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A control system for mechanical ventilation of passive and active subjects

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ABSTRACT

Synchronization of spontaneous breathing with breaths supplied by the ventilator is essential for providing optimal ventilation to patients on mechanical ventilation. Some ventilation techniques such as Adaptive Support Ventilation (ASV), Proportional Assist Ventilation (PAV), and Neurally Adjusted Ventilatory Assist (NAVA) are designed to address this problem. In PAV, the pressure support is proportional to the patient's ongoing effort during inspiration. However, there is no guarantee that the patient receives adequate ventilation. The system described in this article is designed to automatically control the support level in PAV to guarantee delivery of patient's required ventilation. This system can also be used to control the PAV support level based on the patient's work of breathing. This technique further incorporates some of the features of ASV to deliver mandatory breaths for passive subjects. The system has been tested by using computer simulations and the controller has been implemented by using a prototype.

1. Introduction

Mechanical ventilation is a life-saving treatment that is used to ventilate patients who cannot breathe adequately on their own. This essential ICU technique is used to treat respiratory failures as well as during and after major surgical operations. The most commonly used ventilation technique today is positive pressure mechanical ventilation [1] that is applied by using many different modalities [2].

Some of the newer ventilation techniques are designed to automatically control some of ventilation parameters in response to changing patients' requirements [3–5]. In provision of optimal ventilation to patients, an important factor is synchrony of the patient's breathing rate with the frequency of breaths provided by the machine. This is particularly true in weaning when asynchrony of the patient with the machine can lead to patient's distress and fatigue, necessitate administration of sedatives, and unduly prolong mechanical ventilation.

To promote and facilitate patient's spontaneous breathing, several ventilation techniques have been designed to provide respiratory patterns that mimic or follow patient's own breathing pattern. Those are: Adaptive Support Ventilation (ASV), Neurally Adjusted Ventilatory Assist (NAVA), and Proportional Assist Ventilation (PAV).

In ASV, the depth and rate of respiration are automatically adjusted by using a control algorithm [4,6] so that the work rate of breathing is minimized and the rate of respiration mimics the patient's natural breathing frequency.

In NAVA, the patient's own neural ventilatory drive signal is used to trigger the ventilator [7]. This signal is detected by electrodes mounted on a naso-gastric tube positioned at the lower esophagus at the level of diaphragm.

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In PAV, the pressure support applied by the ventilator is proportional to the patient's own breathing effort during inspiration [8,9]. PAV is fundamentally a weaning technique and cannot be used during the management phase of the treatment. The main advantage of PAV is that the ventilator follows patient's effort and there is significant synchrony between the patient and the machine. However, if the patient's own effort decreases with time, the machine's support also decreases and there is no guarantee that the patient receives his required ventilation.

In the system presented in this article, the pressure support level in PAV is automatically adjusted to meet the patient's ventilatory requirements during weaning. In this technique, the ventilatory support level can also be controlled based on patient's work of breathing (WOB) to prevent fatigue during weaning.

The application of this system is not limited to the weaning phase of ventilation and it can be used in the management phase of the treatment as well. In the absence of spontaneous breaths, the inspiratory pressure applied by the ventilator and the rate of respiration are automatically adjusted to minimize the work rate of breathing, which is the mainstay of ASV [10,11].

2. Methods

2.1. General description of the system

Fig. 1 shows a block diagram of the control system. As shown in this diagram, a CO_2 analyzer is used to measure the patient's end-tidal pressure of carbon dioxide (P_{etCO_2}). The volume of gas inhaled by the patient, its flow rate, and the airway pressure are also measured by another monitor and respiratory elastance and airway resistance are determined by a respiratory mechanics calculator. The input data goes through analog to digital conversion and smoothed before processing by the controller. The controller that includes a microprocessor determines the required support level by using the control algorithms and generates control signals for the ventilator.

2.2. The mathematical procedures and algorithms

In PAV, the ventilator provides pressure support in proportion to the patient's own inspiratory effort [8,9]. The pressure developed by the patient's own effort can be written as:

$$P_{mus} = KV + K' dV/dt \quad (1)$$

where P_{mus} is the pressure developed by the patient's muscle, V is the volume of gas inhaled by the patient, and K and K' are the patient's respiratory elastance and airway resistance respectively. In Eq. (1), KV represents the elastic component of P_{mus}, and $K'dV/dt$ is the resistive component of that pressure.

In the PAV mode, the ventilator's support is proportional to the pressure developed by the patient's own effort. The pressure applied by the ventilator can be described as:

$$P_{aw} = K_1 V + K_2 dV/dt \quad (2)$$

where P_{aw} is the pressure applied by the ventilator, and $K_1 V$ and $K_2 dV/dt$ represent the elastic and resistive components of that pressure respectively.

Considering the elastic component of the pressure support, the following step-by-step analysis can be performed during inspiration:

The patient's own elastic muscle pressure is proportional to V and is equal to KV. The pressure support provided by the ventilator is $K_1 V$. Therefore, the total elastic component of airway pressure rises to $KV + K_1 V = V(K + K_1)$. With this amount of pressure, the volume of inhaled gas rises to $V(K + K_1)/K$. At the next step of inhalation, the elastic component of pressure applied by the ventilator that is proportional to this volume increases to:

$$P_{aw} = K_1 \left[\frac{V(K + K_1)}{K} \right] = K_1 V + \left(\frac{K_1^2}{K} \right) V \quad (3)$$

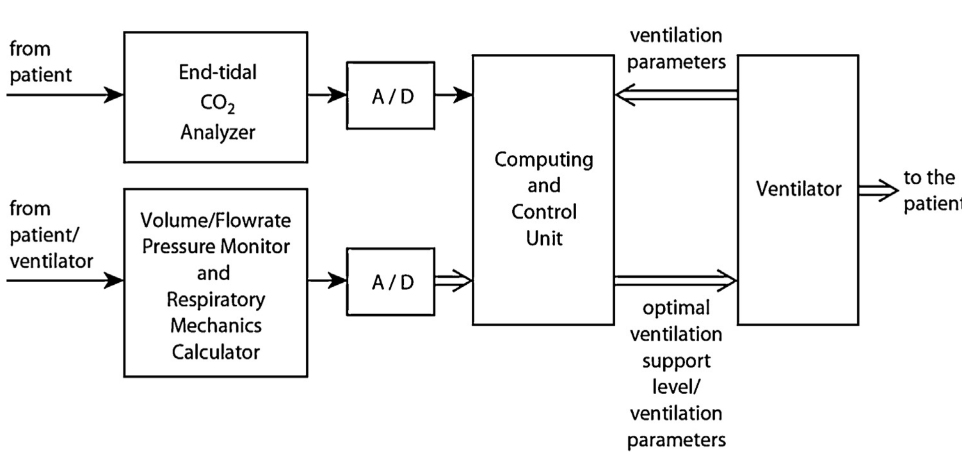

Fig. 1 – A block diagram of the control system.