The Work of Breathing in a Nonlinear Model of Respiratory Mechanics

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Abstract—
Analytical expressions are derived for the work of breathing (WOB) and are subsequently evaluated for a typical pulmonary function laboratory test that includes tidal breathing, panting and the forced vital capacity maneuvers. The analysis is based on a nonlinear model of respiratory mechanics that successfully mimics information presented in the conventional Campbell diagram, which is often used to graphically estimate WOB. In addition, the model reveals the partitioning of elastic WOB among the collapsible airways and lung.

Keywords—
Work of Breathing, Campbell Diagram, Respiratory Mechanics.

I. Introduction

The term *work of breathing* (WOB) refers to the work performed by the respiratory muscles during breathing. This work is done mainly against three groups of forces [1]: (a) elastic forces developed in the tissues when a volume change occurs; (b) dissipative forces caused by the resistance in the airways (flow-resistive) and by the viscoelastic deformation of lung tissue; (c) inertial forces, depending on the mass of tissue and gases. Based on this classification, and in direct correspondence to the terminology employed in this study, the work can be accordingly termed as elastic, dissipative, or inertial (usually considered negligible).

Past research on the work of breathing has mostly been of clinical nature, focusing on either the clinical implications of WOB, especially in the assessment of ventilatory assistance [2], [3], [4], [5], or on the improvement of methodologies and instrumentation required for the accurate recording of muscular effort [6], [7].

A graphical technique introduced by Campbell [8] is commonly used in clinical settings to estimate work of breathing. The Campbell diagram plots in a pressure-volume plane both static and dynamic components of the respiratory system. In particular, pleural (esophageal) pressure is measured on-line and superimposed upon the static compliance curves of the lungs and chest wall. These static curves are measured off-line, usually while the patient executes a relaxation maneuver or is anesthetized [7].

A typical Campbell diagram is shown in Figure 1. The area subtended by the pleural pressure curve and the chest wall compliance curve (area ACBEA) is an estimate of the work of breathing. The elastic component of WOB is denoted by the area subtended by the two compliance curves (area ABEA). As Campbell has demonstrated [8], had resistive forces been absent, the pleural pressure loop would coincide with the lung compliance curve. The area enclosed by the pleural pressure loop alone (area ACBDA), then, represents the total dissipative WOB (dissipative WOB is given by areas ACBA and ABDA during inspiration and expiration, respectively).

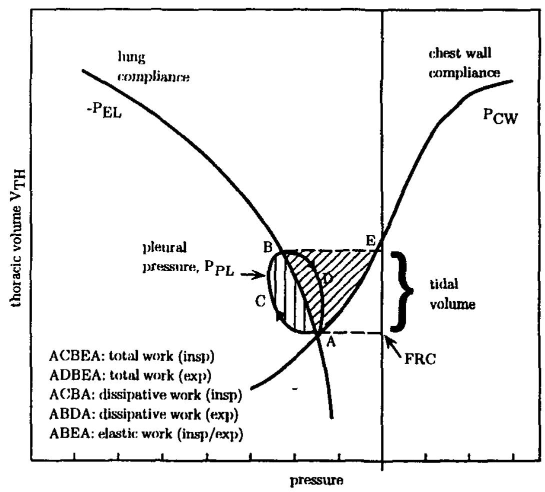

Fig. 1. Typical Campbell diagram.

The conventional construction of the diagram, as discussed above, implicitly assumes a specific model structure to the respiratory system that includes one resistive element and two compliant compartments (lung and chest wall), all connected in series. As a result, the diagram can only estimate the total resistive WOB; in addition, it assumes that the lungs and chest wall undergo exactly the same displacement, and, thus, it identifies a single component to the elastic WOB, as well.

A nonlinear model of the respiratory system is presented in this paper. It is shown that the model can successfully predict total WOB and the components identified in a Campbell diagram. The model further includes an additional compliant compartment, associated with the collapsible airways. The elastic and dissipative WOB associated with that compartment is identified, as well. Early work of this development appears in [9].

