Towards an intuitive expert system for weaning from artificial ventilation

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***Abstract*- The procedure for weaning a patient with respiratory insufficiency from mechanical ventilation is complex and requires expertise obtained from long clinical practice. Fuzzy Knowledge-Based Weaning (FuzzyKBWean) is a fuzzy know-ledge-based control system that proposes stepwise changes in ventilator settings during the entire period of artificial ventilation at the bedside in real time. Information is obtained from a Patient Data Management System operating at the Intensive Care Unit (ICU) with a time resolution of one minute. A large body of the explicitly given and implicitly available medical knowledge of an experienced intensive care specialist could be transferred to the developed fuzzy control system. Periods of deviation from the target are shorter with Fuzzy-KBWean. A physician, who changes the settings of the ventilator manually, applies the system in an open-loop manner in patients who have undergone cardiac surgery. To force the usability of an open-loop system an intuitive user interface approach is currently developed which allows displaying qualitative information instead of numerical information.**

***Keywords*- Intelligent monitoring; weaning; knowledge acquisition; fuzzy knowledge-based control, intuitive user interface.**

I. Introduction

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 [11, 15]. 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 [1, 2, 5, 6, 8]. In order to formalize the knowledge of the system in an easier way, we had to develop a knowledge acquisition tool, the so-called knowledge-based weaning editor FuzzyKBWEdit, 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 Fuzzy-KBWean [9].

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.

Unfortunately, traditional user interface techniques that utilize input devices such as mice and keyboards are not well suited to these inherently open loop control tasks. ICU routine task are driven by a single goal: deliver improved quality of patient care as efficiently as possible.

To accomplish these needs an intuitive user interface approach that allows displaying qualitative information is currently developed with this system.

II. Methods

A. Ventilatory management

During mechanical ventilation as well as during weaning, the goal is to achieve optimal values of the arterial O_2-partial pressure (pO_2) and the arterial CO_2-partial pressure (pCO_2). In addition, the patient has to be carefully treated in order to avoid cardiac failure and respiratory muscle fatigue. The value pO_2 states whether the oxygenation is sufficient. The parameter pO_2 is not continuously available because this would involve taking a blood sample. Thus, O_2-saturation (SpO_2) provided by pulsoximetry is more convenient, because SpO_2 is continuously available. The parameter pCO_2 states whether alveolar ventilation is sufficient. Similarly, the end-tidal CO_2 ($EtCO_2$) is also continuously available, but with the disadvantage of being only an indirect measure of pCO_2. Thus, the main physiological input parameters of the weaning system are SpO_2 and $EtCO_2$. The ventilatory drive efficiency is evaluated according to the measured ventilatory rate (Vrate) and tidal volume.

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) [4, 12].

In this expert system we implemented only the APRV mode because it allows controlled and spontaneous ventilation with one unique mode. The adaptation to the specific needs of a patient necessitates only changes in 3 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 (Fig. 1) [16, 17].

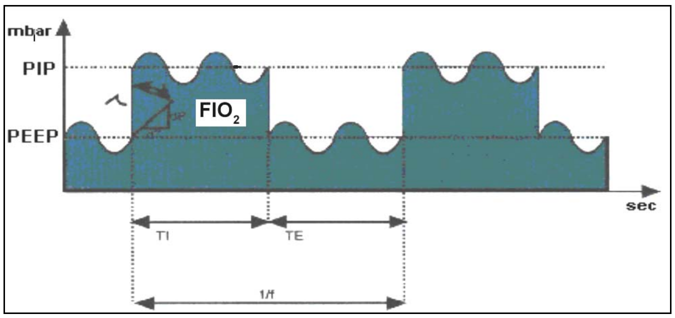

Fig. 1 BIPAP ventilation mode

The mode allows spontaneous inspiration during the entire respiratory cycle and, consequently, a very smooth and gradual change from controlled to spontaneous breathing

Ventilatory adjustments are based on two pressure levels, positive inspiratory pressure (PIP), positive end expiratory pressure (PEEP), and on two durations, namely inspiration time (t_I) and expiration time (t_E), and also on the fraction of inspired O_2 (F_iO_2). Spontaneous breathing is easily achieved at both pressure levels [13]. Within this mode, five parameters can be adjusted. The outputs of the FuzzyKBWean are proposals to adjust these five parameters.

B. Knowledge acquisition

The fuzzy knowledge bases established by using Fuzzy-KBWEdit 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 (Fig. 2.) *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 [3, 7] for defuzzification.

