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Critiquing Treatment and Setting Ventilatory Parameters by Using Physiological Modeling

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***Abstract*—A modeling system is presented that can be used to predict the effects of ventilatory settings on the blood gases of patients on mechanical ventilation. The system uses a physiological model of the patient that includes lungs, body tissue, and brain tissue compartments. The model includes the effects of changes in the cardiac output and cerebral blood flow and lung mechanical factors. The system has applications in critiquing different treatment options and can be used alone or in combination with decision support systems to set ventilatory parameters and optimize treatment for patients on mechanical ventilation.**

Index Terms—**Mechanical ventilation, physiological modeling, decision support systems.**

I. Introduction

SETTING the mechanical ventilation parameters for ICU patients can be a challenging task for many medical personnel. The ICU clinicians need to review large amounts of patients' data, carefully consider the many different ventilatory options available in advanced ventilators, and based on the patients' underlying illnesses, choose appropriate ventilatory treatments for their patients in a timely manner. Several major closed-loop control techniques for mechanical ventilation have become available in recent years that are designed to facilitate this task and help optimize ventilatory treatment [1], [2]. However, most of the available ventilatory modes are still mainly open-loop control techniques in which the parameters of ventilation are set by clinicians. To assist the medical personnel in choosing ventilatory parameters for their patients, many computerized decision support systems have been developed in the past few decades [3], [4]. While decision support systems can be used to help clinicians in setting ventilation parameters more effectively, a computerized model-based system that can test different treatment options and predict the patient's response to different settings, may prove to be a helpful tool to medical personnel in choosing an optimal ventilatory protocol. The system described in this paper is designed to serve this purpose.

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II. Methods

The computerized system used in this study is based on and derived from an earlier physiological model of the human respiratory system [5]. In that model, the respiratory controller is a discrete system, which generates and updates the drive signal to the plant at the end of every breath to represent the Hering Breuer reflex. The controller functions based on inputs from the peripheral and central medullary receptors as well as changing respiratory mechanics and controls the depth and rate of breathing to minimize the respiratory work rate. The plant in the model is a continuous system that includes lungs, body tissue, and brain tissue compartments. The plant also includes cardiac output and cerebral blood flow controllers and a cerebrospinal fluid compartment. The lung volume and dead space are time varying. This model is modified for the purpose of this study. The respiratory control system is replaced by a positive pressure mechanical ventilator providing pressure to the patient's airways and oxygenated gas, and the effects of changing arterial circulation delays are included in the model. Figure 1 shows a block diagram of the modified model used in this study.

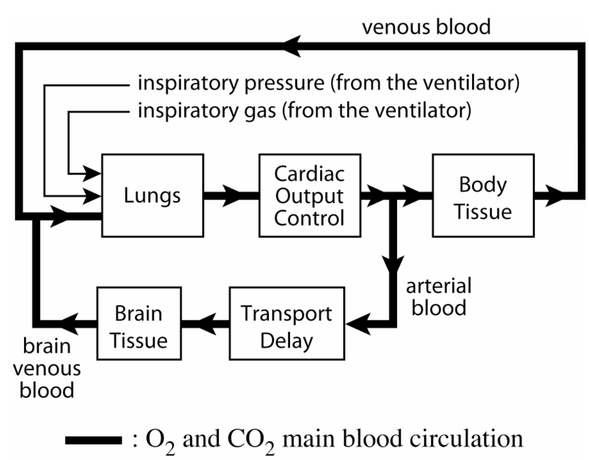

Fig. 1. A block diagram of the simulation model.

