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ORIGINAL ARTICLE / RESEARCH

Fuzzy Expert System for Fluid Management in General Anaesthesia

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ABSTRACT

Background: Fuzzy set and fuzzy logic founded by Prof. Lotfi Zadeh (1965) make it possible to define inexact medical entities as fuzzy sets and models the subjective information. Fuzzy logic is reasoning with fuzzy sets. In medicine, the contradictory natures are common facts. Anaesthetists use *rules of thumb* when managing patients. He adjusts the drug and fluids inflow, or possibly ventilation, to monitor physiological state of the patient. Real-world knowledge is characterised by incompleteness, inaccuracy and inconsistency. It is not possible to define precisely the terms such as high temperature, low mean arterial pressure (MAP), very high intravenous fluid rate (IFR), and alike. The field of surgery and anaesthesia is very wide as many factors contribute to it, such as diagnosis, image processing, and path physiological reasoning and anaesthesia control. Fuzzy logic seems suited to use in anaesthesia because of the way it so naturally represents the subjective human notions employed in much of medical decision making.

Patient and methods: We have selected 71 patient ASA I–II classes, aged between 15 and 50 years and weight between 40 and 85 kg. In this sequel, we have made an honest attempt to incorporate fuzzy techniques and developed a fuzzy expert system for fluid management in general anaesthesia. MAP and hourly urine output (HUO) are the fuzzy input to the fuzzy expert system as the antecedent parts of the rule and the output is the defuzzified value of IFR at the desired level.

Results: We have predicted nine different fuzzy rules by using Min–Max approach, and eventually we find out the action that must be taken by using centroid approach. Then out of nine fuzzy rules four rules will be fired for patients. Based on COA, the computed value of IFR for the above set parameters, which for one sample of patient data was 118 ml/hr. Similarly, we calculated the results of fired rule for all 71 patients and got results that were in the range of predefined limit by the experts.

Conclusion: It could be done with minimal capital outlay by having a human operator periodically enter MAP and HUO values into a personal computer. The objective of the study was to estimate IFR based on the linguistic description of MAP and HUO sum of these four actions. The rates of change of MAP and HUO could be fuzzified into sets such as DECREASING, STABLE, and INCREASING and would serve to indicate the trend in a patient's fluid status. This would allow more precise control of fluid balance. Inputs from the domain experts and the judicious use of fuzzy techniques are important to achieve success. This modal is suitable for application only in otherwise healthy patients undergoing surgery involving minimal blood loss. For other patients undergoing surgeries involving moderate-to-severe blood loss, more complicated modals are needed utilising other parameters as well.

Key words: Fuzzy logic, fuzzy set, fuzzy expert system, general anaesthesia, mean arterial pressure (MAP), hourly urine output (HUO), intravenous fluid rate (IFR)

INTRODUCTION

The complexity of medical practice makes traditional quantitative approaches of analysis inappropriate. Fuzzy set theory, developed by Professor Lotfi Zadeh (1965) [1], makes it possible to define these inexact medical entities as fuzzy sets. Professor Zadeh coined the term linguistic variable in 1973 and that has opened the doors for fuzzy logic based modeling in the variety of areas of science and technology including medical informatics. The concept of partial membership that occurred to Professor Zadeh, Chair Professor Electrical Engineering and Computer Science (EECS) at University of California Berkeley USA in 1964 while he was visiting parents in New York. In 1973, he coined a new term *Linguistic Variable* and that has given rise to the term *Fuzzy logic* that is being extensively used by many in the world. Fuzzy logic is used for a wide variety of devices [2],[3].Fuzzy logic has been used in applications that are amenable to conventional control algorithms on the basis of mathematical models of the system being controlled, such as the high-frequency mechanical ventilator of Noshiro and coworkers [4]. It has a particular advantage in areas where precise mathematical description of the process is impossible and is thus especially suited to support medical decision-making [5].Fuzzy logic is reasoning with fuzzy sets. In medicine, the contradictory natures are common facts. The sources of uncertainty can be classified as follows [6]. (1) Information about the patient. (2) Medical history of the patient, which is usually, supplied by the patient and/or his/her family. This is usually highly subjective and imprecise. (3) Physical examination. The physician usually obtains objective data, but in some cases the boundary between normal and pathological status is not sharp. (4) Results of laboratory and other diagnostic tests, but they are also subject to some mistakes and even to improper behavior of the patient prior to the examination. (5) The patient may include simulated, exaggerated, and understated symptoms, or may even fail to mention some of them. (6) We stress the paradox of the growing number of mental disorders versus the absence of a natural classification [7]. The classification in critical (i.e. borderline) cases is difficult, particularly when a categorical system of diagnosis is considered. Fuzzy logic plays an important