II. Mathematical Model

The model employed here is based on a nonlinear respiratory model described in detail in [10]. It is herein modified to include the lumped dynamic behavior of the thoracic cage and diaphragm. Dynamics of gas exchange, included in [10], are neglected here.

A physical representation of the model, depicting its individual components, appears in Figure 2(A). Figure 2(B) shows the equivalent pneumatic network used to simulate the dynamic behavior of the flow in the model. The vertical branch of the network models incompressible air flow between nodes E, at atmospheric pressure P_E, and node A, at alveolar pressure P_A. Pressures P_D and P_C represent the total pressure at the dead space and collapsible airways, respectively. Three nonlinear resistive elements, labeled R_{UAW}, R_C and R_S, represent resistance to air flow in the upper, collapsible and small airways, respectively.

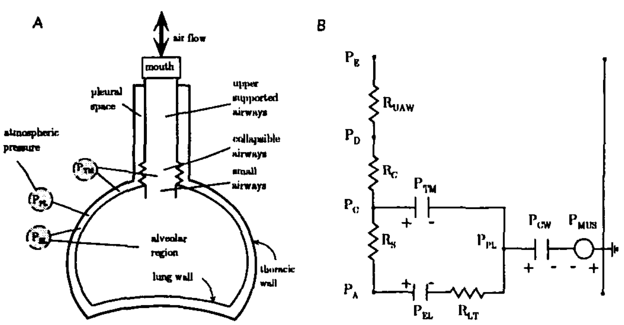

Fig. 2. (A) Physical model of the respiratory system (structure not drawn to scale); (B) Pneumatic analog of respiratory model.

Elastic structures are represented by nonlinear compliant components in the horizontal branches of the network. Figure 2 shows the transmural pressures across them, namely P_{TM}, P_{EL} and P_{CW}, for the collapsible airways, the lung and the thoracic wall, respectively. The pressure generated by the muscles is represented using an independent pressure source, P_{MUS}. Finally the viscous resistance of the lung tissue appears as resistor R_{LT}. The functional dependence of all model variables is summarized in Table I.

The equations governing the motion of the system are developed using a Lagrangian analysis. In matrix form the equations are

$$\mathbf{R}\begin{bmatrix} \dot{V}_C \\ \dot{V}_A \end{bmatrix} + \begin{bmatrix} P_{TM} + P_{CW} \\ P_{EL} + P_{CW} \end{bmatrix} = \begin{bmatrix} P_{MUS} \\ P_{MUS} \end{bmatrix} \quad (1)$$

where V_A, V_C are the volumes of the lung and collapsible airways, respectively, and $\mathbf{R}$ the resistive coefficient matrix,

TABLE I

Model parameters

SYMBOL	REGION	DEPENDENCE
R_{UAW}	upper supported airways	V_{TH} (flow)
R_C	collapsible airways	V_C
R_S	small airways	V_A, P_{PL}
R_{LT}	lung tissue	constant #
P_{MUS}	respiratory muscles	model input
P_{CW}	chest wall	$V_{TH} = V_C + V_A$
P_{TM}	collapsible airways	V_C
P_{EL}	lung tissue	V_A, P_{PL}

$$\mathbf{R} = \begin{bmatrix} R_{UAW} + R_C & R_{UAW} + R_C \\ R_{UAW} + R_C & R_{UAW} + R_C + R_S + R_{LT} \end{bmatrix} \quad (2)$$

The equations of motion are solved numerically using a Runge-Kutta algorithm with adaptive stepsize control.

A. Work of Breathing

The first term on the left side of Equation 1 represents the dissipative forces introduced by the four resistances in the model while the second term represents the elastic forces that characterize the compliant elements. The term on the right side of Equation 1 represents the applied force. The force balance can be easily transformed into an energy balance by multiplying with a differential displacement and integrating. This yields the energy associated with the system which can be partitioned into elastic and dissipative components, corresponding to the forces involved [11].

