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ORIGINAL PAPER

A Novel Fuzzy Logic Inference System for Decision Support in Weaning from Mechanical Ventilation

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Abstract Weaning from mechanical ventilation represents one of the most challenging issues in management of critically ill patients. Currently used weaning predictors ignore many important dimensions of weaning outcome and have not been uniformly successful. A fuzzy logic inference system that uses nine variables, and five rule blocks within two layers, has been designed and implemented over mathematical simulations and random clinical scenarios, to compare its behavior and performance in predicting expert opinion with those for rapid shallow breathing index (RSBI), pressure time index and Jabour' weaning index. RSBI has failed to predict expert opinion in 52% of scenarios. Fuzzy logic inference system has shown the best discriminative power (ROC: 0.9288), and RSBI the worst (ROC: 0.6556) in predicting expert opinion. Fuzzy logic provides an approach which can handle multi-attribute decision making, and is a very powerful tool to overcome the weaknesses of currently used weaning predictors.

Keywords Weaning · Mechanical ventilation · Fuzzy logic · Weaning predictors

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Introduction

Mechanical ventilation offers essential ventilatory support, while the respiratory system recovers from acute respiratory failure [1]. While often life-saving, mechanical ventilation is the most complex of critical care procedures, and is an invasive, costly therapy with well-documented complications [2–6]. Besides increased risk of ventilator associated pneumonia, barotrauma and nosocomial infections, mortality is known to be significantly higher in patients with prolonged mechanical ventilation [1]. That's why we want to wean and extubate patients at the earliest possible time. But failure to predict the right time to wean, may result in respiratory failure and reintubation of the patient, which is also known to increase morbidity and mortality [2].

The search for a reliable predictor of weaning success has yielded numerous predictors, but without reproducible results [7, 8]. Among them rapid shallow breathing index (RSBI) is the most widely used, in part due to its ease of calculation. It is measured after one minute of spontaneous breathing as the ratio of frequency to tidal volume, and a RSBI below the threshold of 105 (breaths/min)/L predicts weaning success with a sensitivity of up to 97% [9]. But its sensitivity decreases with prolonged ventilation, and its specificity is influenced by the disease state [7]. Specificity of 65% observed in patients with COPD, decreases to 28% in patients with acute respiratory failure [7, 10]. The other predictors of weaning represent more detailed parameters of respiratory dynamics, but are not widely used because of the difficulties in required measurements or bedside calculations. That's why the focus of clinical studies was mostly on finding a simple weaning predictor that is easy to measure and calculate.

Currently used weaning predictors almost solely focus on respiratory parameters, and fail to represent the whole clinical picture that forms the basis for readiness for weaning. Most of them ignore systemic perfusion, ventilation and acid–base balance, which have significant impact on the success of weaning trial.

In a recent review Siner and Manthous emphasized the diversity of variables that affect weaning outcomes and state that the process of weaning "will always be art guided but not predicted entirely by science" [11]. This notion, which we partly agree, actually points to the inadequacy of currently used weaning predictors in explaining the chaotic nature of weaning, and the superiority of human reasoning which is much powerful in solving multi-attribute problems. An approach closer to human reasoning may allow design of better predictive systems, and fuzzy-logic is a powerful tool in that respect.

Materials and methods

We have designed a fuzzy logic inference system for decision making in weaning from mechanical ventilation, and tested and compared its efficiency with those of RSBI, pressure time index (PTI) and Jabour' weaning index (JWI), in predicting expert opinion over randomly generated clinical scenarios. We have also explored and compared the behaviors of included predictors over mathematical simulations.