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role in medicine [6],[8],[9],[10]examples showing that fuzzy logic crosses many disease groups are the following. (1) To predict the response to treatment with citalopram in alcohol dependence [11]. (2) To analyze diabetic neuropathy [12] and to detect early diabetic retinopathy [13]. (3) To determine appropriate lithium dosage [14],5]. (4) To calculate volumes of brain tissue from magnetic resonance imaging (MRI) [16], and to analyze functional MRI data [17]. (5) To characterize stroke subtypes and coexisting causes of ischemic stroke [18],[19],[20],[21]. (6) To improve decision-making in radiation therapy [22]. (7) To control hypertension during anesthesia [23]. (8) To determine flexor-tendon repair techniques [24]. (9) To detect breast cancer [25, 26], lung cancer [27], or prostate cancer [28]. (10) To assist the diagnosis of central nervous systems tumors (astrocytic tumors) [29]. (11) To discriminate benign skin lesions from malignant melanomas [30]. (12) To visualize nerve fibers in the human brain [31]. (13) To represent quantitative estimates of drug use [32]. The anesthetists probably use *a rule of thumb based on the principle of approximate reasoning* to determine the extent and direction of the adjustment in administering the fluid at an appropriate to an ailing patient. The decision on the Intravenous Fluid rate (IFR) using infusion pump is a function of both, Mean Arterial Pressure (MAP) and Human Urine Output (HUO). The degree of belief or partial truth in defining low, medium or high MAP, HUO and IFR ranges between 0 and 1. There are no two opinions that there exists uncertainty in decision making in all the sciences including medical sciences. We have to take decisions under the prevailing uncertain situations (in this case the decision on appropriate IFR). This calls for the application of the concepts based on fuzzy set and fuzzy logic Application of fuzzy logic in the field of anaesthesia is expanding rapidly and this sequel is a humble attempt of fuzzy modeling in general anesthesia. Degrees of truth are often confused with probabilities, although they are conceptually distinct, because fuzzy truth represents membership in vaguely defined sets, not likelihood of some event or condition. Fuzzy sets are based on vague definitions of sets, not randomness. Fuzzy logic allows for set membership (The membership function of a fuzzy set corresponds to the indicator function of classical sets) values between and including 0 and 1, shades of gray as well as black and white, and in its linguistic form, imprecise concepts like "slightly", "quite" and "very". Specifically, it allows partial membership in a set. It is related to fuzzy sets and possibility theory.

Patient and Method
Methodologies and the Study

We selected 71 patient ASA I-II classes in age between 15 to 50 yr and weight between 40 to 85 kg, undergoing various surgical procedures. The success of fuzzy rule based system (fuzzy expert system) depends upon the opinion of the domain experts on various issues related to the study.

Experts Opinion on MAP, HUO and IFR

The most important parameters for deciding the IFR are MAP and HUO. The opinions of the experts are detailed below:

Map is to be kept within normal Physiological limits. In low MAP There will be Dehydration, Blood loss, and any types of Shock. Normal MAP is due to normal homodynamic condition. Also High MAP is due to Light Plane of Anaesthesia, Hypertensive Patient, and cardiac Diseases (IHD, VHD). In other expert Observation they have got that the low MAP is due to deep plane of anaesthesia and Hypotension in optimized patient .The other Expert claimed that MAP is very important for vital organs blood Supply and Below 70 mmHg The organs like Liver and Brain likely to suffering from ischemia, In case of Hypotensive anaesthesia the Systolic B.P can be decreased to the tune of 60mmHg where MAP much below the acceptable lower limit for short period where the value can be consider as normal. In individuals who are hypertensive the range to be maintained on higher side. The higher MAP is undesirable. Other experts claimed that MAP of at least 80mmHg should be there for adequate vital organ perfusion and peripheral tissues. MAP below 80mmHg may provide adequate blood to peripheral tissue significantly producing lactic acidosis and produce anaerobic metabolism. MAP of grater than 100mmHg is unnecessary and may actually increased intro-operative blood loss and may results in congested operative field. In other expert idea the reason was that every vital organ in the body has a range of MAP for its optimal functioning. Below this the mechanism of auto regulation fails and the function of that organ will suffer. Therefore taking into consideration this range (<60mmHg) for organs like brain, kidney, liver, and heart. The experts defined their reasons as following: 0.5ml/kg of urine output is necessary to maintain the kidney function. Low map can happen due to dehydration, CRF (Chronic Renal Failer), acute renal Failer (ARF), and also normal due to Normal homodynamic management. High happened due to: over hydration, diabetics, non-diabetics, and ureoacidosis. The urine output is low because of dehydration, blood loss, inadequate fluid replacement, major abdominal surgeries, and laparascopy. The urine output was on higher side due to over infusion, lasix intro-operative and high plane of anaesthesia. Optimum urine output is 0.5-1ml/kg/hr .If higher amount of IV fluid is given the output will be high. We should label the output high only when it goes above the input. When the urine output is less than 0.5ml/kg/hr the kidneys are suffers, the high level of urine output is undesirable. The urinary output denotes adequate renal perfusion, functionally as well patient hydration status. Urinary output of 0.5-1ml/kg/hr is sufficient in normally kidney to ensure adequate perfusion. Urine output of more than 1ml/kg/hr may produce electrolyte imbalance especially hypokalemia. We have made humble attempt to implement the concept of Fuzzy Rule Based Systems that incorporated fuzzy techniques in decision-making on the application of IFR. Fuzzy logic algorithm uses the information on only two parameters in order to arrive to desired level of intravenous fluid rate (IFR). These include Mean Arterial Pressure (MAP), Hourly Urine Output (HUO). The algorithm considers both the values of these parameters at the time of decision are to be made, as well as their rates of change. The values of the parameter are used to arrive at a characterization of the patient's current condition, and the rates of the change are used to decide on the trend in this condition. Both current condition and trend are then used to decide if Intravenous Fluid Rate should be altered and by how much. Of course the duration of operation is an important parameter to be considered but we have sued this parameter while collecting the patient data and have seen that the duration of operation lasts a maximum of two hours (relevant only for the data collected).

A structured questionnaire was prepared for obtaining the experts views on the governing parameters (MAP, HUO, and IFR). The domain experts identified were from different hospitals from Pune and Iran. It was considered appropriate to interview these experts for obtaining the values for different levels (Low, Normal, and High) MAP, HUO and IFR .We were expecting membership grade 1 for some values of the parameters such as MAP Low (say up to 60 mmHg) and then it was a degreasing membership grade for MAP Low up to 75 mmHg (μ=0). Construction of fuzzy sets for the various linguistic descriptions of the parameters is heart of any fuzzy expert system. The exercise was repeated for MAP, HUO and IFR.

Results

Construction of Fuzzy Sets

The first step in the development of the fuzzy logic based expert system is to construct fuzzy sets for the parameters MAP, HUO, and IVF for the various linguistic variables such as low, medium and high in case of MAP, HUO and low, maintain, moderate, high very high. These fuzzy sets are designed based on the knowledge base of the domain experts. To put in other way, each parameter has a so-called range of discourse, which is partitioned into a number of overlapping fuzzy sets. The complexity of the fuzzy algorithm increases dramatically with the number of fuzzy sets. Each fuzzy set has amplitude associated with every point in its range that varies between 0 and 1, depending on how strongly a particular point in the range is considered to belong to that set.

The defined procedure was implemented for MAP and HUO as follows:

Considering MAP first, we note that this quantity may be either too high, acceptable, or too low, so we will divide its range of possible values into three corresponding fuzzy sets. Starting with the set corresponding to acceptable values for MAP, we first ask what range of values for MAP would be designed unquestionably normal. Let this be 70 to 100 mm Hg (not everyone might agree with this, so this choice merely captures the experience of one particular "expert"). We thus create a fuzzy set labeled $NORMAL_{MAP}$ and assign values of MAP between 70 and 100 mm Hg to a membership level of 1.0 in this set (Figure 1). Now we address the more vague issue of what range of values for MAP could possibly be normal but might also be abnormal. Let this be 100 to 120 mm Hg at the upper end and 50 to 70 mm Hg at the lower end. In other words, if MAP is above 120 mm Hg it is unquestionably too high, whereas between 100 and 120 mm Hg it could go either way. Similarly, if MAP is below 55 mm Hg it is without doubt too low, whereas between 50 and 70 mm Hg there is some doubt about whether it is normal or too low. These uncertainties are represented by membership levels in $NORMAL_{MAP}$ that decrease linearly from 1.0 at the inner boundaries of the uncertain regions down to 0 at the outer boundaries (Figure 1). We can construct LOW_{MAP} and $HIGH_{MAP}$ fuzzy sets in a similar manner. These begin at the inner boundaries of the uncertain regions with membership levels of zero and proceed linearly up to membership levels of 1.0 at the outer boundaries, precisely the converse of the situation for $NORMAL_{MAP}$. Above 120 mm Hg we have already established that MAP is too high, so values greater than 120 mm Hg have a membership level of 1.0 in $HIGH_{MAP}$ as well as for values of MAP below 50 mm Hg in LOW_{MAP}. There is no absolute rule that says the uncertain parts of the fuzzy sets must ascend or descend linearly. However, it is important that the various set memberships always add to unity for every value of the fuzzy variable because membership values essentially represent probabilities of set membership. Straight lines are the most straightforward way of achieving this condition.

We were expecting 9 different fuzzy rules, so we asked experts about different levels of IFR and finally from those different opinions we got 5 different levels for IFR as LOW, MAINATIN, MODERATE, HIGH, and VERY HIGH. Then we asked the experts about the values and definite values of IFR in the same fashion as MAP and HUO. Finally we have predicted 9 different fuzzy rules by using Min-Max approach, and eventually we find out the action that must be taken by using centroid approach.

Fuzzy Expert System

A fuzzy expert system is a form of artificial intelligence (Computer hardware and software packages that try to emulate human intelligence, using reasoning and learning to solve problems) that uses a collection of membership functions (fuzzy logic) and rules (instead of Boolean logic) to reason about data. The rules in a fuzzy expert system are usually of a form similar to this: If x is low and y is high, then z = medium, where x and y are input variables (names for known data values), z is an output variable (a name for a data value to be computed), low is a membership function (fuzzy subset) defined on x, high is a membership function defined on y, and medium is a membership function defined on z. The antecedent (the rule's premise) describes to what degree the rule applies, while the conclusion (the rule's consequent) assigns a membership function to each of one or more output variables.

Most tools for working with fuzzy expert systems allow more than one conclusion per rule. The set of rules in a fuzzy expert system is known as the "rule base" (or knowledge base). We set two types of forms and sent those to different experts to collect their knowledge about different levels of MAP, HUO, and IFR.

We are now in a position to define the clinical status of a patient each time a pair of new measurements of MAP and HUO arrives. Each pair of measurements leads to one or more pairs of set memberships. There is finite membership in the set combinations $NORMAL_{MAP}$ and $NORMAL_{HUO}$, $NORMAL_{MAP}$ and $HIGH_{HUO}$, $HIGH_{MAP}$ and $NORMAL_{HUO}$, and $HIGH_{MAP}$ and $HIGH_{HUO}$. The next step is to decide what action should be taken for each combination of set memberships. This question is again addressed in general terms using intuitive notions. Some situations are obvious. For example, if MAP is normal and HUO is normal then IFR should clearly be set at a normal maintenance level. Similarly, if MAP is high and HUO is high then IFR should set to a low level. The way to deal with certain other combinations may be a little less clear, such as when MAP is high and HUO is normal. One expert might argue that this situation calls for a maintenance level of IFR, whereas another might require IFR to be set below the maintenance level. In any case, we must build up a rule table specifying what should be done for every possible combination of fuzzy set memberships for MAP and HUO. For the purposes of this illustration, we will designate five categories of IFR labeled LOW, MAINTENANCE, MODERATE, HIGH, and VERY HIGH. The various membership combinations for MAP and HUO are assigned to these categories.