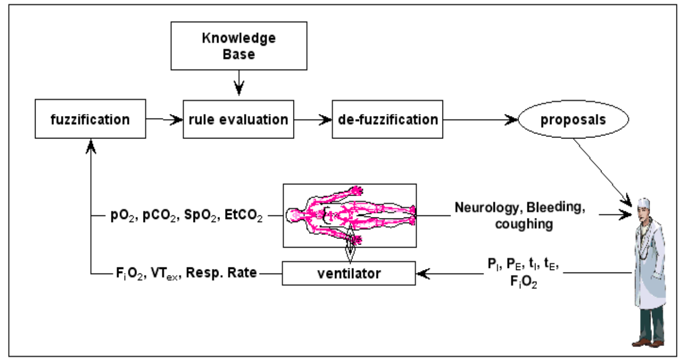

Fig. 2 Structure of the FuzzyKBWean controller

The first step in the fuzzification process is to determine the parameters O_2 and CO_2. The parameter O_2 is determined on the basis of the parameters SpO_2 and pO_2, while CO_2 is determined on the basis of the parameters pCO_2 and $EtCO_2$ (as mentioned above). A sample of membership functions for ventilating (EtCO2) and positive inspiratory pressure (PIP) a patient is shown in Fig. 3.

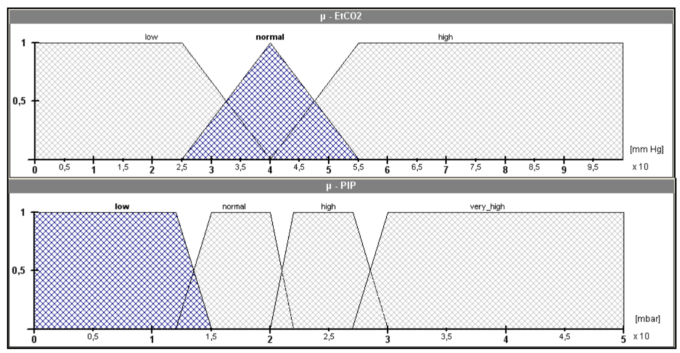

Fig. 3 Membership function example for EtCO2 and PIP

C. 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. FuzzyKBWean 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).

III. RESULTS

A. FuzzyKBWean

The fuzzy control and advisory program FuzzyKBWean (Fig. 4) and the knowledge acquisition tool FuzzyKBWEdit (Fig. 6) have been developed with Delphi® 6.0 running on Windows98/NT/2000/XP® platforms. It has been connected to the PICIS® PDMS at the ICU.

B. User interface

The bedside real time application of FuzzyKBWean is shown in Fig. 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.

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.

Fig. 4 FuzzyKBWean frame application

C. New User Interface approach

To force the usability of an open-loop system a new, more intuitive user interface approach is currently developed which allows displaying qualitative information instead of numerical information.

In order for physicians to be able to make weaning decisions at the bedside, they need to be able to easily retrieve, digest, manipulate, and utilize information relevant to the decision making process.

An approach for intuitive user interfaces has been characterized as a mental models approach to user interface design: find a paradigm that is a metaphor for a given task and is intuitive to users and apply it to the user interface [10, 14]. Providing an interface that is unintuitive will, at best, lead to confusion. The result will be that the systems usability is poor. On the other hand providing an incorrect mental model, however, can lead to disastrous consequences--including incorrect decisions, and worse yet, complete confidence in wrong choices.

User interface designers have also expanded and refined their use of color-coding, consistency, instructions, and other simple heuristics that greatly benefit the user interface (Shneiderman, 1998). Overall, these changes have led to a more intuitive interface that has allowed users to obtain information in a more efficient manner. In this context intuitive means that necessary training is minimal for the use of the system.

What we try to find out is an intuitive user interface that is as simple as possible and even so gives the physician a good perception where the patient is currently positioned in the weaning variation of time. That means from the starting point of the artificial ventilation to the final goal, which is the point where the patient can be extubated.

An interface approach that visualises the actual patient status (position) in the current weaning variation of time is shown in Fig. 5.

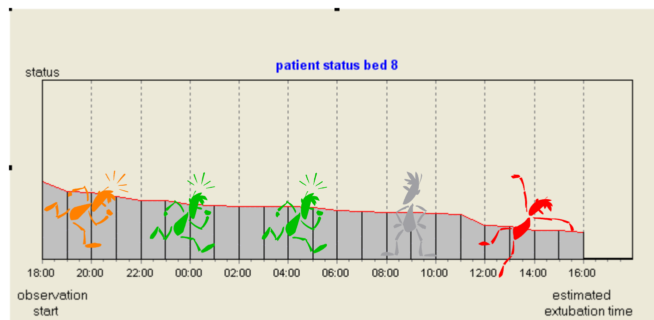

Fig. 5 Progressive weaning and patient actual status

D. FuzzyKBWEdit

With the integrated knowledge acquisition tool Fuzzy-KBWEdit knowledge bases can be formalized with very little restriction (Fig. 6).

