Fuzzy Set Theory and Fuzzy Logic in Medicine

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ABSTRACT: Fuzzy set theory and fuzzy logic are a highly suitable and applicable basis for developing knowledge-based systems in medicine for tasks such as the interpretation of sets of medical findings, the single or differential diagnosis of diseases from various areas of medicine, the optimal selection of medical treatments, and for real-time monitoring of patient data. This was verified by trials with the following systems: FuzzyKBWean–an open-loop fuzzy control system for optimization and quality control of the ventilation and weaning process of patients after cardiac surgery at the intensive care unit (ICU), FuzzyARDS–an intelligent on-line monitoring program for ICU data from patients with acute respiratory distress syndrome (ARDS) employing fuzzy trend detection and fuzzy automata, and CADIAG-II and MedFrame/CADIAG-IV–framework programs (shells) for consultation systems to aid in the differential diagnostic process in Internal Medicine. All the above-mentioned computer systems have reached the state of extensive clinical integration and testing at the Vienna General Hospital.

KEYWORDS: intensive care unit (ICU), fuzzy control, FuzzyKBWean, fuzzy trend detection, fuzzy automaton, FuzzyARDS, Internal Medicine, consultation system, CADIAG-II, MedFrame/CADIAG-IV

INTRODUCTION

Fuzzy set theory and fuzzy logic have a number of characteristics that make them highly suitable for modelling uncertain information upon which medical concept forming, patient state interpretation, and diagnostic as well as therapeutic decision making is usually based. Firstly, medical entities such as symptoms, signs, test results, diseases and diagnoses, therapeutic and prognostic information can be defined as fuzzy sets. The inherent vagueness of these entities will thus be conserved. Secondly, fuzzy logic offers reasoning methods capable of drawing strict as well as approximate inferences. Medicine demands this broad range of possibilities because the body of medical theory includes definitional, causal, statistical, and heuristic knowledge. Practical medicine even has to accept incomplete medical theories where only vague and uncertain empirical information guides the necessary medical procedures. Finally, fuzzy automata may be used as high level patient monitoring devices with real time access to medical information systems. Annotated bibliographics, editorials, and historical notes can be found in Adlassnig (1982), Maiers (1985), Böhm (1990), Steimann (1997), and Teodorescu (1998).

METHODS AND MATERIAL

Fuzzy set theory and fuzzy logic are a highly suitable and applicable basis for developing knowledge-based systems in medicine for tasks such as the interpretation of sets of medical findings, the single or differential diagnosis of diseases from various areas of medicine, the optimal selection of medical treatments, and for real-time monitoring of patient data. This was verified by trials with the following systems:

FUZZYKBWEAN: KNOWLEDGE-BASED WEANING FROM ARTIFICIAL VENTILATION

FuzzyKBWean is an open-loop fuzzy control system for optimization and quality control of the ventilation and weaning process of patients after cardiac surgery at one of the intensive care units (ICUs) of the Vienna General Hospital. The system is directly connected to the Patient Data Management System (PDMS) of the ICU and runs on the bed-side computer, as is described in Schuh (1998b). In one minute intervals, it actively accesses the PDMS data base and takes over the respective medical data.

According to the well-known structure of fuzzy control systems, a fuzzification step is followed by the fuzzy rule evaluation. The rules in FuzzyKBWean contain patient’s physiological parameters and the actual ventilator settings in the fuzzy antecedents, yet crisp proposals for appropriate and timely new settings of the ventilator in the consequences of the rules. The application of the Sugeno control method to combine rule output of the same kind is thus possible (Schuh (1998a, 1999)). Koller (1999) describes a fuzzy set and rule editor FuzzyKBWEdit that puts the cooperating physicians in the position to carry out knowledge base changes directly at the ICU ward.

FUZZYARDS: KNOWLEDGE-BASED MONITORING AND DECISION SUPPORT

FuzzyARDS/MONITOR is an intelligent on-line monitoring program for ICU data of patients with acute respiratory distress syndrome (ARDS) (cf., Steltzer (1999)). Its clinical aim is to detect ARDS in intensive care patients as early as possible and to give appropriate therapy advice.