Fuzzy Rules

We predicted following fuzzy rules by using Mamdani approach

1. **If HUO is Low** and **MAP is Low** Then **IFR is very high**
2. **If HUO is Low** and **MAP is NORMAL** Then **IFR is moderate**
3. **If HUO is Low** and **MAP is HIGH** Then **IFR is low**
4. **If HUO is NORMAL and MAP is Low** Then **IFR is high**
5. **If HUO is NORMAL and MAP is NORMAL** Then **IFR is maintain**
6. **If HUO is NORMAL and MAP is HIGH** Then **IFR is low**
7. **If HUO is HIGH** and **MAP LOW is** Then **IFR is Moderate**
8. **If HUO is HIGH** and **MAP NORMAL** Then **IFR is maintain**
9. **If HUO is HIGH** and **MAP HIGH** Then **IFR is low**

Out of nine fuzzy rules will fire following four rules for patient:

1. IF **NORMAL_MAP** AND **NORMAL_ HUO** THEN **MAINTAIN_ IFR**
2. IF **NORMAL_MAP** AND **HIGH_ HUO** THEN **MAINTAIN_ IFR**
3. IF **HIGH _MAP** AND **NORMAL _ HUO** THEN **LOW_ IFR**
4. IF **HIGH _MAP** AND **HIGH_ HUO** THEN **LOW_ IFR**

Zadeh's Min-Max approach

The following are the two fuzzy rules using Zadeh's Min-Max approach that are depicted in (Fig 2, and 3):

1. If **NORMAL_MAP** (75mmhg with 0.3 membership grade) AND **NORMAL_ HUO** (105 Ml/Hour with membership grade 0.6) Then **MAINTAIN_ IFR** (Membership grade 0.3)
2. If **NORMAL_MAP** (75mmhg with 0.3membership grade) AND **HIGH_ HUO** (105

Ml/Hour with membership grade 0.4) Then **MAINTAIN_ IFR** (Membership grade 0.3)

It is interesting to note that even when the antecedent part of the rule is different, the consequence of these rules could be same. This is shown in the following two fuzzy rules [Table/Fig 4 and 5]

1. If **HIGH _MAP** (118mmhg with 0.8 membership grade) AND **NORMAL_ HUO** (105 ml/Hour with membership grade 0.6) Then **MAINTAIN_ IFR** (Membership grade 0.6)
2. If **HIGH _MAP** (118mmhg with 0.4membership grade) AND **HIGH_ HUO** (105 ml/Hour with membership grade 0.4).Then **MAINTAIN_ IFR** (Membership grade 0.4)

Defuzzification

The objective of the study is to estimate IFR based on the linguistic description of MAP and HUO sum of these four actions. The aggregated or resultant IFR will be based on the four fuzzy rules, which have different antecedent parts, but with the same consequence. The problem is that we have to work out a final numerical value with the fuzzy inputs. This can be achieved only with defuzzification process. In sum, we deal with fuzzy input but the end product must be a crisp value. One of the ways to work out the appropriate IFR value is by the method of Center of Area (Fig 6).

1. IF **NORMAL_MAP** AND **NORMAL_ HUO** THEN **MAINTAIN_ IFR**
2. IF **NORMAL_MAP** AND **HIGH_ HUO** THEN **MAINTAIN_ IFR**
3. IF **HIGH _MAP** AND **NORMAL _ HUO** THEN **LOW_ IFR**
4. IF **HIGH _MAP** AND **HIGH_ HUO** THEN **LOW_ IFR**

Center of Area (COA) Method

The Center of Area (also referred as center of gravity or centroid method in the literature) is by far the most popular defuzzification technique. Unlike Mean of Maximum (MOM), the COA method takes into account the entire possibility distribution in calculating its representative points. The defuzzification method is similar to the formula for calculating the center of gravity in physics, if we view $\mu_A(x)$ as the density of mass at x. Alternately, we can view the COA method as a weighting average, where $\mu_A(x)$ serves as the weight for value x if x is discrete, the defuzzification result of A is:

$$COA(A) = \frac{\sum_x \mu_A(x)\, x}{\sum_x \mu_A(x)}$$

Based on COA, the computed value of IFR for the above set parameters, which was for one sample of patient data, is 118 ml/hr. Similarly we calculated the results of fired rule for all 71 patients and got results that were in the range of predefined limit by the experts.

