A SYSTEM FOR EMERGENCY CARE VENTILATOR CONTROL

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Abstract

Closed-loop control of mechanical ventilators could have a positive impact on pre-hospital patient care. Several methods to achieve this goal have been researched. A current method entitled "Adaptive Volume Ventilation" is being studied in the Department of Anesthesiology at the University of Utah Health Science Center. Preliminary clinical trials using the work of breathing model have shown that optimal settings for respiratory rate are significantly higher and optimal settings for tidal volume are significantly lower than those set by clinicians. Measured respiratory rate and tidal volumes were 9.7 +/- 1.4 bpm and 8.9 +/- 1.9 ml/kg, respectively. Optimal ventilator settings were calculated to be 19.3 +/- 3.5 bpm for respiratory rate and 5.3 +/- 1.3 ml/kg for tidal volume. Using these settings would decrease the work of breathing from 6.9 +/- 1.4 Joules/min of work to 4.6 +/- 2.1 Joules/min of work. Clinical trials to investigate the effects these settings have on patients' blood gas concentration are currently underway. This type of controller has several applications in both civilian and military health systems, including use in the space program.

Introduction

Ventilation is a critical part of emergency care when the respiratory system has been compromised. While several methods exist, such as mouth-to-mouth and bag-valve-mask ventilation, it has been shown that there is increased benefit to patients when mechanical ventilators are used. An essential characteristic of an emergency ventilator is ease of use. By providing closed-loop control for ventilators this can be achieved, allowing for other critical emergency care to be performed.

The use of closed-loop control to regulate mechanical ventilator settings has had a significant amount of investigation throughout the past decades. In the 1950's investigators tested the first controllers on healthy lungs. Since this time a number of controllers based on end-tidal and expired CO2 and arterial pH have been tested. These control mechanisms however did not take into account lung physiology, such as deadspace, and thus hypoventilation could occur in the unhealthy lung. Such would be the case with a pulmonary embolism.

More recently a closed-loop ventilator control system termed "Adaptive Lung Ventilation (ALV)" has been tested on a physical lung model and feasibility tests were performed on several patients. A modified version of this control mechanism entitled "Adaptive Volume Ventilation (AVV)" has been proposed and tested on a software-based ventilator and patient simulation model. Both the ALV and AVV control systems are based on the minimum work of breathing model proposed by Mead. However, ALV uses pressure control whereas AVV uses volume control. Mead suggests that the minimum amount of work done by the lung can be achieved by setting the respiratory rate according to the values predicted by equation 1.

\[
f_w = \frac{\sqrt{1 + 4\pi^2 R C V_A / V_D^2} - 1}{2\pi^2 R C}
\]

Where:
- \(f_w\) = respiratory frequency
- \(R\) = flow resistance
- \(C\) = lung compliance
- \(V_A\) = minute alveolar ventilation
- \(V_D\) = deadspace volume
Laubscher et al., later modified this equation for anatomical deadspace and gross alveolar ventilation, resulting in equation 2.

\[ RR_{tot} = 30 \sqrt{1 + \frac{200 \pi^2 RC}{3 V_{gA}}} - 1 \]  

Where:
- \( RR_{tot} \) = respiratory rate (breaths/min)
- \( V'_{gA} \) = gross alveolar ventilation
- \( V_{ds} \) = anatomical deadspace

Tidal volume can be determined from equation 3.

\[ V_T = \frac{V'_{gA}}{RR_{tot}} + V_{ds} \]  

Thus by knowing certain mechanical properties of the lung, namely the anatomical deadspace, the airway resistance, and the lung compliance, the minimum work of breathing can be achieved for a given gross alveolar ventilation. That is to say that the minimum work required to attain the set gross alveolar ventilation is being done by the ventilator. Because the ventilator is doing the minimum amount of work necessary, there is minimum work being done on the lung tissue and therefore little or no damage should be occurring. A graphic representation of the dependency of respiratory rate on lung mechanics can thus be constructed as in Figure 1.

The research presented here is a continuation of the AVV control method. Clinical trials to evaluate the feasibility of such a control system have started. Comparisons of optimal respiratory rates and tidal volumes with traditional ventilator settings have been completed. Investigation of the effects that the optimal settings have on arterial blood gases is also underway.