ARDS is an ill-defined medical entity and is modelled using the concept of fuzzy automata. States in these automata are considered to be patient’s pathophysiological states or entry criteria for the different forms of applicable therapies. Patients may partially be assigned to one or several states. Transitions in the automata carry fuzzy conditions that have to be true or partially true to go from one state to another. Fuzzy conditions are usually high level medical concepts including linguistically expressed trend information. An extended description of these formal concepts can be found in Steimann (1994a, 1994b). These high level concepts are permanently evaluated in a data-to-symbol conversion step according to an adjustable time granularity.

In the present phase of development, an international study is being conducted to compare and finally improve the various forms of ARDS definitions found at the study centres and compare their therapy entry criteria. A web-based study system FuzzyARDS/STUDY was built allowing data entry at the respective study centres including the definition of fuzzy criteria, the calculation of fuzzy scores, and patient data evaluations based on interval techniques to allow missing variables in the given data sets. Extended reports on this development can be found in Steltzer (1996) and Trummer (1998, 1999).

CADIAG-II AND MEDFRAME/CADIAG-IV: COMPUTER-ASSISTED DIAGNOSIS IN INTERNAL MEDICINE

The CADIAG project is a long term effort to assist in the differential diagnostic process in Internal Medicine by computer programs. CADIAG-II was formally developed and practically tested in 1979/80 (Adlassnig (1980)). The underlying clinical issues are: indicating all possible diseases that explain the given pathological findings of the patient, offering further useful examinations to confirm or exclude gained diagnostic hypotheses or to find stronger support for them, and searching for patient’s pathological findings not yet accounted for by CADIAG-II’s proposed diagnoses. CADIAG-II was described at various stages of development (Adlassnig (1986, 1988)) and tested in different areas of Internal Medicine (Adlassnig (1989a, 1989b), Leitich (1996)). It is fully integrated into the medical information system WAMIS of the Vienna General Hospital (Adlassnig (1986)).

MedFrame/CADIAG-IV is the present successor of the former CADIAG systems. In this system not only positive and negative diagnostic hypotheses but also therapy proposals are offered. It is intended to build a large framework for the development of knowledge-based systems in medicine. An integrated patient data and knowledge base, knowledge base editor modules, differential diagnosis and therapy modules, and an immediate case evaluation module will form the core of MedFrame/CADIAG-IV. Descriptions of parts of MedFrame/CADIAG-IV can be found in Kolousek (1997), Boegl (1996, 1997, 1998), and Brein (1998).

RESULTS

All the above-mentioned computer systems have reached the state of extensive clinical integration and testing at the Vienna General Hospital.

An early study of FuzzyKBWean was published in Hiesmayr (1993); a recent clinical trial—as reported in Kolb (1999)—showed that a number of appropriate proposals for ventilator setting changes are given at a very early stage, earlier then the attending personal would react. Thus the proposed adjustments to stabilize the ventilated patient, to start and end the weaning process earlier, and thus be able to extubate the patient at an earlier point of time yielded to less suffering of the patient and less costs.

Based on the available FuzzyARDS/STUDY system, patient data sets are entered and evaluated in ARDS consensus meetings. The results yielded to better understanding of ARDS as a life threatening disease and its treatment (Steltzer (1999)). A prototypical application of FuzzyARDS/MONITOR is available for clinical tests (Steimann (1994b)). 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.

The integration of CADIAG-II into the medical information system WAMIS and its extended retrospective and prospective testing with real patient data—a recent study is described in Leitich (1999)—forms a broad basis of practical and theoretical knowledge to develop a new and extended system for the ambitious aim to assist the mental diagnostic and therapeutic activity of physicians, nurses, and laboratory personal. The MedFrame CADIAG-IV system—presently in an active development phase—will finally make a huge step towards support and automation of subareas of medical practice.

CONCLUSION

The conducted clinical studies showed the appropriateness of the chosen formal approaches with respect to the necessary medical applicability, the achieved correctness of the results, and also the robustness of the respective patient data and fuzzy knowledge representation and the selected fuzzy inference mechanisms. They further revealed the intuitive understanding of the basic ideas of fuzzy set theory and of fuzzy logic by the medical users. So it is easily understood that the transition from healthy to ill, from normal to pathological which is modelled by fuzzy sets in the above-mentioned knowledge-based systems is a gradual transition and not a crisp one and furthermore, that the partial firing of rules with partially valid antecedent naturally diminishes the validity of the resulting consequence.