As shown in Figure 1, this model includes lungs, body tissue, and the brain tissue. The mass balance equations of these compartments are provided in Reference # 5 and are not repeated here for brevity. In this model, lung volume is continuously time varying and dead space volume is changing with time. Cardiac output, the blood flow rates to

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the tissues and the brain, along-with the arterial transport delay can also change with time. The inspiratory gas is supplied to the patient's airways by the ventilator. The applied pressure causes the expansion of the lungs in accordance with the patient's lung mechanics. The oxygenated gas is delivered to the patient's lungs at a concentration set on the ventilator (F_{IO2}). The venous blood from the body tissue and the brain perfuse the lungs and come into contact with the inhaled oxygenated air in the alveolar space. The venous blood absorbs oxygen from the inhaled gas and looses its carbon dioxide to that gas during inspiration. The gas is then exhaled from the lungs, the oxygenated blood is pumped by the heart through the arteries and the cycle is repeated. In this system, cardiac output can change due to variations in the heart rate or stroke volume, and the transport delay can also change with time. Table 1 shows a list of the required internal parameters of the model and the values of those parameters used in this study. The listed blood flow rates to the body tissue and the brain are based on a cardiac output of 5 liters/minute. The metabolic rates of CO_2 and O_2 listed depend on the patient's basal metabolic rate which in turn is a function of the patient's body weight and several other factors including height, sex, and age. The system uses the listed values if updated measured/estimated values are not provided by the user.

Table 1
A list of the required model internal parameters and their values used in this study

Model Internal Parameter	**The Default/ Measured Value and Unit**
Blood flow rate in the body tissue (Q_T)	4.25 lit/min
Blood flow rate in the brain (Q_B)	0.75 lit/min
Metabolic rate of CO_2 in the body tissue (MR_{TCO2})	0.1722 lit/min
Metabolic rate of O_2 in the body tissue (MR_{TO2})	0.2112 lit/min
Metabolic rate of CO_2 in the brain (MR_{BCO2})	0.054 lit/min
Metabolic rate of O_2 in the brain (MR_{BO2})	0.0555 lit/min
Respiratory elastance	10 cmH_2O/lit
Respiratory airway resistance	5.1 cmH_2O/lit/sec

In this system, application of positive end-expiratory pressure (PEEP) changes the lung volume and affects gas exchange in the lungs. This system can be used to investigate the treatment results of changing ventilation parameters including the inspiratory pressure, tidal volume, respiratory rate, PEEP, and F_{IO2}.

The computer simulation tests of this study were done by using the "Interactive Simulation Language" (ISL) on a PC digital computer.

III. RESULTS AND DISCUSSION

An example of the results is shown and discussed in this section. The physiological data and mechanical ventilation parameters reported for a patient in a previous study [6] are used in these simulation experiments. A computerized system called FLEX was used in the previous study [6] to determine the optimal ventilatory parameters for the patient. FLEX is a new system for ventilatory treatment that can be used both as a closed-loop control technique and as an open-loop decision support system for weaning and management of patients on mechanical ventilation. FLEX uses patient's data such as ideal body weight, temperature, blood gases, respiratory compliance and airway resistance. It also uses input data on the mode of ventilation, the initial ventilatory settings, the patient's spontaneous breathing rate and tidal volume, and the fraction of oxygen in the inspired gas of the patient. FLEX uses this input data to determine the required degree of ventilation assistance and new ventilatory parameters and settings to improve patient's oxygenation. More detail of this system can be found in Reference#6 and is not repeated here for brevity.

The patient whose data is used is a 71 year old male with a weight of 59 Kg. This patient who had suffered a myocardial infarction and had developed aspiration pneumonia was ventilated by using Intermittent Mandatory Ventilation. The clinician's set parameters for the patient were 9 liters of minute ventilation at a total respiration rate of 13 breaths/minute. F_{IO2} was set at 30% and PEEP was 6 cmH_2O.The patient's initial arterial partial pressure of CO_2 was measured at 34 mmHg and his measured arterial oxygen saturation was 100% as was reported [6]. The computerized technique, FLEX, used as a decision support system, recommended changing the ventilation parameters to a minute ventilation of 9.11 liters/minute, total breathing rate of 22 breaths/minute, F_{IO2} of 28%, and did not recommend any change in the PEEP level. The clinician's set of ventilation parameters as well as the recommended parameters by FLEX are applied in two separate simulation tests using the system described in this paper to investigate the effects of different treatment options and predict the patient's arterial blood gases. Figure 2 shows the simulation results of arterial partial pressures of CO_2 and O_2 (respectively, P_{aCO2}, and P_{aO2}) by using the clinician's set values, and Figure 3 shows the blood gas results by using FLEX recommended parameters.

