CHAPTER 20 ■ BEDSIDE ASSESSMENT AND MONITORING OF PULMONARY FUNCTION AND POWER OF BREATHING IN THE CRITICALLY ILL

MICHAEL J. BANNER

IMMEDIATE CONCERNS

Major Problems

Work of breathing per minute, or power of breathing (POB), reflects the balance between patient spontaneous breathing demand (driven by metabolic and neural factors) and the support provided by the ventilator. Increases in respiratory muscle loading and, thus, POB result primarily from increased physiologic elastance and resistance. Because compliance is the reciprocal of elastance, as total compliance (lungs and chest wall) decreases, elastic loading of the respiratory muscles increases. The total resistive load is affected by physiologic airways and breathing apparatus resistances. Elastance, resistance, or both can significantly increase the POB or load on the respiratory muscles, predisposing to muscle fatigue (loss of the force-generating capacity of the muscles), carbon dioxide retention, and hypoxemia.

Ventilatory support may be applied to partially or totally unload respiratory muscles. High levels of ventilatory support totally unload the muscles and, if applied for too long a period, may lead to atrophy. Conversely, too little support risks muscle fatigue. Unfortunately, in either case, the duration of mechanical ventilation may be needlessly prolonged for reconditioning/training if respiratory muscle atrophy is present or to provide needed rest if the muscles are fatigued. Optimization of ventilatory support to each patient’s unique needs requires information of the load on the respiratory muscles as well as gas exchange. This manuscript will focus on POB measurements as my approach to assess the load on the muscles and to provide a quantitative and goal-oriented method for appropriately setting pressure support ventilation (PSV).

STRESS POINTS

1. Respiratory muscles are force generators, and the diaphragm accounts for 70% of normal tidal volume ($V_t$).
2. The diaphragm has high endurance capability well suited to low-tension, high-repetition activity (breathing). However, it can be readily fatigued by increased air flow resistance and duration of respiratory muscle contraction.
3. Imposed POB against a highly resistant ventilator circuit and endotracheal tube leads to fatigue. Patients with an already increased physiologic POB because of respiratory disease tolerate such increases poorly.
4. Bedside measurement of POB, including breath-by-breath analysis, and separation into its component parts are possible with a commercially available bedside monitor.
5. Inaccurate assessments of respiratory muscle loads by using parameters like respiratory muscle pressure ($P_{mus}$) may result because of failure to assess chest wall compliance and its contributions.
6. Factors that load the respiratory muscles include increases of inspiratory flow rate and minute ventilation, physiologic dead space volume-to-tidal volume ratio ($V_D/V_T$), intrinsic positive end-expiratory pressure (PEEP), breathing apparatus resistance, and the ventilator response time. Many of these factors can be altered favorably by careful adjustment and replacement of highly resistant elements of the circuit (particularly the endotracheal tube).
7. Respiratory muscle fatigue results from an imbalance of energy supply and demand.
8. Inferences as to POB, such as increased spontaneous breathing frequency ($f$) and tidal volume ($V_T$) alone can be misleading.
9. Successful weaning from mechanical ventilation often requires a decrease in the imposed POB to a tolerable level. PSV is uniquely capable to decrease or eliminate this workload when titrated in accordance with measured POB.

ESSENTIAL DIAGNOSTIC TESTS AND PROCEDURES

1. Most patients can be followed by conventional assessment. However, when weaning, extubation, or both are difficult or seemingly impossible, measurements of airway pressures, $V_T$, and POB with its component parts may be useful in assessing the patient and guiding ventilatory therapy.
2. Spontaneous and breathing patterns ($f$ and $V_T$), as well as the use of accessory respiratory muscles such as the sternocleidomastoid (SCM) muscle, should be continuously monitored, but their limitations for predicting and assessing diaphragmatic fatigue, as detailed in this chapter, should be well understood.
INITIAL THERAPY

1. Decrease the imposed POB to zero using PSV as the first step. This workload is of no value for muscle conditioning and predisposes to fatigue.

2. Add additional PSV as necessary to reduce the physiologic workload (elastance and resistance) to clinically acceptable levels (i.e., POB of approximately 5–10 joules/minute).

3. Use the largest internal diameter endotracheal tube that is unlikely to result in airway damage. A 1.0-mm increase of the inside diameter is associated with significantly less resistive imposed work (parenthetically to be noted is that less air is needed for cuff inflation with larger tubes, thereby decreasing the risk of cuff-induced tracheal damage).

