system performed better in terms of blood pressure control, but at subsequent intra-abdominal operation it performed slightly worse. The same system can work in reverse if a stable blood pressure during operation is the most important output to address.

Postoperative pain control

Patient-controlled analgesia (PCA), a supply and demand method managed by the patient's conscious feedback, has been a considerable advance in control of postoperative pain. However, drawbacks are that patients may be too drowsy or confused postoperatively to work it, the pain may be too great to allow them to move, the PCA button may be hard to find, and patients may opt not to use it because of stoicism or failure to recognize the nature of the discomfort they are experiencing. For these reasons, analgesic perfusion pumps have been developed that act under fuzzy logic guidance. The best example is an opioid infusion system that reacts to the patient's pain responses, titrating the effect of miniboluses and halting the infusion in the event of desaturation, bradypnoea, or large changes in pulse rate or blood pressure. The patient's target analgesia level was achieved 77% of the time.⁹ These devices are also applicable to work on laboratory animals, where the pain markers can include catecholamine concentrations and pain fibre activity.¹⁰ Although not yet perfect, fuzzy logic systems do seem promising for management of postoperative pain, in conjunction with PCA.

Neuromuscular blockade

The responses of patients to muscle relaxants are highly variable, and neuromuscular blockade is an emerging area for the use of fuzzy logic. The rate of drug delivery can be adjusted in terms of feedback from a sensor that measures muscle relaxation. Studies have been reported with the non-depolarizing agents atracurium,¹¹ pancuronium¹² and rocuronium.¹³ The fuzzy logic adaptation scheme measures the difference between predicted and measured responses (neuromuscular excitability with a train-of-four stimulator), learns from it and adapts the model to provide optimum neuromuscular blockade. Since the drug is infused continuously rather than given in boluses, the degree of relaxation varies little and patients receive the minimum amount necessary to achieve adequate relaxation.¹⁴

DISCUSSION

In the above examples, fuzzy logic usually matched the performance of an anaesthetist and sometimes exceeded it. Automated 'intelligent' systems of this sort are more reliable than manual interventions (they are not prone to stress and fatigue) and by reducing routine workload they should allow the anaesthetist to focus more on critical events. There have been occasions when fuzzy logic systems did not match routine performance by an anaesthetist, but this may be a matter of inadequate programming (fuzzy logic still requires an expert anaesthetist to set the rules). Also fuzzy logic lacks clinical intuition; an advantage of human anaesthetists is that they sometimes rightly ignore the rules. However, failures are rare, and the ability to learn and adapt gives them far greater potential than alternative computerized methods such as fixed Boolean algorithms.^{1,15} Moreover, their output is a smooth function rather than a lurch between all or nothing.

Enthusiasts for fuzzy logic in anaesthetics envisage an all-encompassing system that monitors vital signs and interdependently controls ventilation, relaxation, haemodynamic status, analgesia and sedation. However, nobody sees this replacing the anaesthetist: the aim is to enhance the anaesthetist's potential.

A possible future avenue for the use of fuzzy logic is in the management of patients where no fully trained anaesthetist is available. And, even in a large hospital, one can imagine a single anaesthetist being able to circulate from theatre to theatre, supervising multiple operations and dealing with unpredicted events while fuzzy logic systems make automatic adjustments determined by specific guidelines. The potential applications for fuzzy logic are limited only by our imaginations.

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