Managing Uncertainty in Intensive Care Units

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Abstract

Medical informatics has changed tremendously over the past few decades, and changes in the approach to uncertainty are probably the most important advances in this field. The envisioned role of computer programs in health care is perhaps the most important. Uncertainty is the central, critical fact about medical reasoning. Particularly in the intensive care unit (ICU) environment, where decisions must often be made quickly, or that physicians will follow it rather than openly or surreptitiously limiting care on their own.

This paper surveys the utilization of fuzzy logic on the basis of two medical applications. The first, an intelligent on-line monitoring program for the intensive care data of patients with Acute Respiratory Distress Syndrome (ARDS), so called FuzzyARDS which is using the concept of fuzzy automata, and the second is a fuzzy knowledge-based control system, FuzzyKBWean, which was established as a real-time application based on the use of a Patient Data Management System (PDMS) in an ICU. These complex systems confirm that fuzzy logic is quite suitable for medical application in a per definition uncertainty environment as an ICU, because of its tolerance to some imprecision.

Keywords: Uncertainty, fuzzy logic, medical fuzzy applications, decision making.

1 Introduction

Medicine is one field in which the applicability of fuzzy set theory was recognized in the end-1970s. Within this field it is the uncertainty found in the process of diagnosis of disease that has most frequently been the focus of applications of fuzzy set theory. In other words real world knowledge is characterized by uncertainty, incompleteness and inconsistency. Fuzzy set theory, which was developed by Zadeh [2], makes it possible to define inexact medical entities as fuzzy sets. It provides an excellent approach for approximating medical text. Furthermore, fuzzy logic provides reasoning methods for approximate inference.

Two medical applications, FuzzyARDS and FuzzyKBWean are presented in this paper, representing these concepts.

2 ICU Applications

2.1 FuzzyARDS

FuzzyARDS is an intelligent on-line monitoring program for the intensive care data of patients with Acute Respiratory Distress Syndrome (ARDS) [5]. Its clinical aim is to detect ARDS in patients as early as possible and to give appropriate therapy advice.

ARDS is an ill-defined medical entity and is modeled using the concept of fuzzy automata. States in these automata are considered to be a patient's pathophysiological state or entry criteria for different forms of ARDS therapies.
Patients may be partially assigned to one or several states in such an automaton at the same point in time. Transitions in the automata carry fuzzy conditions that have to be true or partially true to transit from one state to another. Fuzzy conditions are usually high level medical concepts such as low, normal, or high $\text{FiO}_2$, hypoxemia, or linguistically expressed trend information, e.g., rapidly improving oxygenation. These high-level concepts are permanently evaluated in a data-to-symbol conversion step according to an adjustable time granularity. An extended description of these formal concepts can be found in [6, 9, 30].

In the present phase of development, an international study has been conducted to compare and finally improve the various forms of ARDS definitions used at the medical study centers and compare their respective entry criteria used for therapy decision. A web-based system called FuzzyARDS was programmed allowing patient data entry at the study centers, the definition of fuzzy criteria, the calculation of fuzzy scores with respect to fuzzy criteria in the various stages of illness, and patient data evaluations based on interval techniques to consider missing variables in the given patient data sets. Most of the work done so far is described in [7, 8].

2.2 FuzzyKBWean

2.2.1 Background

Patients require mechanical ventilation during surgery, when they are anaesthetized, and must be slowly weaned from mechanical ventilation after major surgery to a point when they can breathe spontaneously. At this point, the patients can be extubated. In other words, the tube that is placed in the trachea to ensure proper ventilation is removed [20, 24, 29]. The aim of an improved weaning process would be to make the transition from controlled ventilation to total independence (extubation) as smooth and brief as possible.