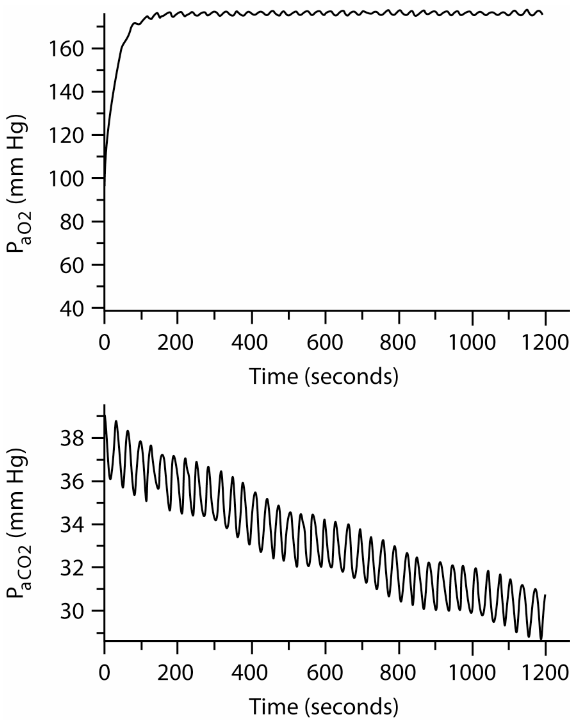

Figure 2. The simulation results of the system by using the clinician's initial set of ventilation parameters for patient D in Reference # 6.

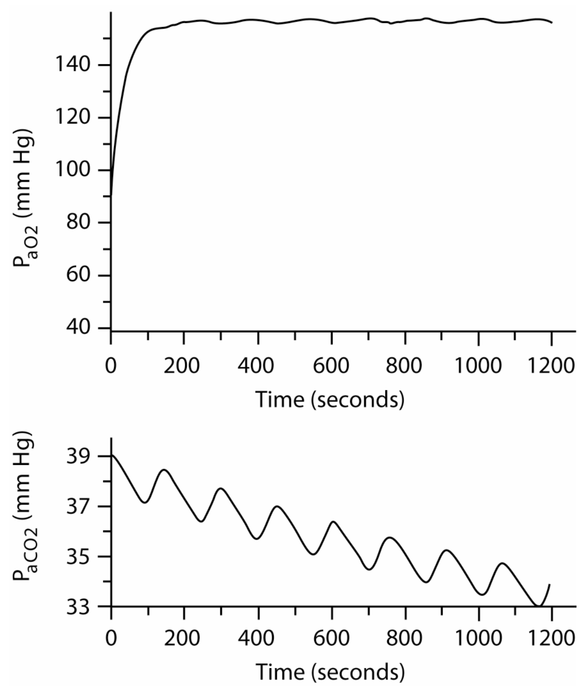

Figure 3. The simulation results of the system by using the ventilation parameters recommended by a system called FLEX, for patient D in Reference # 6.

The results in Figure 2 predict that by using the clinician's set values, P_{aCO2} falls with time, causing hypocapnia, and P_{aO2} rises above 170 mmHg creating hyperoxemia. These predictions are confirmed by the measurement of arterial blood gases of the patient at the next round of evaluation. As reported in Reference 6, the measured P_{aCO2} was 34 mmHg representative of mild hypocapnia, and the arterial oxygen saturation, S_{pO2}, was measured at 100% indicative of high P_{aO2} level and hyperoxemia. The simulation results of Figure 3, however, which were obtained by using the ventilation parameters recommended by FLEX, show less decline in P_{aCO2} over time compared with the results of Figure 2, and P_{aO2} does not rise as high as it does in Figure 2, indicating a better treatment option for the patient. Therefore, use of the simulation system described in this paper would enable the clinician to predict and investigate the effects of different treatments over time by simulation and would provide him with valuable information to choose a better treatment option for his patient.

IV. CONCLUSION

A computer simulation system based on a physiological model of human respiration is presented that can be used to test the effects of different ventilatory treatment options and enables the clinician to critique the options and choose a more optimal treatment method. This system can be used alone or in conjunction with other decision support systems to determine the ventilation parameters of patients on mechanical ventilation.

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