# A Model-Based Decision Support System for Mechanical Ventilation Using Fuzzy Logic

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***Abstract* - In clinical practice, the mechanical ventilation is a very important aided method to improve patients' breath, so parameter setting of ventilator directly affects pulmonary gas exchange. In this report, we try to build a decision support system based on the gas exchange model for mechanical ventilation using fuzzy logic. The gas exchange mathematic model can simulate individual patient's pulmonary gas exchange, and can help doctors to learn patient's exactly situation. The system uses fuzzy logic algorithm, utilizing the measurement of patient, and generates the ventilator settings respond to individual patient. The system was retrospectively evaluated in 10 intensive care patient cases, with mathematic models fitted to the retrospective data, and then used to simulate patient response to changes in therapy. Compared to the ventilator settings set as part of routine clinical care, the system lowers inspired oxygen fraction and breath work and improves gas exchange with the model simulated outcome.**

***Keywords - mechanical ventilation; pulmonary gas exchange model; fuzzy logic***

## 1. INTRODUCTION

Mechanical ventilation is commonly used to reverse hypoxemia and hypercarbia and plays an important role in the intensive care unit (ICU). In order to adapt to varied conditions of patients, parameter settings of mechanical ventilation are also changed, while incorrect mechanical ventilation parameters may increase the risk of ventilator induced lung injury or even be life-threatening.

In the past few decades, there have been many advances in mechanical ventilators to make them more responsive to individual patient's needs. Meanwhile, various ventilation patterns and control systems have been developed aiming at clinical demands[1-6]. These systems focus on implementing clinical guidelines and practical experience so as to automatically adjust ventilation parameters according to situations of patients[1-5], minimize work of patient's breath and keep the patient within a ‘‘zone of comfort’’ during pressure support ventilation [5,6],as well as to achieve weaning from mechanical ventilator in the end. However, focuses of such systems are relatively limited, only targeting at improving partial physiological parameters of patients, failing to combine overall situations of patients and make a preliminary judgment on patient’s state.

Any change of ventilator setting is to improve patient's pulmonary gas exchange and it is expected by clinicians to drive patient’s state to be normal by adjusting parameters of ventilator. Therefore, clinicians need to readjust ventilator setting or treatment plan according to blood air analysis of patients in case patient’s illness does not develop in clinicians’ expectation. However, if the mathematic model of respiratory system can be set up according to patient’s state, gas exchange of patients can be simulated and impact on patients can also be changed by simulating parameters of mechanical ventilation.

Human physiological model-based mechanical ventilation decision support system is gradually developed as another ventilator assist control system [7-9]. In such a human physiological model-based system, parameters of the model can be set according to physiological parameters of patients, enabling the model to reflect patient’s physiological status. Mechanical ventilation parameters suitable for patients are formed in the system based on patient’s physiological model and expert knowledge, providing reference for mechanical ventilation strategy and parameter setting for clinicians or controlling implementation of mechanical ventilation by ventilators directly. However, due to different situations of respiratory systems of different patients, how to accurately simulate real situation of patients turns to the difficulty for implementation of the system.

In this paper, a project combined knowledge-based and model-based decision support system is described. The system uses fuzzy logic theory and protocols based on the clinical knowledge, and tries to build a mathematic model of the respiratory system response to individual patient, so as to provide appropriate patient with adaptive advice on ventilator setting, and aid the clinician in obtaining a deeper understanding of patient's state.

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## II. MATERIALS AND METHODS

The system is composed of man-machine interaction module, human pulmonary mathematic model and fuzzy controller, whose structure is as shown in Figure 1. Physiological parameters of patients and parameters necessary for human pulmonary mathematic model are required by the system via the man-machine interaction interface, while pulmonary mathematic model simulates gas exchange of patients according to the required parameters. Fuzzy controller, with physiological parameters of patients being input, conducts simulation closed-loop control with pulmonary mathematic model, which is fed back to man-machine interaction module as reference value set by ventilator after stable output.

In the following sections, each module will be described respectively.