**Methods**

Preliminary clinical studies, which are aimed at verifying the work of breathing model described above, have been started. The first part of this study was aimed at comparing the ventilator settings traditionally set by clinicians to those optimal settings proposed by the minimization of the work of breathing model.

The primary investigation studied the ventilator settings of 31 patients undergoing coronary artery bypass graft (CABG) surgery. A combined CO₂/Flow sensor with the CAPNOSTAT CO₂ sensor (No. 8951-00, Novametrix, Wallingford, CT) was placed in the breathing circuit of these patients. These sensors were connected to a non-invasive cardiac output monitor (NICO₂, Novametrix, Wallingford, CT).

![Figure 2 - Setup of NIC02 monitor and sensors.](image)

The NICO₂ used the input from the sensors to calculate airway resistance, dynamic lung compliance, and airway deadspace. This monitor was connected to a PC, which continuously collected data for each breath. This data was then used to calculate the actual work of breathing and determine optimal respiratory rate and tidal volume values, which would result in the target work of breathing. The desired gross alveolar ventilation was set for each patient and the actual gross alveolar ventilation was
measured. The desired gross alveolar ventilation was used in determining target respiratory rates, tidal volumes, and calculating the work of breathing.

Results

The findings from this study show that there is a significant difference between tidal volumes and respiratory rates set by anesthesiologists and those settings that would minimize the work of breathing. Typically, clinicians set mechanical ventilator tidal volumes according to the patient's weight, approximately 10-12 ml/kg. The respiratory rate is then adjusted so the end-tidal CO$_2$ is between 35 and 40 mmHg. To achieve the minimum work of breathing, tidal volumes should be set at about 5 ml/kg and respiratory rates near 19 breaths-per-minute (bpm). Figures 3 and 4 show the histograms for the actual and target values of respiratory rate and tidal volume, respectively.

A Student's t-Test was used to analyze the data and p values <.05 were considered. Table 1 shows a brief summary of patient data including lung compliance and resistance. Table 2 shows the average differences observed between actual and target tidal volumes, respiratory rate, and work of breathing. The suggested settings show a 41% decrease in tidal volume and a 100% increase in respiratory rate, resulting in a 31% decrease in the work of breathing, if these settings were implemented.

The lower tidal volumes suggested by the work of breathing model present a possible concern for atelectasis. When undergoing general anesthesia 85-90% of patients develop atelectasis within the first 5-10 minutes$^{16}$. This could cause several physiologic changes to the pulmonary system, such as decreased lung compliance. While the pathophysiologic cause of atelectasis and the role tidal volume plays in this is poorly understood, it has been shown that 5-10 cmH$_2$O of positive-end-expiratory-pressure (PEEP) can reduce anesthesia-induced atelectasis$^{17-19}$.

Future Work

The findings from this study suggest that the work of breathing model could be used to control a ventilator. However, there is no
evidence that the suggested settings do not have a harmful effect on the patients. In the next study the suggested settings will actually be applied to the ventilator and patients' physiological response to these changes will be observed.

The same system as used in the study by Zitting et al., will be used for the new study. Up to 30 patients with different lung physiologies, such as patients with pulmonary disease, will be enrolled. Also, patients undergoing a variety of surgical procedures will be enrolled in the study. The anesthesiologist will set the ventilator to the traditional settings and the patient will be allowed to reach steady state. An arterial blood sample will be drawn and a blood gas measurement made. The anesthesiologist will then adjust the ventilator settings to the target values. After ten minutes another blood sample will be drawn and blood gas measurement made. The blood gas values will then be analyzed. This study will provide evidence relating to the safety of the work of breathing model in closed-loop control.

Upon completion of this second clinical trial a closed-loop controller will be designed and implemented on the system. This controller will be implemented on an Impact Ventilator, which is a portable ventilator that can be used in emergency care situations. This closed-loop controller will then be tested in an animal study.

By using the work of breathing model, an effective closed-loop control system can be developed. This closed loop controller only requires one input and takes into account lung physiology. It will have a broad field of use, primarily in the emergency care of patients with respiratory malfunction. Because the controller maintains constant alveolar ventilation, transportation of unstable patients will be done with more confidence in their safety. This type of controller has several applications in both civilian and military health systems, including use in the space program.

References

