MULTIVARIABLE FUZZY LOGIC VENTILATOR ADVISORY SYSTEM

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Abstract: The purpose of the present study was to develop a Fuzzy Logic based Ventilation Management algorithm, supporting the control of mechanical ventilator tidal volume and frequency settings. The Fuzzy Logic algorithm employs routinely acquired physiological parameters and yields advice for the required changes in ventilator settings, according to the patient needs. Capnography, Oxygen Saturation, Cardiac Output, Body Temperature, Height, Weight, Airways Resistance, and Compliance data, as well as, demographic patient data such as, Age and Sex were the input-data for the fuzzy algorithm. The results of the developed Ventilator Management Advisor were preliminary compared to published data, based on widely accepted knowledge on respiratory control theory, in order to investigate the trend of our system's output. The variation of selected physiological input parameters, while keeping the remaining parameters constant, allows for the testing of the system's performance; the fuzzy logic algorithm was found to be always in line with the expected response, according to the commonly accepted knowledge of respiration physiology.

INTRODUCTION

Mechanically Ventilated Intensive Care Unit (ICU) patients are continuously monitored in terms of respiratory related physiological parameters, in order to evaluate the adequacy of the supplied ventilation. Physiological parameters are either monitored non-invasively on a real time basis, or invasively in variable sampling rates. Modern mechanical ventilators and bedside monitors are equipped with systems that continuously monitor lung mechanics parameters such as Resistance and Compliance, as well as other parameters that are directly related to ventilation adequacy, such as Capnography and Oxygen Saturation. ICU clinicians examine the trends of the recorded values of these parameters and based on patients physiology and pathology, suggest new settings for the mechanical ventilation apparatus. Since the needs of ICU patients are not static, the above procedure is ongoing.

This paper presents an initial fuzzy logic algorithm that aims to produce advisory data on managing mechanical ventilation. The fuzzy logic algorithm was developed to run on a personal computer and utilizes routinely collected physiological parameters for producing suggestions on ventilator's frequency and tidal volume. The development of such an algorithm, beyond its obvious usefulness as an advisory system in ICU, could be also used as a training tool for clinical staff.

BACKGROUND

The respiratory system is a neuro-dynamical system that exhibits high functional and structural specificity. The Respiratory Centers are mainly influenced by chemical factors in arterial blood and extra-cellular fluid (blood O_2 partial pressure: PO_2, blood CO_2 partial pressure: PCO_2 and Hydrogen ions concentration in blood: pH) [1]. The Breathing pattern (Tidal Volume: V_T, Minute ventilation: V_E, Respiration Frequency and Inspiration – Expiration duration: T_I and T_E), is the product of chemical and neural influences on neurons, motor nerves and respiratory muscles, which mainly targets to maintain the level of blood Oxygen and CO_2 within narrow limits [2]. The implementation of an advisory algorithm on ventilation management requires the development of a model of the respiratory control system. The classical approach of building a control system requires that the system should be analyzed in terms of mathematical relations, and then be translated into control blocks, including feedback loops and mathematical equations.

In the past, several attempts have been made, to describe the respiratory controller in terms of analytical mathematical models. S. Grodins [3], suggested a model that described the system by employing two major components, the "Controlled" and the "Controller". A similar approach was made by Saunders [4], in which Grodins' model was adapted to include dead space, shunt and muscle compartment, but utilized a different controller equation. M.Levin et

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al [5], have created a multi-compartment model to analyze the chemoreceptor control of breathing. Mathematical models are considered efficient in terms of describing the general trends of respiration physiology, but their coefficients need to be adapted to the individual.

Other researchers modeled only some aspects of the respiratory system. J.Mead in 1960 modeled the Respiration Frequency [6], M.Rozanek modeled the respiratory system based on its Anatomical Structure [7], and D.L.Fry and R.E.Hyatt modeled the pulmonary mechanics [8].

Recent research has targeted into developing computer-controlled or computer-assisted mechanical ventilation systems that could be used as computer expert systems on ventilation management for advising clinicians. MacPuf 1977 [9], was one of the first computer respiration models written in Fortran Language that incorporated lung mechanics and a ten compartment model. VentPlan, 1991 [10], is a patient –specific mathematical model of cardiopulmonary physiology that produces calculation of ventilation settings. VentEx [11], is a system based on the prototype KUSIVAR [12], and has been build to support ventilator therapy management. The prototype model was build for providing guidance in respiration management and was intended to collaborate with a commercially available mechanical servo-ventilator from Siemens.