Using the expertise for computer-assisted weaning in an appropriate manner is a common problem for such applications [10, 11, 14, 15 17]. In order to formalize the knowledge of the system in an easier way, a knowledge acquisition tool, the so-called knowledge-based weaning editor FuzzyKBWEdit has been developed, which helps intensive care specialists to generate a fuzzy knowledge base. When a knowledge base has been set up, the editor generates a compiled (scanned and parsed) version of it. This executable version of the knowledge base’s ‘source code’ is used as an interface for the FuzzyKBWean [18].

2.2.2 Application

The computer system FuzzyKBWean is a real-time, open-loop knowledge-based control system that contains the knowledge and expertise of experienced intensive care physicians in computerized form. It offers proposals for ventilator control during the weaning process of patients after cardiac surgery. The respirator changes effected by the physician have to be entered into FuzzyKBWean as a feedback for this open-loop system.

The ventilatory mode used for weaning must allow spontaneous breathing and a gradual reduction of the amount of ventilatory support. Three methods of support are currently being used: spontaneous intermittent mandatory ventilation (SIMV), pressure support ventilation (PSV), and airway pressure release ventilation (APRV) [13, 21].

In this expert system the APRV mode is implemented because it allows controlled and spontaneous ventilation with one unique mode. The adaptation to the specific needs of a patient necessitates only changes in three variables without any need for mode switching on the ventilator. The BIPAP (Biphasic Positive Airway Pressure) mode is an APRV mode equipped with a standard ventilator (Figure 1) [25, 26].

![Figure 1: BIPAP ventilation mode](image1.png)
This mode allows spontaneous inspiration during the entire respiratory cycle and, consequently, a very smooth and gradual change from controlled to spontaneous breathing.

The fuzzy knowledge bases established by using FuzzyKBWEdit consist of variables, values, and rules. The variables represent the physiological parameters of the patient and the respirator settings. The values are described in linguistic terms that are formalized by fuzzy sets. The knowledge bases as well as various experimental versions are implemented as plug-in knowledge bases for the FuzzyKBWean frame program.

The FuzzyKBWEdit’s unrestricted user interface design allows adjustment for different ventilation modes.

The knowledge base of a knowledge-based controller consists of a data base and a rule base. The fuzzy inference process is performed by three steps.

1) Fuzzification: input variables are assigned degrees of membership in the predefined variable classes,

2) Rules: the inputs are applied parallel to a set of If/Then control rules.

3) Defuzzification: the fuzzy outputs are combined to yield discrete values for the respirator adjustments.

FuzzyKBWean uses the Sugeno defuzzification method [12, 16] for defuzzification.

2.2.3 Data Input

The respirator settings and physiological parameters are taken as input at one-minute intervals from the Patient Data Management System (PDMS) Picis®. The PDMS Picis (Caresuite 97 Chart +, Paris, Barcelona, 1998) is in routine clinical use in the cardiothoracic ICU and collects data from all available monitoring devices. Fuzzy-KBWean analyzes these data and makes suggestions for appropriate respirator setting adjustments. The attending intensive care specialist is free to decide whether he will follow the advice (open-loop system).

3 Results and Discussion

3.1 FuzzyARDS System

The first system, a web application of FuzzyARDS is shown in Figure 3. Based on the available FuzzyARDS study system, patient data sets are entered at the various study centers and evaluated in ARDS consensus meetings. The results yielded to better understanding of ARDS as a life threatening disease [3, 4, 5, 8]. Based on these results, FuzzyARDS is continuously adjusted to new derived medical knowledge [1].

The system is available for registered users (username and password are required) at: http://medexpert.imc.akh-wien.ac.at/fuzzyards.

The web-application is an ASP (Active Server Pages) application and uses an Access Database (Access 2002) for data storage. Some problems have still to be solved, e.g., the definition and incorporation of idle and delay functions in the on-line monitor to avoid oscillations in the patient states.

Figure 3: FuzzyARDS web application (data input)

3.2 FuzzyKBWean System

The fuzzy control and advisory program FuzzyKBWean has been developed with Delphi® 6.0 running on Windows® platforms.