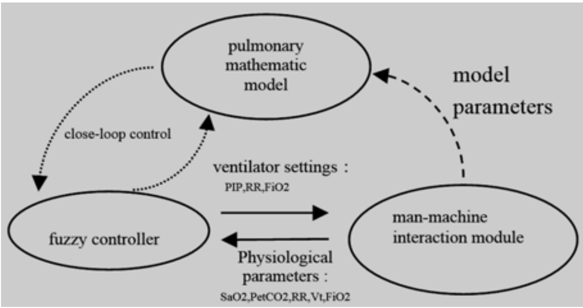


Fig. (1). The Structure of the System

### *A. Model for Pulmonary Gas exchange*

#### *A1. Mathematical Model for Human Body Gas Exchange*

Riley [2] has proposed simplified model for pulmonary air transport (simulating pulmonary gas exchange by single compartment lung) in early stage and pointed out that resistance for pulmonary air transport is from ① pulmonary shunt: only partial pulmonary alveoli perfusion without ventilation; ② the resistance of diffusion (Rdiff) between alveoli and end lung capillary blood. Petors discovered mismatch between ventilation ($\dot{V}$) and perfusion ($\dot{Q}$) of the lung [3], proposed double compartment lung model. Later, Andreassen S and Rees SE put forward air transport model for double compartments lung model[10,11], in which resistance of air transport was described as the product of dual function of pulmonary shunt (fs) and ventilation/perfusion (fA2) mismatch.

By practical clinical comparison and application, Karbing et al. believed that consistency is only of 3% between simulation value of single compartment lung model and practical detection value with clinical patients [4], while that between simulation value of double compartments lung model and practical detection value with clinical patients is of 80%, illustrating that double compartments lung model simulates practical situations of patients more satisfactorily. Double compartments lung model is selected as gas exchange model in this paper.

Double compartments lung model is a series of mathematical formula derived from respiratory physiology and mass balance equations, which can describe the dynamic changes of the blood gases in response to the change in the ventilator settings. The model consists of five compartments: the alveolar compartment, the pulmonary compartment, the arterial compartment, the tissue compartment and the venous compartment. The equations describe the sequence of movement of oxygen and removal of carbon dioxide which is as follows:

1) Human body exchanges air in alveolar compartment with the atmosphere by respiration, improving oxygen content and reducing content of carbon dioxide in pulmonary alveoli.

2) Venous blood passes to the pulmonary compartment where it is oxygenated. Oxygen diffuses from the alveolar compartment to the pulmonary compartment and excess carbon dioxide diffuses from the pulmonary compartment to the alveoli, the rate of which is governed by Fick's Law [12].

3) Not all the venous blood passes to the pulmonary compartment. Part of it may bypass the lung and pass directly into the arterial compartment, which is called the pulmonary shunt. Oxygenated blood is then mixed with the deoxygenated blood in the shunt (the anatomical shunt) and together it passes into the arterial compartment.

4) Arterial blood is carried by the arterial compartment to the tissue compartment where the oxygen is taken up. The amount taken up is determined by air content in the blood, the oxygen consumption and yield of carbon dioxide in the tissues.

#### *A2. Mathematical Models of Lung Mechanics*

Air passes through oral cavity, nasal cavity, trachea and bronchus, and then enters into pulmonary alveoli. According to study of Weibel[13], bronchial trees in lung are divided into 23 classes, each class has different mechanical properties, elasticity and airway resistance. Based on such a study, the complete mechanical mathematic model for lung can be built. For the convenience of study, simplified mechanical model for lung is adopted in this paper, in which lung of human body is regarded as an integral whole and comprehensive lung compliance and airway resistance parameter is given for such an integral whole. By making use of this lung mechanical model, relation between tidal volume (Vt) during lung respiration and peak inspiratory pressure (PIP) can be simply reflected.

*A3. Parameter Setting in the Model*

Parameters in the model can be obtained by arterial blood gas analysis(ABG) and such physiological parameters as saturation of pulse oximetry(SpO2) and partial pressure of end expired carbon dioxide (PetCO2) of patients collected by non-invasive method. Physiological dead space in lung of patients is calculated by using ideal body weight (2.2mL/kg).

Shut and fA2 can be estimated by making use of weighted least square method, enabling the model to simulate real gas exchange in lung of patients to the maximum. In addition, according to method introduced by de Gray et al. [14], value of fs and fA2 can also be calculated by analysis to FiO2/SaO2, making simulated result of the model closest to fitted curve of measured data.