4. Do not reduce PSV below the level that eliminates imposed POB. To do so reloads the respiratory muscles, predisposing to fatigue.

5. In difficult cases, use clinical parameters to supplement—but not to replace—direct noninvasively measured POB.

RESPIRATORY MUSCLES

Respiratory muscles are the force generators that drive the respiratory system (1). Regarded as the primary inspiratory muscle, the diaphragm accounts for approximately 70% of normal \( V_T \) exchange. Other inspiratory muscles that account for the balance of tidal ventilation are the external intercostals, parasternals, and scalenes (2). The SCM muscles are major accessory inspiratory muscles that have a predominantly pump-handle action on the rib cage, elevating the first ribs and sternum (Fig. 20.1). During quiet breathing, they are usually inactive, but are always active during exercise and conditions of respiratory muscle loading.

The internal intercostal and abdominal muscles are involved with exhalation. On contraction, the intercostal muscles lower the ribs, thus deflating the lungs. The external abdominal oblique, internal abdominal oblique, transverse abdominis, and rectus abdominis (1,2) (Fig. 20.1) are the most important and powerful expiratory muscles. When these muscles contract, the abdominal wall is pulled inward, causing increased intra-abdominal pressure that forces the diaphragm cephalad into the thoracic cavity (3). Concomitantly, the lower ribs are pulled downward and medially. The net effect of these actions is deflation of the rib cage. Normally, exhalation is a passive process and the abdominal muscles are inactive. With increased muscle loads (e.g., increased airway resistance), however, the abdominal muscles are recruited and exhalation becomes an active, energy-consuming process.

THE DIAPHRAGM

Because the diaphragm is the primary muscle of inspiration, the physiologic characteristics and responses of this muscle during conditions of loaded and unloaded breathing are described.

**Muscle Fiber Types**

The adult diaphragm is composed of three types of skeletal muscle fibers: Type 1 (≤60%), type 2A (≤20%), and type 2B (≤20%) (4). Skeletal muscle fibers are differentiated on the basis of (a) velocity of shortening (fast and slow fibers), and (b) the major pathway to form adenosine triphosphate (ATP) (oxidative and glycolytic fibers) (5). In general, muscle fibers are composed of two contractile protein filaments: Myosin (thick filament) and actin (thin filament). Fibers containing myosin with high ATPase activity (enzyme that catalyzes the hydrolysis of ATP to adenosine diphosphate [ADP], releasing chemical energy stored in ATP) are classified as fast fibers; those containing myosin with lower ATPase activity are slow fibers. In general, the more energy that is available for contraction, the greater is the velocity of muscle fiber shortening.

**Force Generation and Fatigue**

Muscle fibers differ in terms of size and force development. Glycolytic fibers are larger in diameter than oxidative fibers. A greater force or tension can be developed by a large-diameter muscle fiber. Consequently, a type 2B fiber (strength oriented) can generate more force than a type 1 fiber during contraction (4,5). Fibers also differ in their ability to resist fatigue (muscle fails as a force generator). Type 2B fibers fatigue rapidly, whereas type 1 fibers are resistant to fatigue (endurance oriented), a characteristic that allows them to maintain contractile activity for long periods. Type 2A fibers have an intermediate capacity to resist fatigue (4,6).
Endurance and Strength

In general, the diaphragm is an endurance-oriented (low-tension, low-repetition activity), not strength-oriented (high-tension, low-repetition activity), muscle because most of the muscle mass is composed of type 1, slow oxidative fibers. In fact, it is capable of impressive feats of endurance. An Olympic marathon runner can maintain high minute ventilation of approximately 50 L/minute several hours per day for many days in succession. Despite this endurance performance, the diaphragm can be fatigued in a matter of minutes by an increased resistance to flow rate or increased duration of muscle contraction.

The duration of diaphragmatic contraction is the duty cycle of the breath taken as the ratio of inspiratory time to total respiratory cycle time \( T_I/T_{tot} \). Normally, the \( T_I/T_{tot} \) ratio is approximately 0.33 (7). The diaphragm, although contracting rhythmically from minute to minute, requires time to recover before contraction resumes. Impingement on this recovery time by an increase in respiratory rate, duration of contraction, or both predisposes to respiratory muscle fatigue. An increase in respiratory rate, as in acute respiratory failure, causes a greater reduction in expiratory time than inspiratory time, thus increasing \( T_I/T_{tot} \) and contributing to the development of fatigue (6,7). In patients with severe respiratory muscle loading, we have measured \( T_I/T_{tot} \) ratios as high as 0.50 to 0.60.

