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Review article

Measuring the breathing workload in mechanically ventilated patients*

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In recent years, the development of new modes of partial ventilatory support, such as pressure support ventilation, has renewed the interest in estimating breathing workload. Extensive reviews have been published on this subject [1, 2]. The objective of this article is to examine from a practical point of view how we can evaluate breathing workload in mechanically ventilated patients who can breathe spontaneously. Two complementary approaches can be taken: the assessment of the metabolic activity of the respiratory system, by the determination of the oxygen cost of breathing and the assessment of the mechanical activity of the respiratory muscles.

Assessment of the oxygen cost of breathing

Rationale and methodological considerations

In a healthy subject, the oxygen cost of breathing (O_2COB) during normal respiration is estimated by comparing total body oxygen uptake ($\dot{V}O_2$) at rest and $\dot{V}O_2$ when ventilation is stimulated, for instance by the addition of CO_2 to the inspired gas. The resulting difference in $\dot{V}O_2$ is attributed to the increased activity of the respiratory muscles. In mechanically ventilated patients, particularly during the period of weaning from the ventilator, the O_2COB can be more directly estimated: it is the difference between $\dot{V}O_2$ during controlled ventilation, when respiratory muscles are supposed to be at rest, and $\dot{V}O_2$ during spontaneous breathing.

The major difficulty with the measurement of O_2COB in intensive care unit (ICU) patients is that it represents a relatively small percentage of $\dot{V}O_2$ which may itself change rapidly as the underlying metabolic status changes. Therefore the technique used to measure $\dot{V}O_2$ must be extremely accurate. Using the Swan-Ganz catheter, $\dot{V}O_2$ can be easily computed from the product of cardiac output and the difference between oxygen content of the arterial and mixed venous blood. Unfortunately, this method is subject to multiplicative technical errors in blood oxygen content analysis and especially cardiac output determination. It is also limited by intermittent data availability. Direct calculation of $\dot{V}O_2$ by the method of pulmonary gas exchange is considered more appropriate. It implies the measurement of one ventilatory flow (usually expired flow) and fractional concentrations of gases in the inspired and the expired gas mixture. Besides the cumbersome Douglas-bag technique, which remains the reference method, the measurement of $\dot{V}O_2$ can be achieved by using recently developed systems capable of continuously monitoring pulmonary gas exchange in ventilated patients. Limits and potential sources of error of these systems have been discussed elsewhere [3–5].

The accuracy of the estimation of $\dot{V}O_2$ during controlled and spontaneous ventilation is improved by averaging several values measured for 10 to 30 min. During this period of time, it can be assumed that a patient's metabolic status, and thus extrarespiratory $\dot{V}O_2$, remains stable. So, changes of $\dot{V}O_2$ from controlled to spontaneous respiration can be ascribed to changes in the O_2COB.

Another concern is the fact that during controlled ventilation a certain degree of hyperventilation is often necessary to ensure purely passive respiration, without any inspiratory or expiratory effort. This may lead to an increase in blood pH. It has been shown that $\dot{V}O_2$ is pH dependent, respiratory alkalosis being associated with an increase in $\dot{V}O_2$. So, $\dot{V}O_2$ might be slightly overestimated during controlled ventilation, and thus the O_2COB of spontaneous breathing might be slightly underestimated.

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Results and interpretation

All published values of O_2COB in ICU ventilated patients are well above the 1%–2% of basal $\dot{V}O_2$ (or 0.5 to 1 ml O_2/l of ventilation) which is considered to be the oxygen consumption of the respiratory muscles in a normal subject at rest [1, 6–11]. At least three factors can explain these results. First, the O_2COB assessed as explained above incorporates not only the amount of oxygen consumed by the respiratory muscles, but also all activities related to spontaneous breathing. In particular, the stress of changing from a passive to an active mode of ventilation is responsible for an increase in catecholamine release, heart rate, blood pressure and myocardial oxygen uptake. Secondly, the patients must assume additional inspiratory work (see below) to trigger the ventilator and to overcome the resistance of the breathing apparatus. Finally, a major contributor of this high level of O_2COB is the underlying lung disease. Indeed, in postoperative patients with normal preoperative pulmonary function tests, we found the O_2COB to be close to 10% of $\dot{V}O_2$, or 2.6 ml O_2/l of ventilation [9]. In similar conditions, we found values ranging from 14% to 24% (mean 17% or 4.2 ml O_2/l of ventilation) in patients with chronic obstructive pulmonary disease (COPD) at the onset of weaning from the ventilator [11]. Values up to 59% of $\dot{V}O_2$ have been reported in COPD patients who failed extubation [10].