Fuzzy set theory and fuzzy logic employed in knowledge-based systems will become a standard methodology of systems with computational intelligence in medicine.

REFERENCES

Adlassnig, K.-P., 1980, “A Fuzzy Logical Model of Computer-Assisted Medical Diagnosis”, Methods of Information in Medicine 19, pp. 141–148.

Adlassnig, K.-P., 1982, “A Survey on Medical Diagnosis and Fuzzy Subsets”, in Gupta, M. M. & Sanchez, E. (Eds.) Approximate Reasoning in Decision Analysis, North-Holland Publishing Company, Amsterdam, pp. 203–217.

Adlassnig, K.-P., 1986, “Fuzzy Set Theory in Medical Diagnosis”, IEEE Transactions on Systems, Man, and Cybernetics SMC-16, pp. 260–265.

Adlassnig, K.-P., 1988, “Uniform Representation of Vagueness and Imprecision in Patient’s Medical Findings Using Fuzzy Sets”, in Trappl, R. (Ed.) Cybernetics and Systems ’88, Kluwer Academic Publishers, Dordrecht, pp. 685–692.

Adlassnig, K.-P.; Akhavan-Heidari, M., 1989a, “CADIAG-2/GALL: An Experimental Expert System for the Diagnosis of Gallbladder and Biliary Tract Diseases”, Artificial Intelligence in Medicine 1, pp. 71–77.

Adlassnig, K.-P.; Kolarz, G.; Scheithauer, W.; Grabner, H., 1986, “Approach to a Hospital-Based Application of a Medical Expert System”, Medical Informatics 11, pp. 205–223.

Adlassnig, K.-P.; Scheithauer, W., 1989b, “Performance Evaluation of Medical Expert Systems Using ROC Curves”, Computers and Biomedical Research 22, pp. 297–313.

Boegl, K., 1997, “Design and Implementation of a Web-Based Knowledge Acquisition Toolkit for Medical Expert Consultation Systems”, Dissertation, Technische Universität Wien, Wien.

Boegl, K.; Kainberger, F.; Gahleitner, A.; Adlassnig, K.-P., 1998, “Web-Based Knowledge Acquisition: An Attempt at Collaborative Building of Radiological Knowledge Bases for a Medical Expert Consultation System”, in Proc. Computer-Assisted Radiology CAR’98, Elsevier, Amsterdam, pp. 415–420.

Boegl, K.; Leitich, H.; Kolousek, G.; Rothenfluh, T.; Adlassnig, K.-P., 1996, “Clinical Data Interpretation in MedFrame/CADIAG-4 Using Fuzzy Sets”, Biomedical Engineering—Applications, Basis & Communications 8, pp. 488–495.

Böhm, W., 1990, „Die Theorie der unscharfen Mengen und ihre Anwendungen in der Medizin“, Diplomarbeit, Technische Universität Wien, Wien.

Brein, L.; Adlassnig, K.-P.; Kolousek, G., 1998, “Rule Base and Inference Process of the Medical Expert System CADIAG-IV”, in Trappl, R. (Ed.) Cybernetics and Systems’98, Austrian Society for Cybernetic Studies, Schottengasse 3, A-1010 Vienna, Austria, pp. 155–159.

Hiesmayr, M.; Gamper, J.; Neugebauer, T.; Mares, P.; Adlassnig, K.-P.; Haider, W., 1993, “Clinical Application of Patient Data Management Systems (PDMS): Computer-Assisted Weaning from Artificial Ventilation (KBWEAN)”, in Lenz, K.; Metnitz, P.G.H. (Eds.) Patient Data Management in Intensive Care, Springer-Verlag, Wien, pp. 129–138.

Kolb, M.; Schuh, Ch.; Koller, W.; Zelenka, Ch.; Adlassnig, K.-P.; Hiesmayr, M., 1999, “FuzzyKBWean: from the written protocol to a fuzzy control expert system for weaning from artificial ventilation”, submitted to AI in Medicine.

Koller, W.; Schuh, Ch.; Zelenka, Ch.; Hiesmayr, M.; Adlassnig, K.-P., 1999, “The Fuzzy Set and Rule Editor KBWEdit of the Medical Expert System KBWean”, OEGAI-Journal 18, No. 2, Vienna, Austria, pp. 27–29.