Measurement of Work of Breathing

The load on the respiratory muscles is a reverse force that opposes, or contractile force of the muscles and may be assessed by measuring the work of breathing per breath, that is, by integrating the change in esophageal pressure (Pes) and \( V_T \) (8,9).

\[
\text{Work} = \int \text{Pes} \, V_T
\]

POB, the rate at which work is done, is a better assessment of respiratory muscle loads than work per breath because it is a measure over time, not for an individual breath. Because of wide variations in breath-to-breath work measurements, at times this method of assessing respiratory muscle workloads is difficult to interpret. POB is determined by averaging work per breath data over 1 minute.

The total respiratory muscle work performed by a spontaneously breathing, intubated patient connected to a mechanical ventilator includes imposed and physiologic components (Table 20.1). Imposed POB (work per minute performed by the patient to breathe spontaneously through the endotracheal tube, ventilator breathing circuit, and demand-flow system) is an additional flow-resistive workload superimposed on the physiologic work (10–12). Imposed POB may equal or exceed the physiologic work under some conditions (13–15). Imposed POB of the ventilator and endotracheal tube, a series resistance, is assessed by integrating the change in pressure measured at the carinal end of the endotracheal tube and \( V_T \) (16). Pressure at the carinal or tracheal end of the tube is measured by inserting a narrow (1-mm outside diameter), air-filled catheter through the tube and positioning it at the carinal end. \( V_T \) is measured by integrating the flow signal from a miniature flow sensor (pneumotachograph) positioned between the Y piece of the breathing circuit and the endotracheal tube.

<table>
<thead>
<tr>
<th>TABLE 20.1</th>
<th>WORK PER BREATH TO DETERMINE POWER OF BREATHING PERFORMED BY A SPONTANEOUSLY BREATHING, INTUBATED PATIENT (SEE FIG. 20.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total work per breath</td>
<td></td>
</tr>
<tr>
<td>Physiologic work</td>
<td></td>
</tr>
<tr>
<td>Elastic and flow resistive</td>
<td></td>
</tr>
<tr>
<td>Imposed work</td>
<td></td>
</tr>
<tr>
<td>Resistive work imposed by breathing apparatus (endotracheal tube, breathing circuit, demand-flow system, exhalation valves)</td>
<td></td>
</tr>
</tbody>
</table>

These data are, in turn, averaged over 1 minute to determine imposed POB (Fig. 20.2). Imposed POB should be nullified to zero by using appropriate levels of PSV (Fig. 20.2A).

Physiologic work per minute or power of breathing includes elastic (work required to overcome the elastic forces of the respiratory system during inflation) and flow-resistive (work required to overcome the resistance of the airways and tissues to the flow of gas) components, and is approximately 4 to 8 joules/minute (8,17). Based on studying over 500 adults in a 10-year span, a clinically acceptable range for total POB appears to be about 5 to 10 joules/minute.

The Campbell Diagram

POB performed by the patient on the respiratory system (physiologic power of breathing) and the ventilator and endotracheal tube (imposed power of breathing) during spontaneous ventilation is calculated by integrating the changes in esophageal pressure (indirect measurement of intrapleural pressure) and volume. Intraesophageal pressure is measured with a balloon catheter positioned in the middle to lower third of the esophagus. Correct position is confirmed using an occlusion test as described by Baydur et al. (18) (i.e., after occlusion of the airway opening, the change in pressure at the airway opening and in the esophagus are nearly the same during spontaneous inspiratory efforts). \( V_T \) is measured as described previously. Data from these measurements and measurement of chest wall compliance are processed and the work of breathing calculated using the Campbell diagram (9,19,20) (Fig. 20.3). Work per breath measurements are then averaged over 1 minute to compute POB.