*B. Fuzzy Controller*

Fuzzy controller under this topic sets ventilator parameter through fuzzy control strategy based on ventilator pressure support. The controller is set with five inputs and three outputs. Five inputs are arterial saturation of pulse oximetry ($SpO_2$), fraction of inspired oxygen (FiO2), partial pressure of end expired carbon dioxide (PetCO2), respiratory rate (RR) and tidal volume (Vt), basically covering physiological parameters of human body related to gas exchange in mechanical ventilation, while three outputs include inspiration pressure (Pinsp), FiO2 and RR of mechanical ventilation under the ventilator pressure support mode.

*B1. Fuzzification of Input and Output*

Fuzzification is a process of conversion of input determined value of fuzzy controller to corresponding fuzzy linguistic variables, which is an important process to realize fuzzy control. Subordinating degree functions of trimf and trapmf are adopted in the topic for dividing input into interval structures, with two intervals for SpO2 and FiO2 respectively, three for PetCO2, Vt and RR respectively, which are as shown in Figure 2.

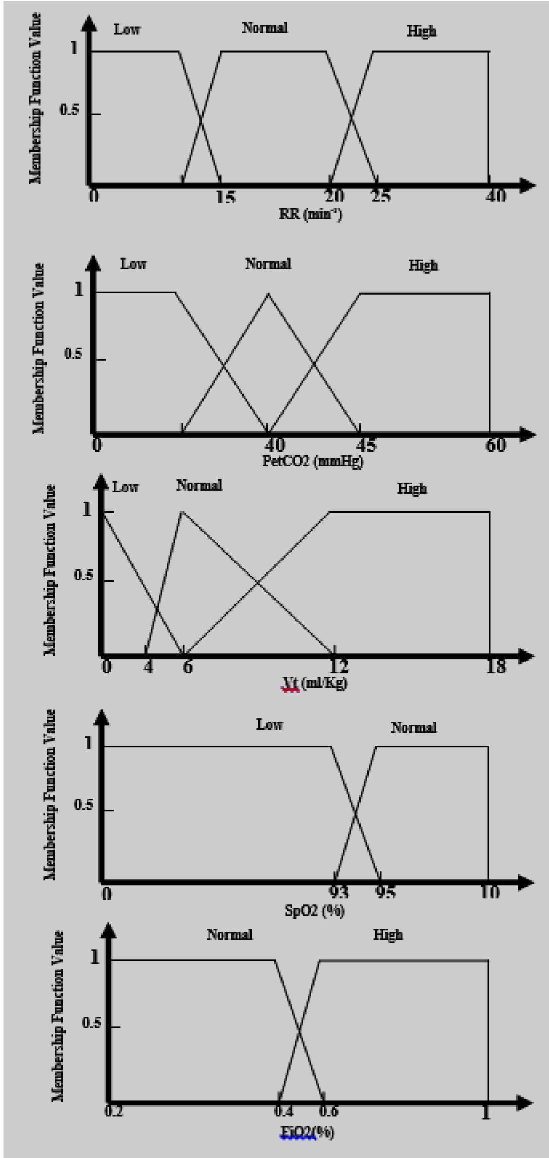

Fig.(2). Input Fuzzy Set Structure

Output control quantity can also be expressed by interval structure. Pinsp, FiO2 and RR are divided into five interval structures respectively, being “small amount reduction”, “little reduction”, “status quo maintaining”, “small amount increase” and “little increase” respectively, which are as shown in Figure 3.