Kolousek, G., 1997, “The System Architecture of an Integrated Medical Consultation System and Its Implementation Based on Fuzzy Technology”, Dissertation, Technische Universität Wien, Wien.

Leitich, H.; Adlassnig, K.-P.; Kolarz, G., 1996, “Development and Evaluation of Fuzzy Criteria for the Diagnosis of Rheumatoid Arthritis”, Methods of Information in Medicine 35, pp. 334–342.

Leitich, H.; Kiener, H.-P.; Kolarz, G.; Schuh, Ch.; Graninger, W.; Adlassnig, K.-P., 1999, “A prospective evaluation of the medical consultation system CADIAG-II/RHEUMA in a rheumatological outpatient clinic”, submitted to Methods of Information in Medicine.

Maiers, J.; Sherif, Y. S., 1985, “Applications of Fuzzy Set Theory”, IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-15, No. 1, January/February, pp. 175–189.

Schuh, Ch., 1998a, „Wissensbasierte Entwöhnung vom Respirator unter Verwendung von Fuzzy- und Nichtfuzzy-Regelungsmodellen“, Dissertation, Technische Universität Wien, Wien.

Schuh, Ch.; Hiesmayr, M.; Adlassnig, K.-P.; Zelenka, Ch.; Klement, E. P., 1998b, “Integration of Crisp- and Fuzzy-Controlled Weaning in an ICU PDMS”, in Proc. of the World Automation Congress, WAC’98, TSI Press, Albuquerque, pp. 299–304.

Schuh, Ch.; Koller, W.; Kolb, M.; Zelenka, Ch.; Hiesmayr, M.; Adlassnig, K.-P., 1999, “KBWean: Control Systems for Ventilation and Weaning in the Intensive Care Unit”, OEGAI-Journal 18, No. 2, Vienna, Austria, pp. 24–26.

Steimann, F., 1997, “Fuzzy Set Theory in Medicine”, Artificial Intelligence in Medicine 11, pp. 1–7.

Steimann, F.; Adlassnig, K.-P., 1994a, “Clinical Monitoring with Fuzzy Automata”, Fuzzy Sets and Systems 61, pp. 37–42.

Steimann, F.; Adlassnig, K.-P., 1994b, “Two-Stage Interpretation of ICU Data Based on Fuzzy Sets”, in AI in Medicine: Interpreting Clinical Data, Stanford 1994 Spring Symposium Series, American Association for Artificial Intelligence, Stanford University, pp. 152–156.

Steltzer, H.; Fridrich, P.; Steimann, F.; Rossaint, R.; Adlassnig, K.-P.; Hammerle, A., 1996, “Definition of Severity and Compiling of Entry Criteria in Patients Undergoing ECLA: The Use of a Fuzzy Logic Expert System”, Acta Anaesthesiologica Scandinavica 40, Supplement 109, pp. 125–126.

Steltzer, H.; Trummer, B.; Höltermann, W.; Kolousek, G.; Fridrich, P.; Lewandowski, K.; Adlassnig, K-P.; Hammerle, A.F., 1999, „Wissensbasierte Diagnostik und Therapieempfehlung mit Methoden der Fuzzy-Set-Theorie bei Patienten mit akutem Lungenversagen (ARDS)“. Anästhesiologie Intensivmedizin Notfallmedizin Schmerztherapie, 34, pp. 218–223.

Teodorescu, H.-N. L.; Kandel, A.; Jain, L. C, 1998, “Fuzzy Logic and Neuro-Fuzzy Systems in Medicine and Bio-Medical Engineering: A Historical Perspective”, CRC Press, Florida, USA, pp. 3–16.

Trummer, B.; Steltzer, H.; Kolousek, G.; Adlassnig, K.-P.; Hammerle, A.F., 1998, “Knowledge-Based Definition of ARDS Therapy Entry Criteria Using Fuzzy Set Theory”, Acta Anaesthesiologica Scandinavica 42, Supplement 112, pp. 238–239.

Trummer, B.; Steltzer, H.; Kolousek, G.; Adlassnig, K.-P.; Hammerle, A.F., 1999, “FuzzyARDS/STUDY: Definition of Therapy Entry Criteria in Patients Suffering from ARDS”, OEGAI-Journal 18, Nr. 2, pp. 34–36.