Chest Wall Influence on Power of Breathing Measurements

To calculate work of breathing so as to determine POB using the Campbell diagram, chest wall compliance must first be measured. Accuracy in measuring chest wall compliance requires a relaxed and mechanically ventilated patient. To measure chest wall compliance, one approach is to administer adequate sedation (1–2 mg of intravenous midazolam) or induce pharmacologic paralysis to induce relaxation, and then the mechanical ventilator rate is increased transiently to approximately 10 to 12 breaths/minute. Under conditions of
Section II: Monitoring

FIGURE 20.2. Work imposed by the breathing apparatus is determined during spontaneous breathing by measuring change in pressure at the tracheal or carinal end of the endotracheal tube (P<sub>ET</sub>) and change in volume (tidal volume) between the Y piece of the ventilator breathing circuit and the endotracheal tube. P<sub>ET</sub> and the change in volume are directed to a respiratory monitor and are integrated to display a pressure–volume (work) loop and provide real-time calculations of the inspiratory imposed work of breathing (i.e., the shaded area of the loop). I, inhalation; E, exhalation (see Fig. 20.2A). (continued)

Alternative Measurements

Measurement of the area enclosed within an esophageal pressure–volume loop during spontaneous breathing underestimates the work per breath, and thus POB, because the area of the loop includes only the resistive work (physiologic plus imposed) and a small portion of the elastic work (see Fig. 20.3). Some investigators fitted a right triangle to the esophageal pressure–volume loop to infer elastic work; however, this approach also underestimates elastic work of breathing (22). Measurement of the pressure change at the Y piece of the ventilator breathing circuit tubing or at the carinal end of the endotracheal tube and the change in volume during spontaneous breathing allows calculation only of the work imposed by the ventilator and ventilator plus the endotracheal tube, respectively (11,16). Thus, accurate measurement of the total POB (physiologic plus imposed) requires monitoring equipment with appropriate hardware and software to use the Campbell diagram.

Using Pmus, the sum of elastic pressure (V<sub>T</sub> divided by respiratory system compliance) and resistive pressure (flow rate times total resistance, which is respiratory system resistance plus endotracheal tube resistance) alone to predict work per breath via a conversion factor has been advanced (23). However, in our experience this is an inaccurate method of predicting work of breathing per breath. This method does not take into consideration the effects of decreased chest wall compliance on increasing elastic work and, thus, total work per breath.

We measured total work per breath (imposed plus physiologic work) with an esophageal balloon catheter using the Campbell diagram, as well as calculating POB on over 200 adults receiving PSV while simultaneously calculating Pmus.
FIGURE 20.2. (Continued) Recordings of imposed work of breathing obtained by integrating the changes in pressure at the tracheal or carinal end of the endotracheal tube (P<sub>ET</sub>) and volume at the Y piece of the ventilatory breathing circuit for a patient intubated with an 8.5-mm internal diameter endotracheal tube and connected to a ventilator (7200A, Puritan-Bennett) while breathing spontaneously with zero end-expiratory pressure. Inspiratory flow rate (V) and airway pressure (P<sub>AW</sub>) are measured at the Y piece of the breathing circuit (see Fig. 20.2). The pressure-volume loop moves in a clockwise direction during inhalation (I) and exhalation (E), and the area circumscribed within the loop to the left of zero pressure is imposed work.

A: No pressure support ventilation (PSV) is applied. Notice the value of imposed work and that P<sub>ET</sub> decreases by a greater amount than P<sub>AW</sub> during spontaneous inhalation because of the resistance of the endotracheal tube.

B: PSV of 10 cm H<sub>2</sub>O is applied, and imposed work decreases to zero. P<sub>AW</sub> increases to a greater level, and P<sub>ET</sub> does not decrease during inhalation compared with A. Notice that volume increases from approximately 0.35 L in A to 0.50 L in B as a result of PSV. A minimal level of PSV is that which corresponds to zero imposed work of breathing.

We found that P<sub>mus</sub> was a poor predictor of work per breath (r<sup>2</sup> = 0.42). Because this approach resulted in both over- and underestimations of the work of breathing per breath, it is not recommended for use in clinical practice for patients attached to life-support ventilators.

