On-line Estimation of Patient and Ventilator Respiratory Work

Tyrone Fernando†, John Packer† and John Cade‡

†Dept. of Electrical and Electronic Engineering, University of Melbourne, Parkville, Victoria 3052, Australia.
‡Intensive Care Unit,Royal Melbourne Hospital, Parkille, Victoria 3052, Australia.

Abstract— **An algorithm that estimates the patient and ventilator work components of mechanically ventilated patients is presented. The algorithm requires the continuous measurement of inspiratory airflow rate and mouth pressure and it is suitable to be incorporated in ventilators for on-line estimation of the patient and ventilator contributions to the total work of breathing.**

Keywords— **Work of breathing, compliance, airway resistance, alveolar pressure**

I. Introduction

Under normal breathing conditions the respiratory muscles perform the necessary work to maintain the airflow required for gas exchange. However, under abnormal conditions, the respiratory muscles may fail to ventilate the lungs adequately or may even fail completely. In these situations, it is necessary to provide partial or total support with a ventilator. Depending on the respective levels of support supplied by the ventilator and by the respiratory muscles, three types of breaths may be identified, namely, spontaneous, controlled and assisted. Spontaneous breathing occurs as a result of active muscular contraction. The energy required to suck air through the conducting airways into the alveoli is supplied by muscular effort. A breath that is unassisted by active muscular contractions is a controlled breath where all energy is supplied by a ventilator. On the other hand energy for an assisted breath is supplied both by the ventilator and the muscles of respiration. In this paper necessary equations are derived for separating the patient and ventilator components of work.

II. Properties of the Respiratory System

The ability to force air to flow from the mouth into alveoli depends on the compliance or elastance of the lung structure and the airway resistance.

A. Compliance

The compliance is defined as the gradient of the relaxation pressure curve [1]. This curve records the pressure in the alveoli at any lung volume when the respiratory muscles are relaxed (i.e $P_{\text{mus}}(t) = 0$). The curve of change in inflation pressure (ΔP) against the change in volume produced in the lungs (ΔV) is then the relaxation pressure curve. Compliance (C) is expressed as

$$C = \frac{\Delta V}{\Delta P}. \tag{1}$$

B. Airway resistance

Airway resistance refers to the ease with which air flows through the tubular structures of the respiratory system, starting from the mouth and leading up to the alveoli. For a given airway structure, resistance is a constant and the airflow rate varies proportionally with the pressure differential

$$P_{\text{m}}(t) - P_{\text{alv}}(t) = R\dot{V}(t), \tag{2}$$

where t is time, $P_{\text{m}}(t)$ is the pressure at the mouth, $P_{\text{alv}}(t)$ is alveolar pressure, $\dot{V}(t)$ is the inspiratory airflow rate and R is airway resistance.

III. Work and pressure-volume relationships

The total work of breathing has been defined in [2], [3] and [4] as

$$W_{\text{total}} = \int_0^{T_{\text{insp}}} \dot{V}^2(t)R\,dt + \frac{1}{2C}\left(\int_0^{T_{\text{insp}}} \dot{V}(t)dt\right)^2, \tag{3}$$

where T_{insp} is the inspiratory time. From the definition of compliance it is clear that if the muscles of respiration are relaxed, then alveolar pressure varies according to $P_{\text{alv}}(t) = \frac{1}{C}\int_0^{T_{\text{insp}}} \dot{V}(t)dt$ during inspiration. However if they are not relaxed the contraction of these muscles brings about a reduction in pressure and therefore alveolar pressure during inspiration can be written as

$$P_{\text{alv}}(t) = \frac{1}{C}\int_0^{t} \dot{V}(t)dt - P_{\text{mus}}(t), \tag{4}$$

where $P_{\text{mus}}(t)$ is the reduction in pressure created by the muscles of respiration. Combining (2) and (4) gives,

$$P_{\text{m}}(t) + P_{\text{mus}}(t) = R\dot{V} + \frac{1}{C}\int_0^{t} \dot{V}(t)dt. \tag{5}$$

From (3) and (5) it is clear that

$$W_{\text{total}} = \int_0^{T_{\text{insp}}} (P_{\text{m}}(t) + P_{\text{mus}}(t))\dot{V}(t)dt. \tag{6}$$

The above integral represents the sum of areas bounded by the curves $P_{\text{m}}(t)$ and $P_{\text{mus}}(t)$ with the volume axis. When there is no energy contribution from the respiratory muscles (i.e. $P_{\text{mus}}(t) = 0$ and $P_{\text{m}}(t) > 0 \;\forall\; 0 < t < T_{\text{insp}}$) all the energy is supplied by the ventilator and (6) reduces to

$$W_{\text{total}} = W_{\text{vent}} = \int_0^{T_{\text{insp}}} P_{\text{m}}(t)\dot{V}(t)dt, \quad (7)$$

where W_{vent} is the energy component of the ventilator. Similarly, when there is no energy contribution from the ventilator (i.e. $P_{\text{m}}(t) = 0$ and $P_{\text{mus}}(t) > 0 \; \forall \; 0 < t < T_{\text{insp}}$) all the energy is supplied by the muscles of respiration and (6) reduces to

$$W_{\text{total}} = W_{\text{pati}} = \int_0^{T_{\text{insp}}} P_{\text{mus}}(t)\dot{V}(t)dt, \quad (8)$$

where W_{pati} is the energy component of the patient. From (6), (7) and (8) the following can be written:

$$W_{\text{total}} = W_{\text{pati}} + W_{\text{vent}}. \quad (9)$$

The expression for W_{pati} in (8) can be rewritten in terms of measurable quantities by combining (5) and (8),

$$W_{\text{pati}} = \int_0^{T_{\text{insp}}} \left(R\dot{V}(t) + \frac{1}{C}\int_0^t \dot{V}(t)dt - P_{\text{m}}(t) \right) \dot{V}(t)dt. \quad (10)$$