Design of the fuzzy logic inference system

The system designed includes nine parameters, which are easy to collect in practice, and use them to evaluate appropriateness of systemic perfusion, ventilation, acid–base balance and mechanical endurance of respiratory muscles for weaning (Fig. 1). For each input parameter a specific fuzzy logic interpreter with five linguistic variables has been designed (Fig. 2) [12, 13]. Outputs of fuzzy logic interpreters have been presented to the relevant rule blocks, each using Mamdani center of gravity (COG) algorithm for defuzzification (Fig. 3 and Table 1) [13]. Outputs of each of the four rule blocks in turn have been presented as inputs to a final rule block, using Mamdani COG algorithm, to be translated to a weaning probability.

The system has been designed over fuzzyTECH 5.54 (IMFORM, Aachen, Germany). The generated java code has been incorporated into a software (Bilgitay, Ankara, Turkey), developed in NetBeans 6.1 IDE, which can calculate fuzzy weaning prediction, RSBI, PTI and JWI, and can generate random clinical scenarios (Fig. 4).

Mathematical simulations

Mathematical simulations for evaluation of the behavior of predictors have been performed by changing two input

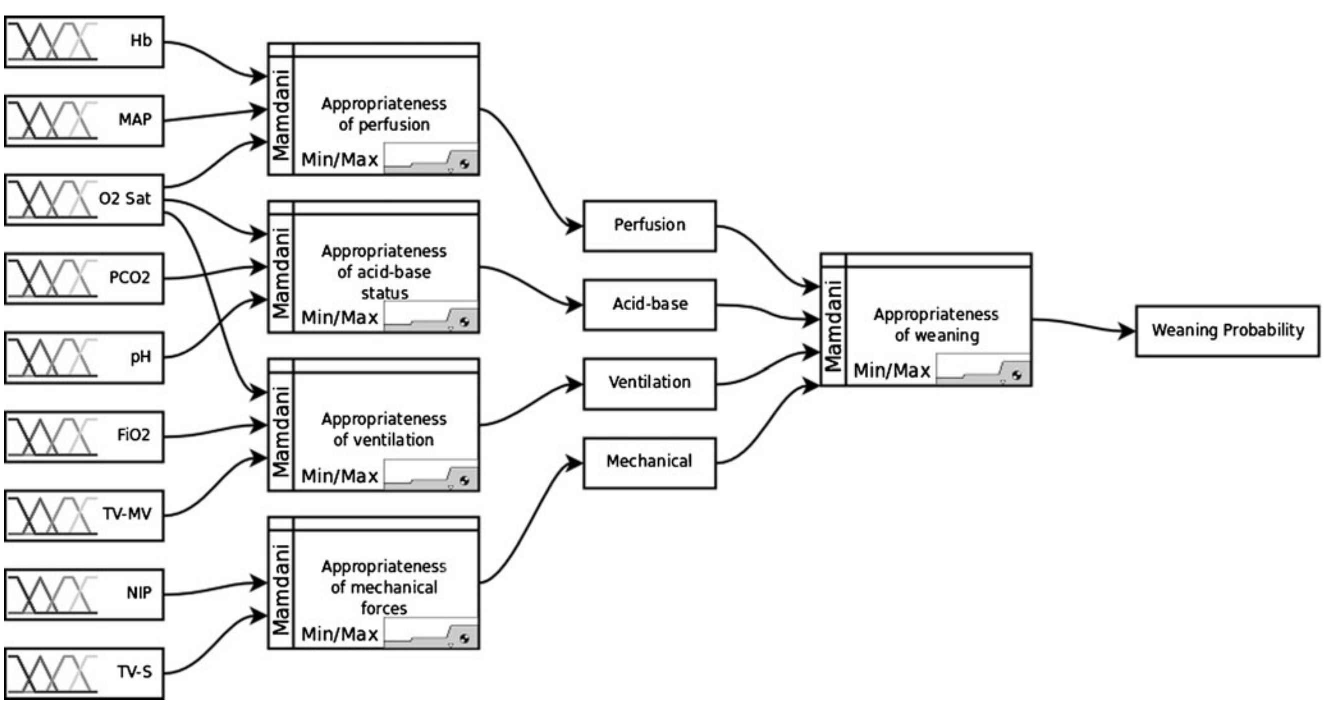

Fig. 1 The schematic outline of the system. (*Hb* hemoglobin, *MAP* mean arterial pressure, O_2 *Sat* arterial oxygen saturation, PCO_2 arterial partial CO_2 pressure, *pH* arterial pH, FiO_2 fractional inspired oxygen, *TV-MV* tidal volume on mechanical ventilation, *NIP* negative inspiratory pressure, *TV-S* tidal volume on spontaneous ventilation)