Fuzzy models [13-15] have also been used in the field of respiratory-ventilation. T.Nemoto et Al. [16] used fuzzy logic for formulating a weaning process for controlling ICU pressure support ventilators, utilizing measurements of heart rate, tidal volume, breathing frequency and Oxygen Saturation. Y.Sun [17], evaluated clinically the performance of a feedback fuzzy controller of inspired concentrations of oxygen and isoflurane. Y.Sun et Al. [18] suggested and clinically tested a fuzzy controller that adjusted the inspired oxygen concentration in ventilated newborns. The limitation of the above approaches is that they do not examine respiration physiology in a holistic approach, but they observe each time a rather limited aspect of it, without taking into account the rest parameters that influence the outcome.

METHODS

Our aim was to develop a fuzzy system that would be able to utilize respiration related physiology parameters, and that would easily and continuously be employed in an ICU, in order to acquire data, and to produce advice, concerning basic ventilator settings such as Frequency and ventilator Tidal Volume.

A Fuzzy logic algorithm was employed for the controller, because fuzzy controllers can model complex systems efficiently. Fuzzy logic acknowledges that most natural classes are of fuzzy rather than of deterministic nature. Fuzzy systems are knowledge-based systems that are exhibiting tolerance to imprecision and perform with adequate reliability, when processing a large number of input parameters.

Blood Gas partial pressures have an apparent and well documented relationship with respiratory control [1,19,20], and they were considered as important input variables for the model. However, since they require invasive measurements, Capnography and Oxygen Saturation were used instead. Both parameters were acquired non-invasively, in real time, by employing appropriate ICU medical equipment and they produce a good estimation of the arterial and the venous gases partial pressures (concentrations).

Height and Weight, are factors traditionally used in ICU to estimate the Body Surface Area (BSA), in order to estimate the required minute ventilation of the patient [6,21]. Sex and Age also are predicting factors of ventilation settings. Radford's Nomogram is widely used as a predictor of tidal volume and rates in mechanically ventilated subjects [21].

Lung mechanics, and more specific Lung Resistance and Compliance, are also determinants of respiration frequency and volume, since they have a bearing on flow patterns of gases during breathing [6,8,20]. Lung mechanics are also related to lung pathology and by introducing them into our system we can simulate pathological conditions.

Since respiration is a cardiopulmonary function, a model that does not include the heart compartment will not be representative enough. Advanced approaches in modeling respiratory system have included the cardiopulmonary compartment [3]. For that reason Cardiac Output was adopted as an input variable of the system.

Last but not least, the body temperature was also an input parameter of the system. Body temperature regulates human breathing, both, in terms of frequency, and of volume. An increase of the body temperature leads to an overall increase of the minute ventilation [20].

All the above variables were employed to produce results for advising clinicians in the management of ventilation settings. Modern ventilators are designed to control multiple ventilation parameters such as Oxygen concentration in inspired gas, Tidal volume (V_T), Frequency (frq), Inspiration and Expiration time (T_I and T_E), Flow patterns, Peak Pressure, Positive End Expiratory Pressure (PEEP) and ventilation modes. Producing a fuzzy controller that could offer advice on the regulation of all the above parameters, would result in highly complicated fuzzy structure. For that reason, it was decided in this preliminary system to produce advice concerning only the most basic ventilation parameters (V_T and frq) necessary to sustain adequate ventilation in Continuous Mandatory Ventilation (C.M.V.) mode.

The fuzzy system was developed with MathWorks -Matlab. The system accepts the measured input variables and produces an advice on Tidal Volume and Respiration frequency. The system calculates and graphically presents the controller response on eight points between the present and the final value of the parameter (Figures 7 to 10). These eight points are equally spaced. This feature helps the user to examine the controllers' progression logic between the initial and the final input value, especially when these values are distantly spaced.

The system is made up from four fuzzy controllers. The core controller (Figure 1), is accepting the following input data: Oxygen Saturation: S_pO_2, Capnography: E_TCO_2, Airways Resistance: R, Compliance: C, Temperature and Cardiac Output: C.O. Input values are assigned a degree of association ranging from zero, no association, to one, maximum association, with the fuzzy controller membership functions. This process is termed as fuzzification. A set of rules are embedded into the controller which imposes the response of the controller. The rules that relate S_pO_2, E_TCO_2 with minute ventilation were developed based on the well documented relationship between Venous CO_2 partial pressure and Arterial O_2 partial pressure with VE [19,20].