The bedside real time application of FuzzyKBWean is shown in Figure 4. The user interface has two main- units. The online (real time-data) unit, and a so called history (data base related) unit. It is possible to toggle between these units, so that always one or both
of them have the focus. The top panel displays actual values and proposals, middle panel allows data review from any previous time point and, bottom panel displays key variables of the ventilation process together with the proposed new settings.

Figure 4: FuzzyKBWean frame application

1) The online (real time-data) unit:
This unit shows the current time, a set of the patients’ real time parameters and the proposals i.e. the fired rules of the expert system.

2) The history (data base related) unit:
The history unit has themselves two units. A textual based, and a chart based unit. With navigator bars it is possible to navigate through the patients history data. The chart navigation also allows zooming and panning of the chart data. The graphics include also a display of the change proposed by the FuzzyKBWean.

With the integrated knowledge acquisition tool FuzzyKBWEdit knowledge bases can be formalized with very little restriction (Figure 5). Nevertheless, knowledge bases have to be formalized syntax-guided in order to make them usable for the expert system, in our special case for the expert system FuzzyKBWean. When a knowledge base has been formed, the editor generates a compiled (scanned and parsed) version of it. This executable version of the knowledge base’s “source code” is used as an interface for the computer-assisted expert system FuzzyKBWean. This entire concept permits the creation of various experimental versions of the knowledge bases. Furthermore, the interface can be easily modified for using other computer-assisted applications in future.

The system is used for postoperative cardiac patients in an ICU at the Vienna General Hospital. The advantages of the system are its easy application and the generation of more specific knowledge bases, which allow smoother treatment of weaning patients. FuzzyKBWean is currently being tested with a pilot sample of 28 prospective randomized cases currently undergoing treatment.

It can be found that the clinical staffs react with a longer delay to hyper- or hypoventilation then the program does. The mean delay in case of hyper- ventilation was 127 minutes, Standard Error of Mean (SEM) 34; the corresponding value for hypoventilation was 50 minutes (SEM 21).

Figure 5: FuzzyKBWEdit (oxygenation rule)

A large body of implicit medical knowledge was transferred to the fuzzy control system. The obtained results confirm the applicability of FuzzyKBWean to represent medical knowledge, thus rendering the weaning process transparent and comprehensible. Periods of deviation from the target are shorter with FuzzyKBWean. Nevertheless, the use of fuzzy sets provides a basis for a smoother adaptation of mechanical ventilation to the patients’ advantage, since small changes in the ventilator settings are made continually. Manual settings cannot be very precise, because the minimal step to be set in that environment is one mbar. Only a closed-loop application, i.e. a direct connection
between the FuzzyKBWean and the ventilator, would allow smooth adaptation continuously.

When a robust performance is achieved in the current randomized trial, a transfer to other clinical settings is planned in order to fully validate the experimental concept.

4 Conclusion

In medicine, two fields of fuzzy applications were developed since the nineteen seventies: computer assisted diagnostic systems and intelligent patient monitoring systems. Both developments of Zadeh’s rule of max-min composition, namely fuzzy relations and fuzzy control, have been applied in these areas. For obvious reasons, the available body of medical data (on patients, laboratory test results, symptoms, and diagnoses) will expand in the future. As mentioned above, computer-assisted systems using fuzzy methods will be better able to manage the complex control tasks of physicians than common tools. Most control applications in the hospital setting have to be performed within critical deadlines.

Fuzzy Logic in medicine is still a largely untapped area that holds great promise for increasing the efficiency and reliability of health care delivery. These two medical applications described above, and others [19, 22, 23, 27, 28] showing generally promising results, the literature on fuzzy logic applications in medicine remains modest. Fuzzy logic provides a means for encapsulating the subjective decision making process in an algorithm suitable for computer implementation.

Furthermore, the principles behind fuzzy logic are straightforward and its implementation in software is relatively easy. Nevertheless, the applications of fuzzy logic in medicine are few. In addition, fuzzy logic may support the automation of some types of devices used in the delivery of health care services.

References