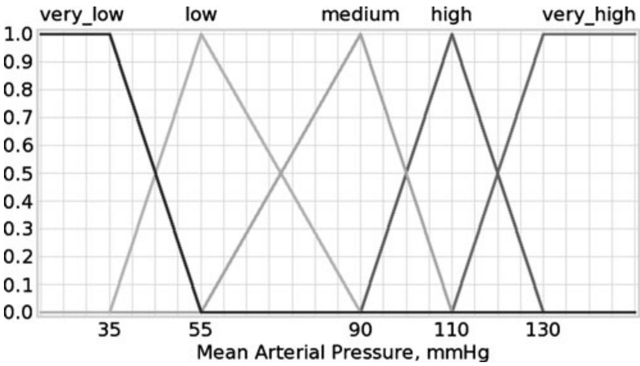

Fig. 2 Fuzzy logic interpreter for mean arterial pressure

parameters over their physiological range, while keeping the other variables stable.

Expert opinion

A surgeon involved in treatment of critically ill patients, and who was unaware of the study objectives, has been asked to make predictions on 100 computer generated clinical scenarios. The efficiency of calculated predictors have been evaluated to predict expert opinion. Statistical analysis has been performed in R Statistical Environment. Discrimination characteristics of the predictors have been expressed as the area under the receiver operating characteristics curve (ROC).

Results

The simulations have clarified that RSBI, PTI and JWI either use simple linear approximations or totally ignore important parameters of readiness for weaning, and fuzzy system shows a much more reliable behavior.

In a simulation that changes tidal volume and frequency during spontaneous ventilation, RSBI has shown a linear cut-off, beyond which a steep up-slope was observed in the calculated RSBI. For the same simulation fuzzy system has shown a sigmoidal behavior, which is a more physiologic approximation (Fig. 5). In another run of simulations, in which partial pressure of CO_2 and pH have been changed, JWI has shown a linear behavior, which is because it ignores pH.

Fuzzy logic system has shown a much more reasonable behavior, in which at extremes of pH and PCO_2 weaning probability decreases rapidly and optimum levels of both is required to be translated into a high weaning probability (Fig. 5).

RSBI has failed to predict expert opinion in 52% of scenarios. In that respect fuzzy weaning predictor was the best (ROC: 0.9288), and followed by Jabour' weaning index (ROC: 0.8559) (Fig. 6). Performance of PTI (ROC: 0.7290) and RSBI (ROC: 0.6556) were below the acceptable level.

Discussion

Care of critically ill patients causes a significant economical burden on health care industry and use of already limited resources. Need for complicated procedures and treatments may cause increased rates of complications and morbidity. That's why good clinical judgment is of paramount importance in timely and appropriate direction of therapy.

Mechanical ventilation comprises the most complicated critical care procedure, which if prolonged or inappropri-

Fig. 3 Translation of mean arterial pressure and oxygen saturation to appropriateness of perfusion