Discussion

Fuzzy logic is utilized for improved monitoring in pre-term infants [33]. A self-organizing anomaly detection system for an electrocardiogram (ECG) using a fuzzy logic reasoning method was also developed [34]. In anesthesia, many applications have been reported in the use of fuzzy logic to control drug infusion for maintaining adequate levels of anesthesia, muscle relaxation, and patient monitoring and alarm. In the field of orthopedics, there has been no reported application of fuzzy control. The field of anesthesia is where most of the applications of fuzzy control have been reported. It involves monitoring the patient vital parameters and controlling the drug infusion to maintain the anesthetic level constant. It includes depth of anesthesia [35], muscle relaxation [36] and [37], hypertension during anesthesia [38], arterial pressure control [39] and mechanical ventilation during anesthesia [40], and post-operative control of blood pressure [41]. Different methods have been used which utilize fuzzy logic, the first being a real-time expert system for advice and control (RESAC) based on fuzzy logic reasoning [42]. Later examples involve a basic fuzzy logic controller [43], self-organizing fuzzy logic controller [44], and hierarchical systems [45]. Recent work in anesthesia monitoring and control concentrated on a multi-sensor fusion system using cardiovascular indicators, such as systolic arterial pressure (SAP), heart rate (HR) and audio evoked response signals (AER) [46]. It is interesting to consider how a fuzzy logic algorithm for controlling fluid balance might be implemented in practice. One of the ways is given below:

It could be done with minimal capital outlay by having a human operator periodically enter MAP and HUO values into a personal computer. Intravenous fluid flow could then be manually adjusted according to the resulting fuzzy logic calculation. However, the best and more efficient approach is to design fuzzy logic based pump for the management of fluid during anesthesia. This would greatly increase both reliability and savings in labor. Automation would require the following series of steps: (*1*) MAP and HUO would be measured at regular intervals by suitable transducers (such as a urine container placed on an electronic scale), (*2*) the values of MAP and HUO would be acquired by a computer, (*3*) the fuzzy calculations would be made, and (*4*) the computer would control the fluid delivery rate from a motorized dispenser. Realizing these various steps is an engineering problem, readily soluble given sufficient resources. It is easy to see how the algorithm could be extended to include additional fuzzy variables such as heart rate or central venous pressure. The rates of change of MAP and HUO could also be obtained by taking differences between successive hourly measurements. These rates of change could be fuzzified into sets such as DECREASING, STABLE, and INCREASING and would serve to indicate the trend in a patient's fluid status. This would allow more precise control of fluid balance. Of course, for each additional variable there is a substantial increase in algorithm complexity because the rule table gains an additional dimension which means considering many more scenarios. Expert knowledge is the key to success as all the fuzzy logic based expert systems needs adequate infuses from the domain experts. A balance, therefore, needs to be struck between the number of independent fuzzy variables used and the number of fuzzy sets for each variable versus the precision of control achieved. This modal is suitable for application only in otherwise healthy patients undergoing surgery involving minimal blood loss. For other patients undergoing surgeries involving moderate to severe blood loss more complicated modals are needed utilizing other parameters as well.