Assessment of mechanical activity of the inspiratory muscles

Work of breathing

When a patient breathes spontaneously through an artificial airway and a ventilatory circuit the inspiratory muscles work against two main forces: (1) elastic forces resulting from the distension of the tissues of the lung and chest when a volume change occurs and (2) flow-resistive forces offered by the breathing apparatus and the airways to the flow of gas. Since expiration is usually passive, expiratory mechanical work will not be considered. We will also neglect inertial forces, which are very small in comparison with elastic and flow-resistive forces, and distorting forces of the chest wall and the abdomen, which are probably only important at high ventilation such as that achieved during muscular exercise [2].

In a physical sense, work is performed when a transmural pressure (P_{tm}) changes the volume (V) of a distensible structure. Applied to the respiratory system, work performed during the inspiration of a tidal volume is described by the relationship $W = \int_{CRF}^{CRF+V_t} P_{tm} \cdot dv$ (where CRF is functional residual capacity and V_t is tidal volume) and is most often expressed as Joules per litre of ventilation ($J \cdot l^{-1}$). The power of breathing is the product of work by minute ventilation ($J \cdot min^{-1}$ or watt).

So, the determination of the work of breathing necessitates measurements of pressures and flow. Airflow is conveniently measured by a heated pneumotachometer connected just distal to the endotracheal tube. Volume is calculated by integration of the flow signal. Two relevant pressures are considered: airway pressure (P_{aw}) and pleural pressure, estimated by oesophageal pressure (P_{es}). P_{es} is measured by a thin-walled latex balloon filled with 0.5 ml air and positioned in the lower third of the oesophagus. The validity of the oesophageal pressure is assessed using the occlusion test [12]: the patient is asked to make inspiratory effort after occlusion of the airways. When the inspiration-induced deflections of P_{aw} and P_{es} are of the same amplitude, this indicates an adequate position of the oesophageal balloon.

Two different inspiratory works can be calculated, depending on the pressure which is considered (Fig. 1).

(1) Inspiratory work calculated from airway pressure. By measuring airway pressure and flow, we can calculate the external superimposed flow-resistive work, or additional work, i.e., the work expended by the spontaneously breathing patient in overcoming the impedance of the breathing equipment attached to the airway: valve opening and eventual imbalance between the patient's inspiratory demand and the inspiratory flow delivered by the ventilator.

For the computation of additional work (W_{add}), two methods are available. The first method consists of integrating the P_{aw}-flow product during inspiration after digitization of the signals and treatment by appropriate algorithm [13]. The alternative is to plot airway pressure against volume using an X-Y recorder and to measure by planimetry the area enclosed by the loop during inspiration (Fig. 1).

The assessment of W_{add} represents an objective way to evaluate a respirator set on a spontaneous breathing mode. For instance, during CPAP ventilation with demand valve systems incorporated into conventional ventilators, W_{add} has been found to be clearly greater than that measured with a continuous flow system [13–16]. With new generation ventilators, the delay time of valve opening is shortened and the flow delivered upon detection of the patient's inspiratory effort is closely adjusted to satisfy inspiratory requirements. Indeed, W_{add} is similar with these ventilators as with continuous-flow systems [17]. It represents approximately 10–20% of the total work of breathing during CPAP ventilation [17].

(2) Inspiratory work calculated from the transpulmonary pressure or from esophageal pressure. It is possible to estimate the major part of inspiratory work required by the inspiratory muscles to inflate the whole respiratory system (lung-airway system and chest wall). If the patient is still connected to the ventilator, this can be achieved by plotting the transpulmonary pressure (P_{es}-P_{aw}) against volume. If the patient is transiently disconnected from the ventilator, only P_{es} is to be taken into consideration.

According to the Campbell approach [18, 19], inspiratory work is estimated by measuring the area enclosed between the pressure-volume loop during inspiration and the relaxation curve of the chest wall (Fig. 1). Beginning and end of inspiration are marked by the zero-flow pressure points. The chest wall compliance line (C_w)