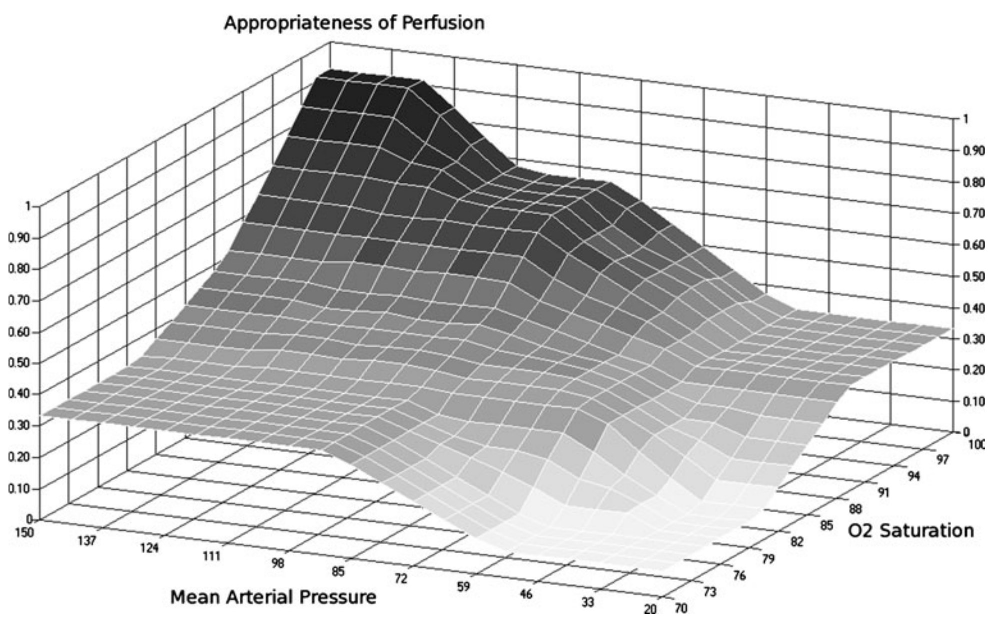

Table 1 Condensed rule block for appropriateness of mechanical forces (endurance of respiratory muscles)

Negative inspiratory pressure	Spontaneous tidal volume	Approriateness of mechanical forces
Very_high	Very_high	Very_high
Very_high	High	Very_high
Very_high	Medium	High
Very_high	Low or very_low	Low
High	Very_high	Very_high
High	High	High
High	Medium	Medium
High	Low or very_low	Low
Medium	Very_high	High
Medium	High or medium	Medium
Medium	Low	Low
Medium	Very_low	Very_low
Low	Very_high	Medium
Low	High or medium	Low
Low	Low or very_low	Very_low
Very_low	Very_high or high or medium	Low
Very_low	Low or very_low	Very_low

ately managed can cause significant complications and mortality [1–6]. That's why weaning the patient from the ventilator at the earliest possible time is very important.

On the other hand premature extubation may result in recurrent respiratory failure and necessitate reintubation [2, 14]. Ten percent to 20% of successfully weaned patients require reintubation within 48 h of extubation [3, 15–18]. Reintubated patients have a much higher mortality (30–40%) than successfully extubated patients (3–5%) [17, 19]. Identification of patients at risk of failed weaning trial and reintubation can prevent complications and prolongation of mechanical ventilation.