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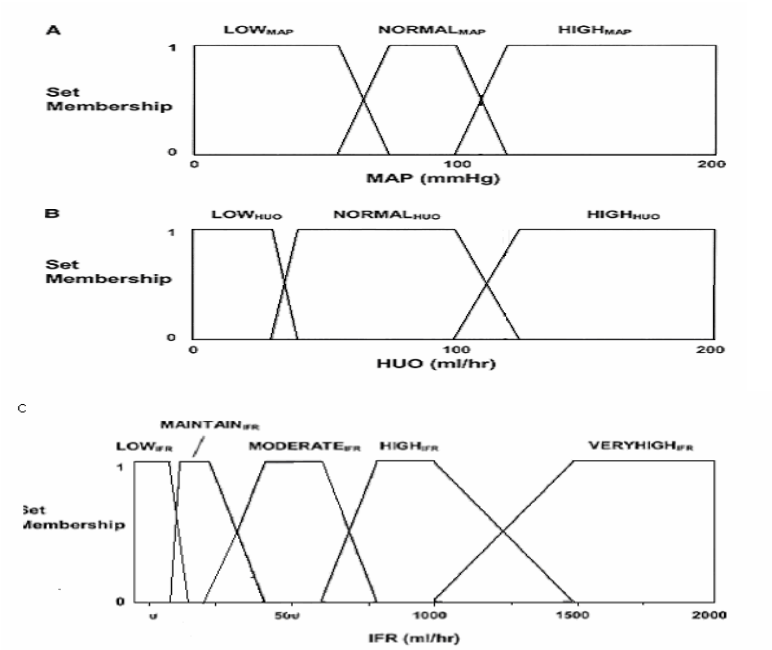
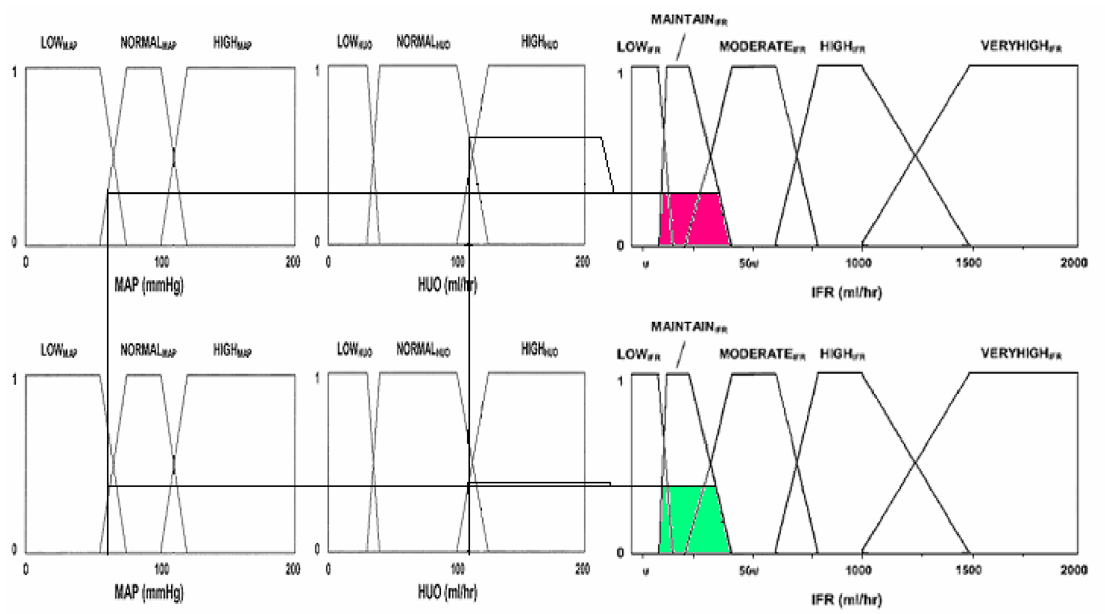
Table/Fig 1



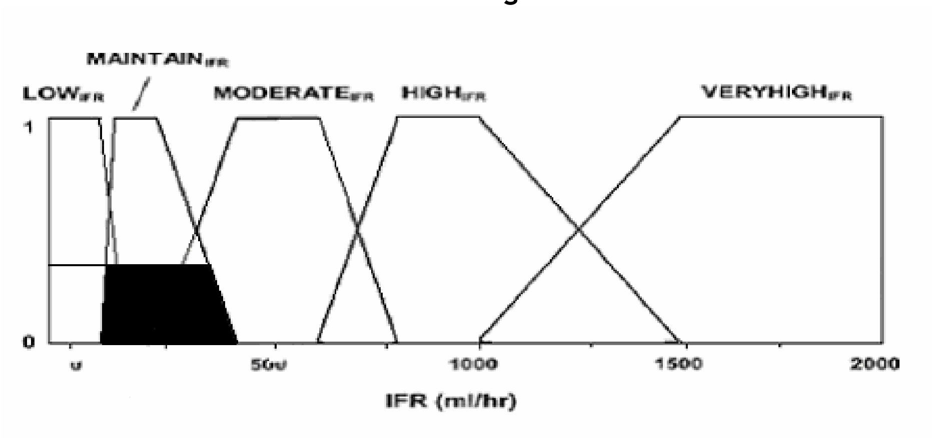
Fuzzy sets for (A) MAP, (B) HUO and IFR. The two variables have each been divided into three overlapping sets labelled LOW, NORMAL, and HIGH in case of MAP and HUO, and five overlapping sets in case of IFR.