It is clear from (7) and (10) that the measurement of W_{vent} and W_{pati} requires measuring inspiratory airflow rate, mouth pressure, compliance and airway resistance. The measurement of compliance and resistance can be done by delivering the patient a controlled breath. From (5) it is clear that the flow and pressure relationship of such a breath satisfies

$$Y = A * \begin{bmatrix} R \\ \frac{1}{C} \end{bmatrix} + \Upsilon. \quad (11)$$

The terms Y, A and Υ are defined as follows

$$Y' = \begin{bmatrix} P_{\text{m}}(0) & P_{\text{m}}(T) & \dots & P_{\text{m}}(nT) \end{bmatrix}$$

$$A' = \begin{bmatrix} \dot{V}(0) & \dot{V}(T) & \dots & \dot{V}(nT) \\ V(0) & V(T) & \dots & V(nT) \end{bmatrix}$$

$$\Upsilon' = \begin{bmatrix} \epsilon(0) & \epsilon(T) & \dots & \epsilon(nT) \end{bmatrix},$$

where n is a positive integer, T is the sampling time, $\epsilon(iT)$ is the measurement and modeling error at the i^{th} sample and A' is the transpose of A. Using the method of least squares it follows that

$$\begin{bmatrix} R \\ \frac{1}{C} \end{bmatrix} = (A'A)^{-1}A'Y. \quad (12)$$

IV. Results

Figure 1 is a recording which shows the airflow and mouth pressure waveforms of a controlled breath and the estimated compliance and airway resistance measurements. Figure 2 shows a sample pressure-volume curve of an assisted breath. Using (7) and (10), the ventilator and patient components of work was found to be 8.08 and 5.24 Joule respectively.

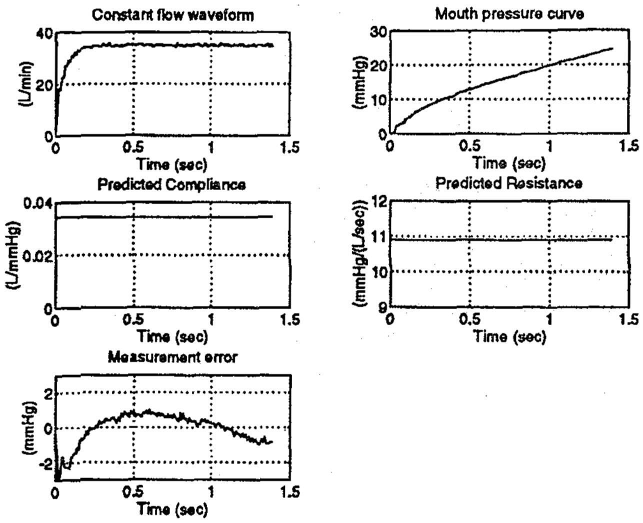

Fig. 1. Pressure and airflow waveforms used to calculate Compliance and Resistance

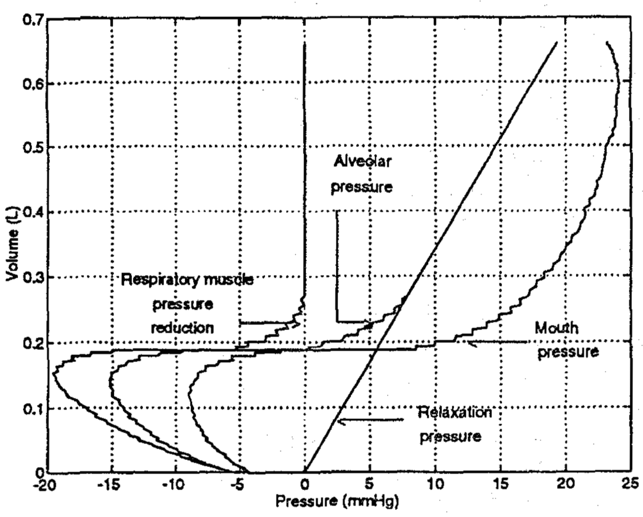

Fig. 2. Pressure-Volume Curve of an Assisted Breath Delivered From A Ventilator

V. Conclusions

This paper has presented an algorithm for finding the patient component and ventilator component of work. The proposed algorithm is non-invasive and can be used in ventilators for on-line estimation of work components.

References

[1] H. Rahn, A.B. Otis, L.E. Chadwick and W.O. Fenn, "The pressure-volume diagram of the thorax and lung", *Am. J. Physiol.*, 146:161-178,1946.

[2] A. B. Otis, H. Rahn and W.O. Fenn, "Mechanics of breathing in man," *J. Applied Physiol.*, 2:592-607, 1950.

[3] E.J.M. Campbell, The respiratory muscles and the mechanics of breathing, Lloyd-Luke Ltd, 1958.

[4] J.J. Marini, R.M. Rodriguez and V. Lamb, "The inspiratory workload of patient-initiated mechanical ventilation ," *Am Rev Respir Dis*, 134:902-909, 1986.