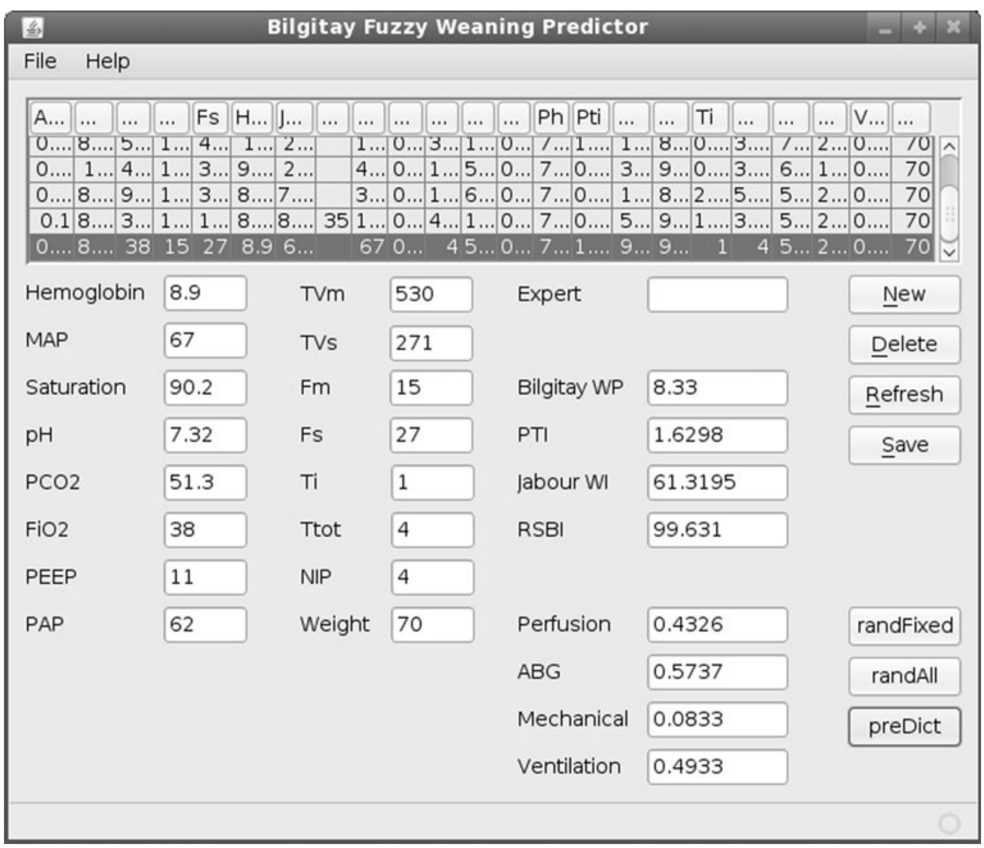

Fig. 4 Designed software which can calculate fuzzy weaning prediction, RSBI, PTI and JWI, and can generate random clinical scenarios