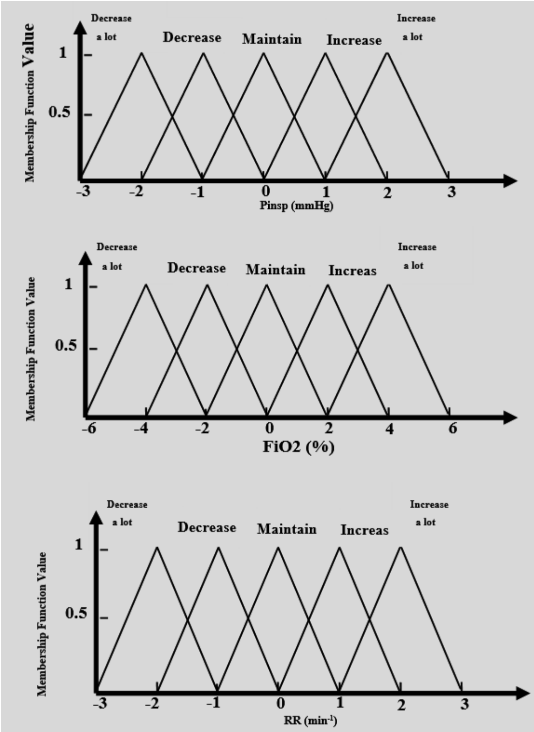

Fig.(3). Output Fuzzy Fet Structure

*B2. Fuzzy Control Rules and Visualization Calculation*

Fuzzy control system makes description and expression by making use of a series of language based on expert knowledge. Conditional statement of "if…then…" is usually adopted for expert knowledge. Fuzzy control rules described and expressed by such conditional statement constitute set of fuzzy control rules. Five inputs are available in the topic and 2×2×3×3×3=108 pieces of fuzzy control rules are formulated based on system control principle and clinical practical experience. All these rules shall meet the following requirements.

1. If PetCO2 rises, then increase respiratory rate, Pinsp and minute ventilation.

2. If SaO2 is lower than 85% and FiO2 is higher than 0.6, then increase Pinsp and tidal volume (Vt).

3. If SpO2 is low and FiO2, RR and Pinsp are all within normal range, increase RR, FiO2 and Pinsp in succession.

4. If SpO2 is low and end tidal carbon oxide (PetCO2) is low, then raise FiO2 and then decrease Pinsp and RR.

5. If Vt is high, then reduce Vt and increase RR.

According to the above principles, three fuzzy control rules are listed as follows:

IF SpO2=low and RR=normal and FiO2=high and Vt=normal and PetCo2=normal, THEN Pinsp=increase and RR=Maintain and FiO2=Maintain.

IF SpO2=low and RR=normal and FiO2=high and Vt=normal and PetCo2=low, THEN Pinsp=decrease and RR=Maintain and FiO2=increase.

IF SpO2=low and RR=normal and FiO2=normal and Vt=High and PetCo2=normal, THEN Pinsp=decrease a lot and RR=increase and FiO2=increase.

Fuzzy output value is required by fuzzy inference. Method of weighted mean is adopted to convert fuzzy output set visualization to accurate controlled quantity.

2.3 Man-Machine Interaction Module

Man-machine interaction module is the port for information interchange between clinicians and the system. Clinicians can enter current mechanical ventilation parameter of patients in ventilator setting function on top left corner as is shown in Figure 4 and then the system can simulate the optimal mechanical ventilation setting value of patient, thus providing reference for clinicians. On top right corner, clinicians can enter testing result of blood-gas analysis of patient and such values related to parameters of patient blood as cardiac output, and the system will set up and adjust current pulmonary gas exchange model of patient according to such parameters. The relevant lung parameters are shown on left bottom corner, including lung compliance, airway resistance and physiological dead space of lung. On right bottom corner, the current lung shunt fs and the relevant fA2 value of ventilation/instillation ($\dot{V}_A/\dot{Q}$) is estimated by the system by making use of weighted least square method according to the current lung gas exchange model of patient. Meanwhile, clinicians can also choose nine values from 21% to 100% of FiO2 according to method introduced by de Gray et al. [14], and collect SaO2 or SpO2 after FiO2 is changed for 5 to 10 minutes each time. And then the acquired data match the FiO2/SaO2 curve via point depiction method. Moreover, the system can also acquire the simulated FiO2/SaO2 curve according to the estimated fs of pulmonary shunt and the relevant fA2 value of ventilation/instillation ($\dot{V}_A/\dot{Q}$). If the estimated value is unsatisfactory, clinicians can change the fs and fA2 manually, by which a FiO2/SaO2 curve can also be obtained. Three FiO2/SaO2 curves of different parameters can be depicted in interface on right bottom corner, for clinicians' more favourable judgment on patient's situations.