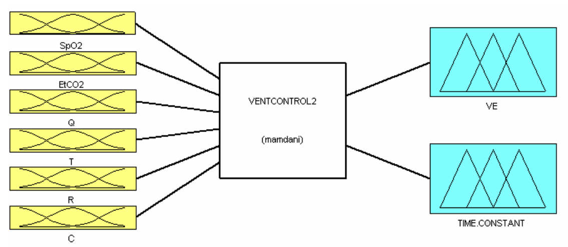

Figure 1: Core fuzzy system.

The set of rules are also taking into consideration the Haldane and Bohr effect [19]. Temperature increase, leads to an increase in the minute ventilation both in terms of V_T and Frq. Change in body temperature of 1^oC, results in approximately 12% change in oxygen consumption [1]. The response to changes of Cardiac output, which is considered to be related to the changes of Heart Rate, was designed to produce changes in the Minute Ventilation, in the same direction. Heart Rate increase is reported to be related to hypoxia [21]. When Saturation levels decrease, there is a substantial increase in Heart Rate. Once the rules have been applied, the output variables have been assigned to output fuzzy sets. The final stage is the so called defuzzification, where the output variables obtain numerical values, by employing a centroid methodology.

The core system output is the desired Minute Ventilation (VE), and an RC constant which corresponds to the lung mechanical characteristics of the patient. The output of the system is best described by the surface graphical representation, which shows the relationship of the controller output versus the input variables. An example of the two outputs (VE and RC), in response to R and C and S_pO_2 and E_TCO_2 inputs respectively, is given in Figures 2 and 3.

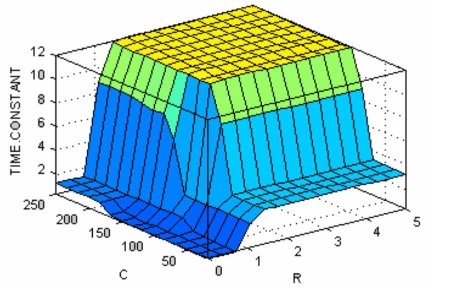

Figure 2: Surface Graph of C –R vs. Time Constant.

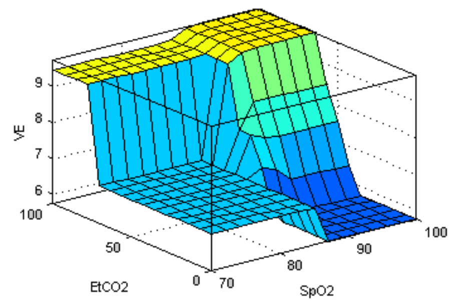

Figure 3: Surface Graph of EtCO2 –SpO2 vs. VE.

A second fuzzy system is following, aiming to produce the desired ventilation frequency based on the output provided by the preceding core system. The inputs to the system are the RC constant, expressing the lung mechanics, and the Minute ventilation (V_E). The response of the frequency system was based on the article of J.Mead [6]. Figure 4, shows the surface graph of the system.

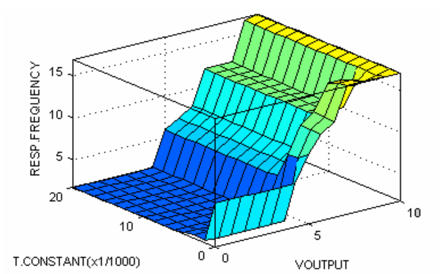

Figure 4: Surface graph of V_E – RC vs. Respiration Frequency.

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Since patients' somatometric characteristics Height and Weight, have not been yet taken into consideration in the two previous controllers, a third fuzzy system is introduced. The purpose of the third system is to "trim" the controllers output, based on Body Surface Area (BSA). The BSA is estimated by using the calculation formula of Equation 1 [22]. The BSA is the input to the system (Figure 5), while the output is the proposed change in minute ventilation (DVE, could be either positive or negative).

$$BSA=0.007184 \times H^{0.725} \times W^{0.425} \quad (1)$$

H: cm
W: kg

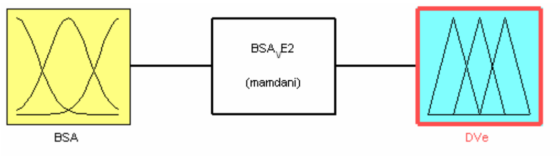

Figure 5: BSA – VE Differentiation system.