Energy associated with the applied external force equals the total work of breathing, or

$$W = \int_0^{\mathbf{q}} \begin{bmatrix} P_{MUS} \\ P_{MUS} \end{bmatrix}^T \begin{bmatrix} dV_C \\ dV_A \end{bmatrix} \quad (3)$$

$$= \int_0^{\mathbf{q}} \begin{bmatrix} P_{CW} - P_{PL} \\ P_{CW} - P_{PL} \end{bmatrix}^T \begin{bmatrix} dV_C \\ dV_A \end{bmatrix} \quad (4)$$

where $\mathbf{q} = [V_C \ V_A]^T$. In clinical practice WOB is partitioned into its elastic and resistive components. These can be written as

$$W_{el} = \int_0^{\mathbf{q}} \begin{bmatrix} P_{TM} + P_{CW} \\ P_{EL} + P_{CW} \end{bmatrix}^T \begin{bmatrix} dV_C \\ dV_A \end{bmatrix} \quad (5)$$

$$W_{diss} = \int_0^{\mathbf{q}} \begin{bmatrix} \dot{V}_C \\ \dot{V}_A \end{bmatrix}^T \mathbf{R}^T \begin{bmatrix} dV_C \\ dV_A \end{bmatrix} \quad (6)$$

III. Results

Figure 3 shows the conventional Campbell diagram with model-generated data for each of the three breathing maneuvers (Equation (4)). The area enclosed by the left branch of the pleural pressure loop and the chest wall compliance curve represents the total work done on the system by the muscles that are active during inspiration. The area between the right branch of the loop and the compliance curve represents the total work done on the muscles during expiration. The dotted curves are constructed from laboratory measurements of volume and pleural (esophageal) pressure.

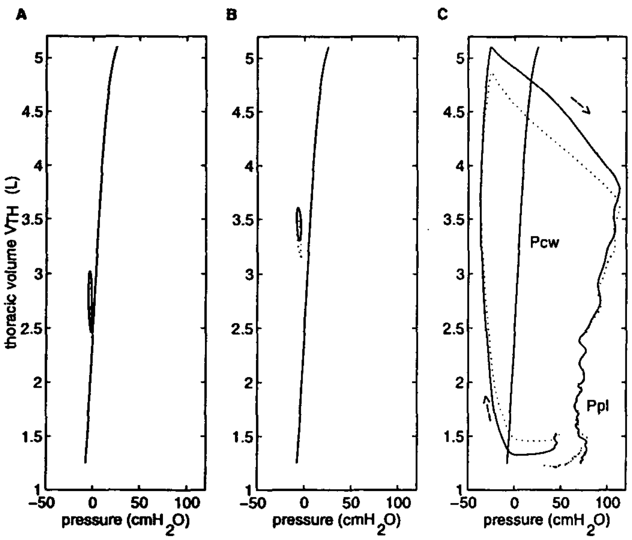

Fig. 3. Simulated Campbell diagram: (A) tidal breathing; (B) panting; and (C) FVC. Dots depict experimental data while solid lines denote model generated predictions in the three panels.

A. *Distribution of WOB*

In our model, representation of the elastic and dissipative components of WOB is possible for both the lung and the collapsible airways. Due to the differences in the relative volume displacement of the two structures, results cannot be plotted on the same volume axis. Figure 4 is a simulated Campbell diagram that renders the WOB (elastic and dissipative) associated with the lung only. This is in contrast to the conventional Campbell diagram where the volume used is the total thoracic volume, as it is measured with a pneumotachograph attached at the subject's mouth. In each graph, the elastic recoil of the lung, pressure P_{EL}, is plotted in the background along with the recoil of the chest wall, pressure P_{CW}. Elastic energy is given by the area subtended by the two curves (see Equation 5). The area enclosed within the pleural pressure loop equals the dissipative work. Figure 5 follows a similar layout in depicting the work associated with the collapsible airways.