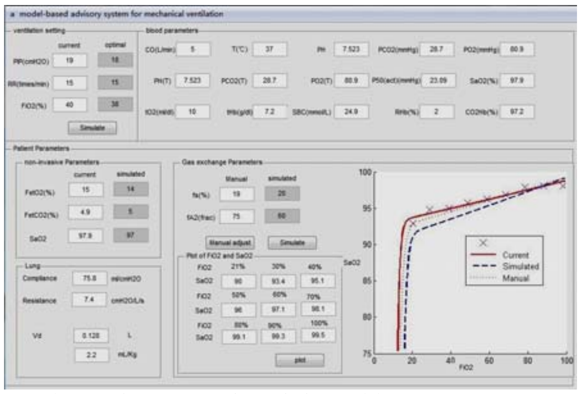

Fig.(4). The User Interface of The Decision Support System

## III. RESULT

Select 10 patients receiving mechanical ventilation in the ICU, 7 males and 3 females. See Table 1 for specific information. All these patients are plagued with acute respiratory distress syndrome (ARDS) and need ventilator for assisted respiration. SpO2 and PetCO2 of patient are obtained by measurement of bedside monitor (Drager Infinity Delta XL, Lubeck, Germany). Such parameters as FiO2, RR, Vt, compliance and airway resistance are all observed from the ventilator (Drager Evita 4, Lubeck, Germany), while the relevant parameters of patient blood are measured by blood-gas analyzer (ABL90, Radiometer, Danmark).

TABLE 1. SUMMARY OF PATIENT INFORMATION

| Patients ID | Sex (M/F) | Age (yr) | Weight (Kg) | Compliance (ml/cmH2O) | Resistance (cmH2O/L/s) | Admission Diagnosis |
|---|---|---|---|---|---|---|
| 1 | M | 78 | 60 | 86.1 | 7.03 | sancreatitis, serious pulmonary infection |
| 2 | M | 81 | 70 | 49.03 | 14 | subdural edema, pulmonary infection |
| 3 | F | 70 | 48 | 75.8 | 7.4 | aspiration pneumonia |
| 4 | F | 26 | 52 | 87 | 14 | cervical vertebra bone fracture, pulmonary infection |
| 5 | M | 59 | 72 | 79.1 | 5 | gastric perforation, pulmonary infection |
| 6 | M | 40 | 65 | 21 | 38 | extensive burns, pulmonary blast injury |
| 7 | M | 55 | 70 | 100 | 16 | traumatic brain injury |
| 8 | F | 46 | 46 | 21 | 9 | acute left heart failure, uremia(CKD5), pulmonary edema, pulmonary infection |
| 9 | M | 53 | 64 | 41 | 38 | gallbladder carcinoma |
| 10 | M | 23 | 68 | 100 | 7 | cone fracture, paraplegia |

The system simulates gas exchange of these 10 patients based on achieved physiological parameters of them and offers relevant setting reference value (PIP, RR, FiO2) of mechanical ventilator appropriate for current conditions of patient through simulation. Comparison is given in Figure 5 between resulting simulated value of FiO2 and current value of these 10 patients. Figure 6 and Figure 7 show the comparison of Pinsp and RR between resulting simulated value and currently-received value of these 10 patients under pressure support ventilation (PSV) mode.

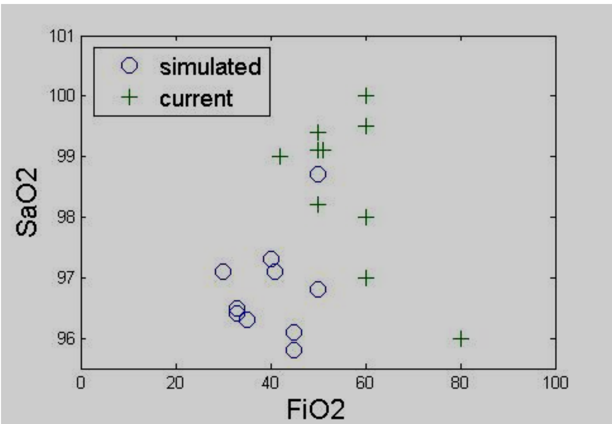


Fig.(5). Compare Clinical Values of FiO2 and SaO2 With System Simulated FiO2 and SaO2.

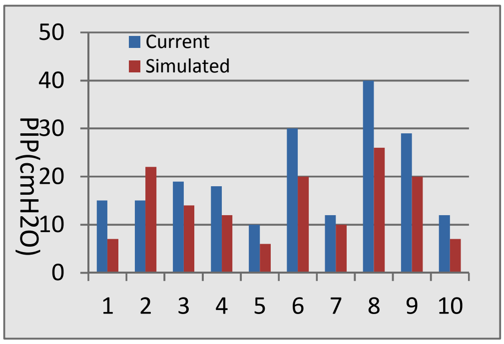


Fig.(6). Compare Clinical Values of PIP With System Simulated PIP.