**Noninvasive Measurement of Power of Breathing**

Power of breathing can be calculated noninvasively (POB<sub>N</sub>) with reasonable clinical accuracy for patients receiving ventilatory support by using an artificial neural network (ANN) (24). An ANN is a contemporary computational tool used for predicting, as in predicting a physiologic parameter for example. In one clinical study (24), data from an esophageal balloon catheter and airway pressure/flow sensor were used to measure POB invasively as defined above. A pretrained ANN provided real-time calculation of POB<sub>N</sub>. The ANN used five parameters, each readily determined from pressure and flow tracings obtained at the airway opening of an individual patient to predict POB (i.e., spontaneous minute ventilation, intrinsic positive end-expiratory pressure [PEEP<sub>i</sub>], inspiratory pressure trigger depth, inspiratory flow rise time, and P<sub>mus</sub>) (Fig. 20.4). Invasive POB and POB<sub>N</sub> were measured at various levels of PSV, ranging from 5 to 25 cm H<sub>2</sub>O. POB<sub>N</sub> was highly correlated
Section II: Monitoring

**FIGURE 20.3.** Clinical method of measuring the patient’s work of breathing (physiologic plus imposed work). Work is computed using the Campbell diagram, which relates the change in volume plotted over the change in esophageal pressure (inference of intrapleural pressure) during spontaneous inhalation (I) and exhalation (E). The change in volume is measured at the connection between the Y piece of the breathing circuit and the endotracheal tube with a miniature pneumotachograph (flow sensor). Esophageal pressure (Pes) is measured with an intraesophageal balloon positioned in the middle to lower third of the esophagus. The Pes–volume loop moves in a clockwise direction; the slope of the loop is lung compliance ($C_L$). Chest wall compliance ($C_{CW}$) is obtained previously by mechanically ventilating a relaxed patient. Under these conditions the Pes–volume loop moves in a counterclockwise direction (not shown); the slope of the loop is $C_{CW}$. This compliance value is stored in the monitor’s computer memory and is used to construct the Campbell diagram. Inspiratory resistive work of breathing includes the physiologic resistive work on the airways and the imposed resistive work on the endotracheal tube and ventilator breathing circuit. Elastic work of breathing is the triangular-shaped area subtended by the lung and chest wall compliance curves. Total measured work of breathing, the sum of resistive and elastic work, is 1.5 J/L in this example. (From Banner MJ, Kirby RR, Gabrielli A, et al. Partially and totally unloading the respiratory muscles based on real time measurements of work of breathing: a clinical approach. Chest. 1994;106:1835.)

With invasive POB ($r = 0.91, p < 0.002$) (Figs. 20.5 and 20.6). A Bland–Altman plot comparing POB$_{N}$ and invasive POB revealed that bias was zero and precision was clinically acceptable at 2.2.

This method obviates the need for inserting an esophageal balloon catheter, and thus greatly simplifies measurement of power of breathing. It could be fully automated into mechanical ventilators. POB$_{N}$ may be a clinically useful tool for consideration when setting PSV to unload the respiratory muscles.

**LOADING FACTORS**

For healthy, asymptomatic individuals, the load on the respiratory muscles results from normal impedance (compliance and resistance) and ventilation loads (25). Increases in respiratory muscle loading result from a variety of physiologic and breathing apparatus factors. Physiologic factors include decreases in lung or chest wall compliance, or both, secondary to pulmonary abnormalities (Figs. 20.7 and 20.8, and Table 20.2) or bronchoconstriction, leading to peripheral, widespread narrowing of the airways that increase elastic and resistive loading, respectively. To assess these factors, respiratory system compliance and resistance can be measured with the patient attached to a ventilator. Spontaneous inspiratory flow rate demand affects resistive POB directly. This relationship can be explained by an analogy of the Ohm Law of electricity (i.e., change in pressure equals inspiratory flow rate demand multiplied by airway resistance). Assuming a fairly constant airway resistance over a range of flow rates, increases in the patient’s peak inspiratory flow rate demand result in greater changes in pressure. Because work = $\int$Pes V, a greater change in pressure with the same change in volume produces greater work per breath, and thus POB (17).

**Minute Ventilation**

Increases in the $V_D/V_T$ ratio and minute ventilation also are forms of respiratory muscle loading that lead to increased POB (23). Under both conditions, the respiratory muscle pump is
Chapter 20: Bedside Assessment and Monitoring of Pulmonary Function and Power of Breathing in the Critically Ill

205

Fuzzy Logic Inference System (FIS)
Artificial neural network (ANN) and real-time calculation of noninvasive power of breathing (POB<sub>N</sub>) based on pressure and flow rate data
Display of pressure, flow, volume, and partial pressure end-tidal carbon dioxide (PetCO<sub>2</sub>) waveforms, with spontaneous breathing frequency (f) and tidal volume (V<sub>T</sub>) and f/V<sub>T</sub> ratio data

**FIGURE 20.4.** Schematic representation of a patient with acute respiratory failure attached to a ventilator and connected to respiratory monitoring equipment (NICO, Respironics) containing an artificial neural network (ANN) for the noninvasive determination of power of breathing (POBN).