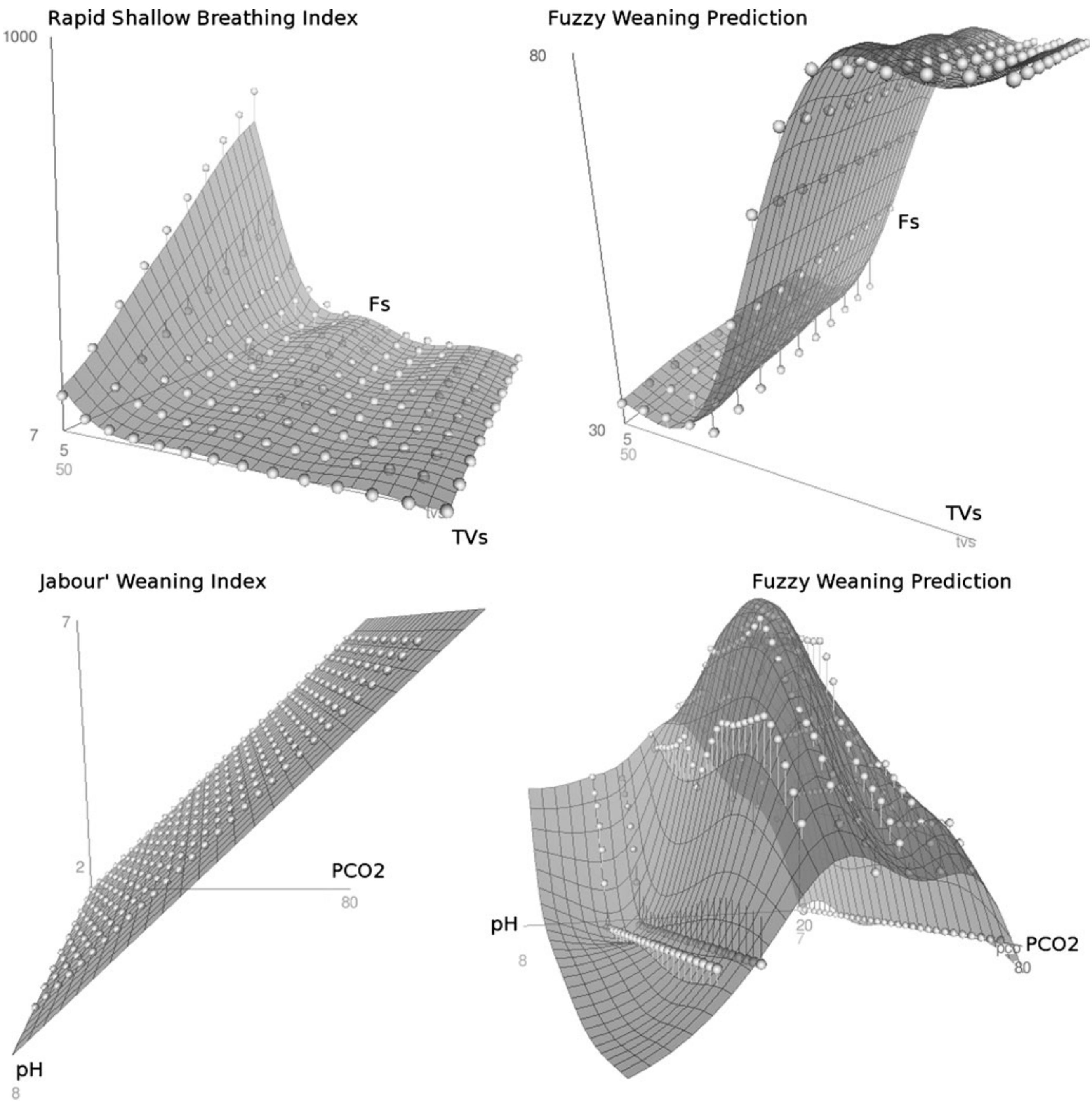

Fig. 5 Comparison of the behavior of different predictors in mathematical simulations

Weaning refers to the process of discontinuing mechanical ventilation [3,20]. Its aim is to predict the earliest moment when a patient has recovered sufficiently to breath indefinitely without ventilatory support, so one can extubate the patient without causing the complications of prolonged mechanical ventilation and avoid the risks of failed extubation and reintubation [11, 18, 21, 22].

Currently the most widely used weaning predictor is the rapid shallow breathing index (RSBI) which below the threshold of 105 (breaths/min)/L predicts weaning success with a sensitivity of up to 97% [9]. But its sensitivity decreases with prolonged ventilation, and its specificity significantly decreases in patients with acute respiratory failure [7, 10]. In general the results of clinical studies related to weaning predictors are not uniformly reproducible [7, 8]. This is probably based on the fact that they mostly focus on respiratory parameters, and ignore important clinical parameters which may be associated with weaning failure.

In order to start weaning, the original disease state which has caused initiation of mechanical ventilation must have been reversed, patient must be awake and have adequate respiratory drive in addition to the ability to sustain spontaneous

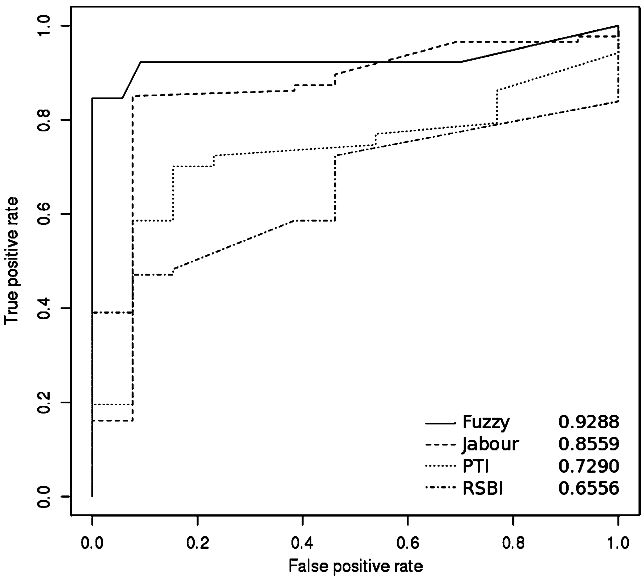

Fig. 6 Discrimination characteristics (ROC curves) of compared systems in predicting expert opinion

ventilation without distress, and there should not be a concern about their ability to protect their airway [3].