The last fuzzy system is designed to adapt ventilation frequency according to patient age. The fuzzy rules design was based on Radford's Nomogram [22]. The system uses as input the patient age and responds with a proposed change in ventilation frequency (DFrq), which was calculated in the second fuzzy system. The Age-Frequency Differentiation fuzzy system is described in Figure 6.

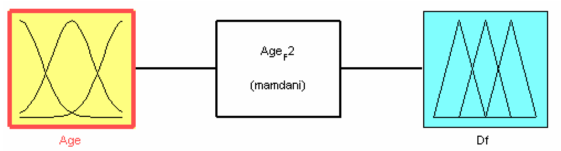

Figure 6: Age – Frequency Differentiation system.

The Tidal Volume is then calculated by dividing the final minute ventilation (VE ± DVE), by the estimated frequency (Frq ± DF). Sex in our model was incorporated into Minute Ventilation as 60% of the calculated DVE. Specific for females, the form VE = VE ± 0.6* DVE was employed.

The above system was designed to comprise of subsystems, in order to simplify the fuzzy rules that control its overall response. A single fuzzy controller that would have to utilize ten inputs (S_pO_2, E_TCO_2, R, C, Temp, C.O., Age, Sex, Weight, Height), and would produce two outputs (V_T and Frq), would have needed an extremely complicated set of fuzzy rules.

RESULTS

The system's response was tested by changing variables either as singles or as pairs. For our model the following values were considered as physiological:

Table 1: Physiological Values

Oxygen Saturation S_pO_2 = 99%	**Cardiac Output** C.O.= 5.6 L/min
End Tidal Capnography E_TCO_2 = 40mmHg	**Age** = 20
Airways Resistance R=1cmH2O (ml/sec)	**Sex** = Male
Airways Compliance C= 133ml/cmH2O	**Weight** = 80 Kg
Body Temperature Temp. = 37°C	**Height** = 180 cm

Figures 7 and 8 show the results acquired by changing a single input parameter, while keeping all other variables constant, and within the physiological limits. Table 2 describes the induced changes of each variable, from the physiological value to the final value, after 8 linear steps. Since changing patients' age is related to weight and height, all three variables were changed simultaneously.

The two output graphs in Figures 7 and 8, describe the "advised" changes in V_T (liters) and Frq (Breaths/min) respectively, to achieve adequate ventilation. Minute Volume (V_E) is calculated by the product of V_T x Frq at any step of the graphical representation.

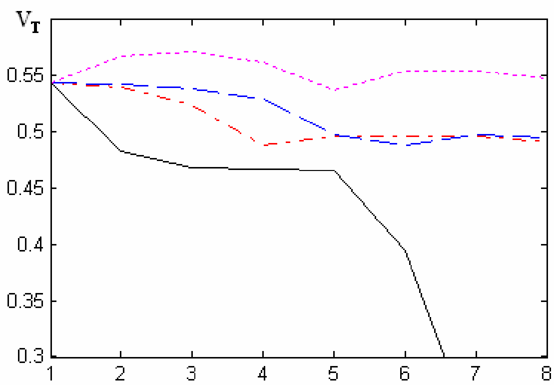

Figure 7: Variation of Tidal Volume: V_T, versus single input variable change.

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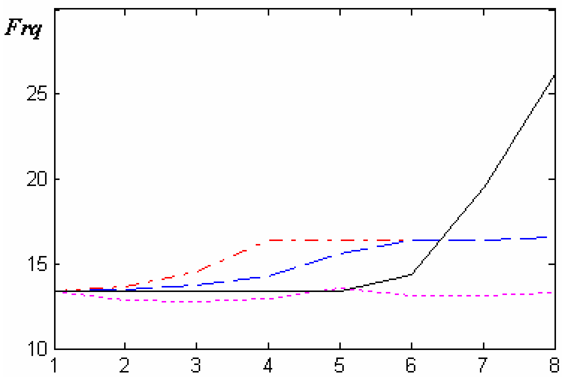

Figure 8: Variation of Respiration Frequency: Frq, versus single input variable change.