Table/Fig 2



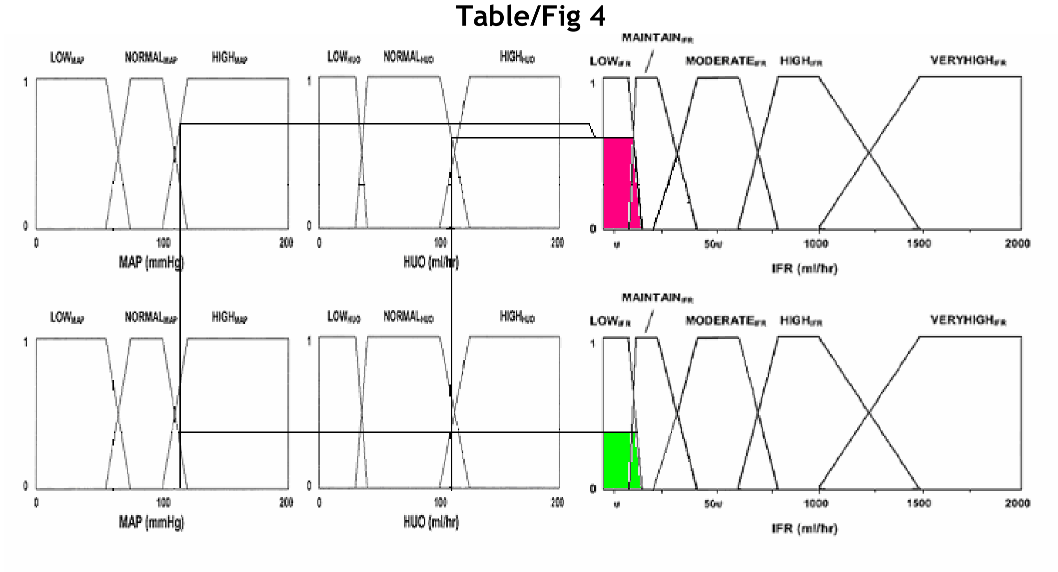
Fuzzy rules and Min-Max approach.

Table/Fig 3



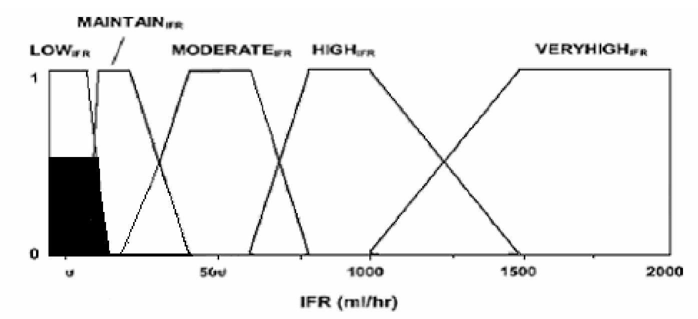
Aggregation of the above two fuzzy rules.

Table/Fig 4



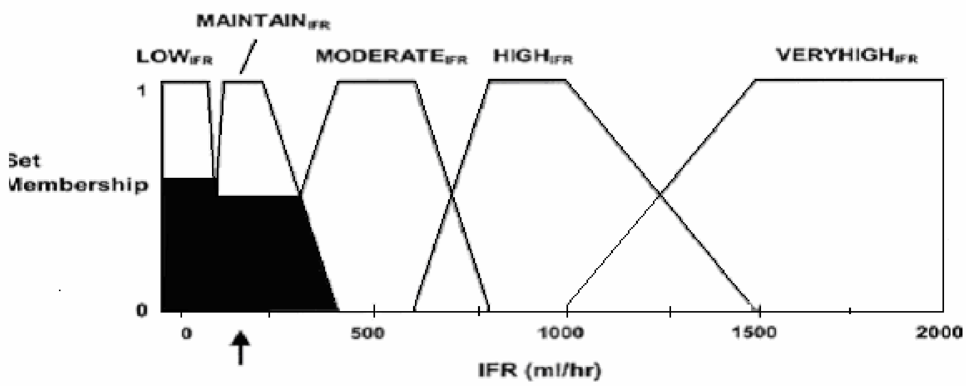
Fuzzy rule with same consequence with different antecedents.

Table/Fig 5



Aggregation of the above two rules.

Table/Fig 6



IFR is divided into five overlapping fuzzy sets. The set memberships arising from the measurements of MAP and HUO indicated in [Table/Fig 1] give rise to membership levels in the IFR sets indicated by the shaded region. The centroid of this region is indicated by the vertical arrow and is the final 'crisp' value of IFR to be implemented in the patient. The ranges of IFR for which the five fuzzy sets have membership of unity are, in ascending order, 0-70, 100-200, 400-600, 800-1000 and 1500-2000 ml/hr.

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