Functional force reserve of the respiratory muscles and endurance capacity of the respiratory pump must be adequate. There is a level of force above which the respiratory muscles can not sustain repetitive loads for prolonged periods, and muscle fatigue ensues, eventually leading to weaning failure [1]. Additionally factors related to acid–base balance or systemic perfusion may trigger an augmented respiratory drive, in which respiratory load can not be balanced by decreased respiratory capacity due to muscle weakness, a frequent problem in critically ill patients on prolonged mechanical ventilation [1].

Systemic perfusion must be adequate and the patient must be able to increase cardiac index and oxygen delivery, in order to overcome the unwarranted effects of increased ventricular afterload and enhanced oxygen extraction during spontaneous breathing trial [1]. Increased PCO_2 or decreased O_2 saturation during a spontaneous breathing trial are known to be associated with weaning failure [23, 24].

Further complicating the problem, disease states observed in critically ill patients have a chaotic nature, in which a temporal and dynamic relation is present between organ dysfunctions and therapeutic interventions [25, 26]. That's why decision making in critical care requires multi-attribute decision making (MADM) [27]. Decisions are given under time pressure, and decision context changes over time in an inherently unstable environment [28].

Inherent characteristics of the problem mentioned above, requires an approximate reasoning, close to human reasoning, rather than precise reasoning based on linear mathematical formulas. Fuzzy logic is the most appropriate and powerful tool in that respect. In our study, the developed fuzzy logic inference system has shown the best performance in predicting the expert opinion, and the way it interprets multi-attribute input was much reasonable compared to the other predictors.

Conclusions

Currently used weaning predictors ignore important dimensions of weaning outcome. Fuzzy logic provides an approach which can handle multi-attribute decision making, and is a very powerful tool to overcome the weaknesses of currently used weaning predictors.

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Appendix 1. Calculation of conventional weaning predictors

- Rapid Shallow Breathing Index has been calculated as

$$\mathrm{RSBI} = f_\mathrm{S}/\mathrm{TV}_\mathrm{S}$$

- Pressure Time Index has been calculated as

$$\mathrm{PTI} = (P_\mathrm{breath}/\mathrm{NIP}) \times (T_\mathrm{I}/T_\mathrm{TOT})$$

where

$$P_\mathrm{breath} = \left(P_\mathrm{peak} - \mathrm{PEEP}\right) \times (\mathrm{TV}_\mathrm{S}/\mathrm{TV}_\mathrm{M})$$

- Jabour' Weaning Index has been calculated as

$$\mathrm{JWI} = \mathrm{PTI} \times (\mathrm{VE}_{40}/\mathrm{TV}_\mathrm{M})$$

where

$$\mathrm{VE}_{40} = (f_\mathrm{M} \times \mathrm{TV}_\mathrm{M}) \times (\mathrm{PaCO}_2/40)$$

P_breath	Avarage inspiratory muscle pressure per breath
NIP	Negative inspiratory pressure
T_I	Inspiratory time
T_TOT	Total breath duration
P_peak	Peak airway pressure
PEEP	Positive end expiratory pressure
TV_S	Tidal volume on spontaneous breathing
TV_M	Tidal volume on mechanical ventilation
VE_{40}	Estimate of minute volume required to achieve a PCO_2 of 40 mmHg
f_M	Frequency on mechanical ventilation
f_S	Frequency on spontaneous ventilation

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