Table 2: Changes in single variables

Parameter	Line Style	Initial Value	Final Value	Step
C.O.	- . -	5.6 l/min	7 l/min	0.175 l/min
Temp	— —	37°C	40°C	0.375 °C
Airway Resistance (R)	- - -	1 cmH_2O/(ml/s)	0.8 cmH_2O/(ml/s)	0.025
Height	——	180 cm	90 cm	11.25 cm
Age		20 years	5 years	1.875 years
Weight		80 Kg	30 Kg	6.25 Kg

The results presented in Figures 7 and 8 are interpreted with the aid of table 2. Based on our system's "if … then" fuzzy rules, the system responds in such a way as to maintain adequate minute ventilation and at the same time to provide patient with the correct flow patterns. Examining changes in temperature from 37 °C to 40 °C, we observe that while Tidal Volume is held relatively constant, there is a considerable increase in ventilation frequency, from 12 up to 17 breaths/min. Once ventilation frequency becomes high, above 15 breaths/min, V_T decreases to make possible the intake of adequate ventilation, for the predefined lung mechanics values, as described in Table 1.

The controller responds in the same way to variation of patient's age, accompanied by changes in height and weight. As the patient's age decreases adequate minute ventilation is accomplished by decreasing V_T and increasing respiration frequency.

Figures 9 and 10 present the results from the simultaneous variation of two input parameters as indicated in Table 3. While S_pO_2 and E_TCO_2 progresses in the opposite direction, that is E_TCO_2 increases and S_pO_2 decreases, minute ventilation increases dramatically. The effect of both parameters, changing in opposite directions, is additive.

Table 3: Changes in pair variables

	Parameter Pair	Line Style	Initial Value	Final Value	Step
Pair 1	SpO_2	— —	99%	70%	3.62%
	E_TCO2		40 mmHg	45 mmHg	0.625 mmHg
Pair 2	SpO_2	- - - -	99%	70%	3.62%
	E_TCO2		40 mmHg	37 mmHg	0.375 mmHg

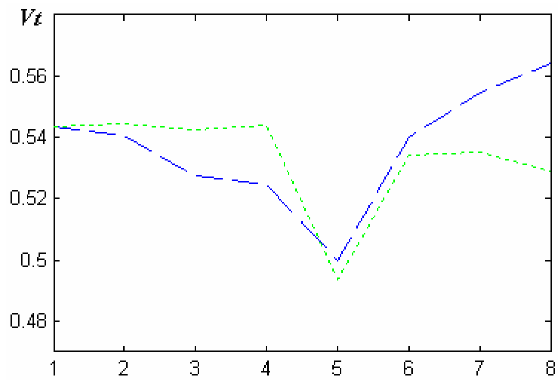

Figure9: Variation of Tidal Volume: VT, versus the change of a pair input variables.

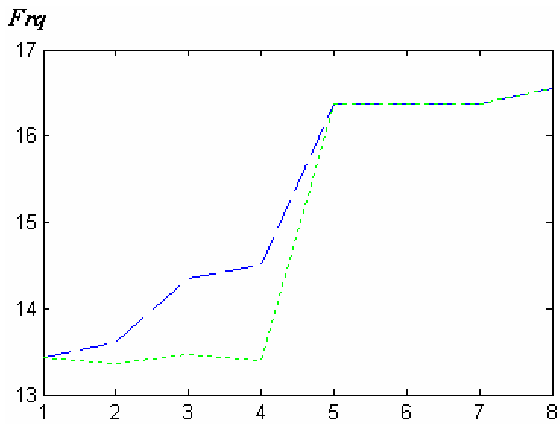

Figure 10: Variation of Respiration Frequency: Frq, versus the change of a pair input variables.

While both parameters change to the same direction, only when Oxygen Saturation is sufficiently low (compare step 5, $SpO_2 \approx 84\%$), there is an overall increase in V_E.

Lung mechanics, namely R and C, for a given change in minute ventilation impose the maximal flow patterns. The system adapts both Frq and V_T in order to achieve a given V_E.

The increase in V_E could be achieved by increasing both V_T and Frq. However since lung mechanics are expected to limit the maximal gas flow the controller responds by balancing the Volume with the frequency. In steps 4 to 5, it is obvious that the controller responds by decreasing V_T and increasing Frq in order to provide sufficient V_E and maintain maximal flow low.

DISCUSSION

The output of the system was laboratory tested for the efficiency and the efficacy of indicating the trend of the required variation for the ventilator settings versus the input variables' changes. The examined fuzzy logic algorithm based system found to be always in line with the expected response according to the commonly accepted knowledge of respiration physiology.

However, in order to employ the system clinically, under real world conditions, it is imperative to undertake a long-term retrospective clinical study, by comparing the system's advisory results with acquired monitored patient data. Such a study is in planning for the near future.

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