IV. Conclusions

Analytical formulas are established for the identification of clinically useful work of breathing (WOB), an index of the muscular effort during breathing (Equation (4)). The study is based on a nonlinear model of the human lung that is capable of predicting breathing function for a wide range of air volumes and for a variety of respiratory maneuvers. Figure 3 employs the Campbell diagram to compare model generated data against data collected in a pulmonary function laboratory. The figure shows that the model successfully predicts total WOB for three different breathing maneuvers.

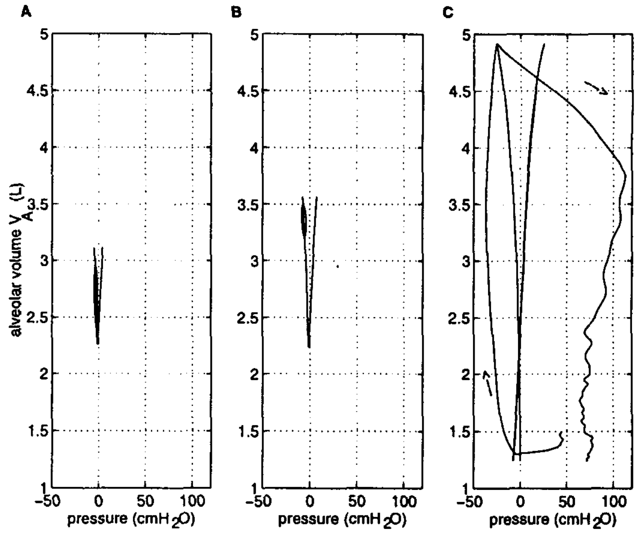

Fig. 4. Simulated Campbell diagrams for the lung: (A) tidal breathing; (B) panting; and (C) FVC. Each panels plots pleural pressure P_{PL}, chest wall compliance P_{CW}, and lung compliance P_{EL} (negative of P_{EL}).

The elastic and dissipative components of the total WOB are expressed analytically as well (Equations (5) and (6)). The distribution of elastic and dissipated energy among the two parallel compliant structures in the model, namely the collapsible airways and lung, is revealed in Figures 4 and 5. The figures show that both elastic and dissipative work associated with the collapsible airways is an order of magnitude smaller than that associated with the lung, in all three maneuvers.

Acknowledgments

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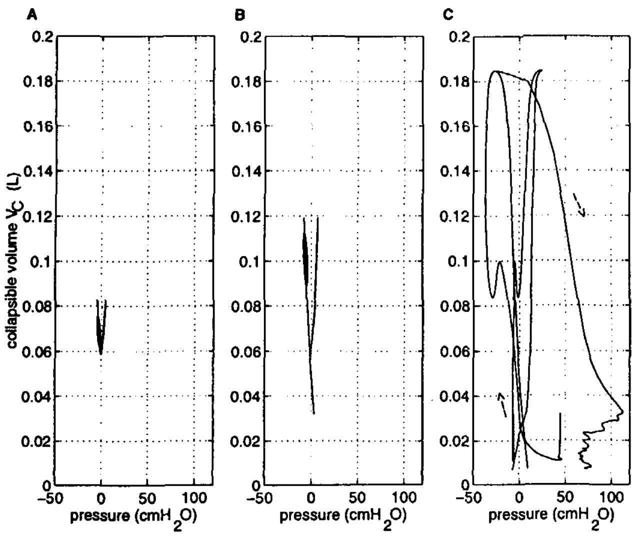

Fig. 5. Simulated Campbell diagrams for the collapsible airways: (A) tidal breathing; (B) panting; and (C) FVC. Each panels plots pleural pressure P_{PL}, chest wall compliance P_{CW}, and collapsible airways compliance P_{TM} (negative of P_{TM}).

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