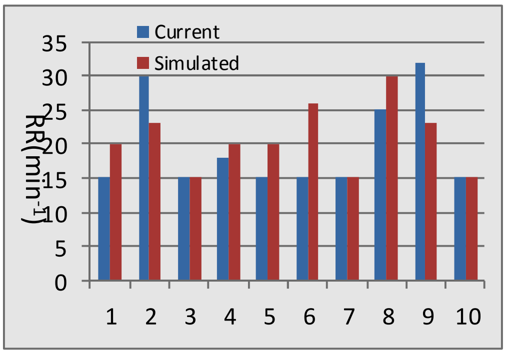


Fig.(7). Compare Clinical Values of RR With System Simulated RR.

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## IV. DISCUSSION

A model-based decision support system for mechanical ventilation using fuzzy logic is introduced in this paper. The system is designed to model and simulate gas exchange of patient's lung by utilizing the acquired patient physiological parameters through mathematic modelling and to simulate appropriate mechanical ventilation setting parameters for patient on the basis of the established gas exchange model of fuzzy control system so as to provide parameter setting reference for clinical ventilator users.

Compared with the mechanical ventilation automatic regulatory system under extensive study currently, the model-based decision support system for mechanical ventilation using fuzzy logic boasts the following advantages: 1) gas exchange mathematic model of pulmonary in the system is able to simulate real gas exchange situations of patient's lung in a satisfying way; 2) fuzzy control rules in the fuzzy logic-based control system are formulated on the basis of expert knowledge base and clinical treatment principle as well as practical experience, reflecting practical clinical requirements satisfactorily with relatively higher safety and accuracy; 3) mechanical ventilation makes preliminary simulation of gas exchange model of human body, enabling the acquired parameters to be more suitable for demands of patient's illness and anticipating impact on patient by change of mechanical ventilator settings; 4) reference mechanical ventilator settings set by simulated can reduce oxygen consumption as much as possible, reduce work of patient's breath and mechanical injury on patient lung incurred by mechanical ventilation while clinical demand of patient's mechanical ventilation is satisfied.

As is shown by result of the trial, different mechanical ventilation strategies are adopted in the system on the basis of patient situations. To minimise the risks of ventilator associated lung injury (VALI), system adopt protection strategy of decreasing inspiration pressure and increasing respiratory rate (as is shown in Figure 6 and Figure 7) , which improve the $\dot{V}_A/\dot{Q}$ mismatch and helps achieve better gas exchange.

High values of FiO2 can straightforwardly improve oxygen levels but they can also cause collapse in the alveolar regions as oxygen is rapidly absorbed into the blood, reducing alveolar volume below critical collapsing volume. Under the premise that mechanical ventilation demand of patients is met, FiO2 value recommended by the system is generally lower than that of the current value of patient (as is shown in Figure 5), reducing hyperventilation rate of patient, effectively requiring the least amount of supplemental oxygen needed to satisfy gas exchange requirements.

The model-based decision support system for mechanical ventilation using fuzzy logic is developed to provide compatible mechanical ventilation parameter setting value to patient's demands for clinical ventilator users and to simulate gas exchange of patient's lung in a noninvasive way, thus facilitating mastery of patient's situations by clinicians and reducing the frequency of such invasive detection as blood-gas analysis. However, mechanical ventilation is a complicated process and involves numerous correlative parameters. For easy realization, complexity decrease of the process and timeliness improvement of the system, only three major parameters are selected from mechanical ventilation parameters, as a result of which the system fails to satisfy clinical user's demands to the best extent. More mechanical ventilation parameters will be covered in future study to meet clinical usage demands. Meanwhile, intensive study will also be made on automatic close-cycle control and on optimization of gas exchange model of human body in the system so as to make automatic ventilator parameter control and regulation realized.

## V. CONCLUSION

In conclusion, a decision support system for mechanical ventilation using fuzzy logic based on human body gas exchange mathematic model is set up in this study. Clinical trials have proved that the system is able to offer satisfactory assistance and suggestions for clinicians in treatment and mechanical ventilator setting with patient's situations being taken into consideration. Owing to simulation of gas exchange of patients, the model-based decision support and control system for mechanical ventilation can realize better satisfaction to patient's illness and is bound to be the development trend of mechanical ventilation automatic control and will expect wide clinical application in the future.

## CONFLICT OF INTEREST

The authors confirm that this artical content has no conflicts of interest.

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