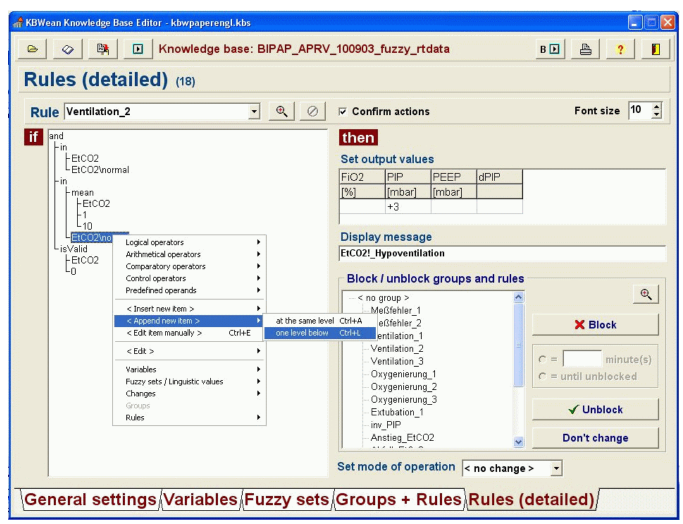

Fig. 6 FuzzyKBWEdit application generating an oxygenation rule

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 Fuzzy-KBWean (Fig. 7).

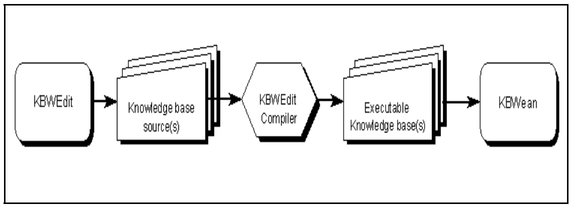

Fig. 7 Knowledge base compilation process

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 weaning applications in future. The rules of the knowledge bases are simple to generate, because a large set of predefined operators is available. These are based on logical, arithmetical, comparison, and control operators. With the latter, information concerning the completion of realized rules is generated. For this reason, all data involved in the weaning process have to be stored in a database. FuzzyKBWean and FuzzyKBWEdit are especially designed to interact with the Interbase® database.

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. Fuzzy-KBWean is currently being tested with a pilot sample of 28 prospective randomized cases currently undergoing treatment.

We found that the clinical staffs react with a longer delay to hyper- or hypoventilation then the program does. The mean delay in case of hyperventilation was 127 minutes, Standard Error of Mean (SEM) 34; the corresponding value for hypo-ventilation was 50 minutes (SEM 21). The delay of staff's reaction in the case of hyper-ventilation expressed by low $EtCO_2$ is shown in Table I.

TABLE I
MEAN DELAY OF STAFF-REACTION IN THE CASE OF HYPERVENTILATION

Patient	Episode	Proposed change	Effective change	Delay (min)
X	1	16:30	19:42	192
	2	23:50	01:55	125
	3	04:27	07:43	187
B	1	21:17	03:58	407
D	1	22:57	23:16	19
E	1	22:30	01:15	165
	2	01:15	01:50	45
K	1	13:45	14:45	60
	2	20:20	20:48	28
C	1	17:03	18:27	104
	2	08:48	16:36	460
G	1	20:02	20:12	10
	2	20:12	20:30	18
	3	20:30	22:47	137
	4	22:47	23:22	35
K	1	21:05	21:40	35

IV CONCLUSION

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.

However, the system is still sensitive to artefacts. Therefore, FuzzyKBWean is only applied in an open-loop manner with a physician who changes the settings of the ventilator manually. Regarding a future closed-loop system, artefacts seem to be the greatest obstacle in the way of save performance of 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.

A new user interface with a qualitative output and intuitive representation of the patients' status is a clinical requirement. Clinicians (experts & users) are reluctant to follow a machine that does not exactly show the decision process. Thus the machine should give arguments its support its suggestion in an open loop system.

With their assistance and expertise we aim at finding the optimal knowledge base and user interface design to improve the weaning process in future. The ultimate purpose is to generate an ideal system by handling the artifacts for a closed-loop system, which can be integrated into the ventilator. This would finally allow exact and continuous adjustments of settings and thus guarantee an optimal weaning process. 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.

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