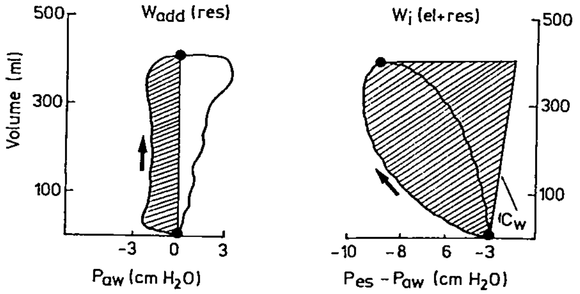

Fig. 1. Pressure-volume tracings illustrating methods of measuring inspiratory work in an individual patient. The patient is connected to the ventilator and breathes spontaneously. One breathing cycle is depicted. *Closed circles* indicate points of zero flow (beginning and end of inspiration). On the left, airway pressure (P_{aw}) on the *abscissa* is plotted against volume on the *ordinate*. Additional resisting work (W_{add}(res)) is the *shaded area* on the left of the vertical line, limited by the inspiratory P_{aw}-volume curve. On the right, transpulmonary pressure (P_{es}-P_{aw}) on the *abscissa* is plotted against volume on the *ordinate*. Inspiratory work (W_i (el + res)) is the *shaded area* delimited on the left by the inspiratory part of the transpulmonary pressure-volume loop, and on the right by the static chest-wall compliance line (C_w). Note that, in this example, there is no intrinsic PEEP, so that the elastic recoil pressure of the chest-wall coincides with the zero-flow pressure point which marks the beginning of inspiration

is passed through the elastic recoil pressure of the chest wall at end-exhalation, which normally coincides with the zero-flow pressure point (see below). It should be stressed that this graphical analysis does not permit the measurement of the chest-wall resistive work [2]. In addition, two specific difficulties must be taken into consideration. Firstly, the compliance of the chest wall is rarely measured (its measurement requires curarisation of the patient, and the determination of the slope of the P_{es}-volume relationship). So, C_w is usually estimated from normal published values: 4% of vital capacity per cmH_2O [20]. The second concern deals with dynamic hyperinflation, and thus intrinsic PEEP ($PEEP_i$), which is particularly frequent in COPD patients. In that case, the elastic recoil pressure of the chest wall at end-exhalation no longer coincides, on the pressure-volume loop, with the zero-flow pressure point. Indeed, the patient must generate a negative inspiratory pressure, equivalent in magnitude to the $PEEP_i$ before inspiration can start [21, 22]. From a practical point of view, the elastic recoil pressure of the chest wall is marked on the pressure-volume loop as the negative deflection that occurs before the beginning of inspiration [16]. With this correction, inspiratory work can be estimated as explained above.

Finally, is should be stressed that the resistive component of inspiratory work is markedly dependent on ventilatory flow and endotracheal tube size [23]. Therefore, in patients with chronic lung disease or ventilatory muscle dysfunction, selection of an appropriately sized endotracheal tube is critical.

Diaphragmatic pressure-time index

With the exception of one recent study [10], a poor correlation has been found between the external work of breathing, measured as explained above, and the O_2COB [2, 24, 25]. This is reflected by the striking variability of the calculated efficiency of the respiratory muscles (the ratio of mechanical work to O_2COB); values from 1% – 25% have been published [2]. Theoretically, an index that assesses both the tension developed by the respiratory muscles and the duration might reflect a larger proportion of the O_2COB than the work of breathing. Such an index has been proposed by Bellemare and Grassino [26]. It is defined as the product of the mean transdiaphragmatic pressure (P_{di}), expressed as a fraction of maximal transdiaphragmatic pressure (P_{di}/P_{dimax}), and the inspiratory duty cycle (T_i/T_{tot}). Mean P_{di} is calculated by averaging P_{di} values measured during the inspiratory duty cycle. For the calculation of T_i/T_{tot}, it has been suggested that the duration of inspiration is determined on the P_{di} tracing rather than on the flow tracing [27]. Indeed, this method allows us to take into account the early contraction of the diaphragm which precedes inspiratory flow in the presence of $PEEP_i$ and the late contraction of the diaphragm which may exist after the interruption of the inspiratory flow.

Another index designed to quantify the diaphragmatic work has been proposed [28]. The pressure-time product of the diaphragm is obtained by computing, for 1 min, the integral of P_{di} over time (the area under the P_{di} against time tracing). The theoretical interest of this index is to take into account the patient's respiratory rate. The limitation of diaphragmatic indices is that they reflect only diaphragmatic activity, whereas patients often use many other muscles during spontaneous breathing. However, they have been found to be correlated with the O_2COB, which depends on all respiratory muscles, in normal subjects breathing against inspiratory resistance [25], and in COPD patients on pressure support ventilation [11].

Conclusion

All the methods for the evaluation of the breathing workload in mechanically ventilated patients are subject to serious theoretical criticisms, due to the numerous assumptions and approximations on which they are based. Nevertheless they are of great interest in providing an objective evaluation of the ability of different forms of partial support ventilation to reduce the breathing workload. They have been applied successfully to assist-controlled ventilation [29, 30], SIMV [31], and pressure support ventilation [10, 11].

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