Increased levels of PEEPi, or auto PEEP, as a result of increased expiratory airway resistance, inadequate exhalation time, or both, is another form of respiratory muscle loading. PEEPi must be counterbalanced by an equivalent change in alveolar pressure before air can flow into the lungs (26). Consider a patient with dynamic hyperinflation and a PEEPi level of 5 cm H<sub>2</sub>O breathing room air spontaneously. Intra-alveolar pressure must decrease by at least 6 cm H<sub>2</sub>O (instead of 1 cm H<sub>2</sub>O under normal conditions) so that alveolar pressure falls below ambient pressure. A pressure gradient between the mouth and alveoli must occur for air to flow into the lungs. Under these conditions, a greater decrease in pleural pressure is required than normal, and a greater POB results.

**Intrinsic Positive End-expiratory Pressure**

Breathing Apparatus

Several breathing apparatus factors affect the imposed work of breathing. The endotracheal tube is probably the most significant resistor in the breathing apparatus (11,12,27–29). Breathing through a narrow internal diameter endotracheal tube attached to a highly resistive demand-flow continuous positive airway pressure (CPAP) system requires a large increase in pressure to move a specific volume. An increased resistive workload is imposed by the apparatus (30,31) (Fig. 20.9).

**Ventilator Response Time and Automatic and Variable Inspiratory Pressure Assist**

The response time of the ventilator (time delay from the initiation of spontaneous inhalation to the onset of flow in the airway) directly affects the imposed POB. It is partly affected by the method of triggering the system “on,” and partly by the ventilator’s sensitivity/trigger setting. The response characteristics of a ventilator’s demand-flow CPAP system are improved by moving the pressure-measuring/triggering site physically closer to the respiratory muscles (i.e., at the tracheal or carinal end of the endotracheal tube) (32). Significantly less imposed work results from pressure-triggering the system on at

**FIGURE 20.5.** Relationship between directly or invasively measured power of breathing requiring the use of an intravesophageal balloon catheter (y axis) and noninvasively predicted/calculated power of breathing (POB) (x axis) using the nonlinear multilayer Perceptron artificial neural network model is shown. A highly significant correlation (r = 0.91, p < 0.002) between the two was found. The model was a very good predictor of POB as evidenced by the high value for the coefficient of determination, r<sup>2</sup> = 0.83, p < 0.002. (From Banner MJ, Euliano NR, Brennan V, et al. Power of breathing determined noninvasively using an artificial neural network in patients with respiratory failure. Crit Care Med. 2006;34:1052–1059.)
Section II: Monitoring

FIGURE 20.6. Examples of trend plots of patients with low, moderate, and high values of power of breathing (POB) while treated with pressure support ventilation are shown. Two patients are shown in each category. Note that noninvasively predicted/calculated POB tracked in a nearly identical manner with invasively measured POB for all three categories of patients. The artificial neural network used for predicting/calculating POB appears to be accurate over wide ranges of POB as might be expected in clinical practice. (From Banner MJ, Euliano NR, Brennan V, et al. Power of breathing determined noninvasively using an artificial neural network in patients with respiratory failure. Crit Care Med. 2006;34:1052–1059.)

the carinal end of the endotracheal tube compared with the conventional method of pressure-triggering from inside the ventilator or using flow-by (flow-triggered) initiation (33,34). During spontaneous inhalation, automatic and variable inspiratory pressure assist results when using tracheal pressure rather than breathing-circuit Y-piece pressure to control the operation of the ventilator, which, in turn, acts to decrease imposed resistive work of breathing to nearly zero (35). This is described as a closed-loop tracheal pressure ventilator control system (Figs. 20.10 and 20.11).

With pressure-triggering from inside the ventilator or with flow-by triggering, an initial pressure drop across the

FIGURE 20.7. Pressure at the Y piece of the breathing circuit, referred to as “airway pressure”; flow rate during inhalation (I) and exhalation (E); and tidal volume are shown during a conventionally applied ventilator breath (left) and then using an end-inspiratory pause (EIP) (right). An EIP is used for the purpose of measuring respiratory system compliance ($C_{RS}$) and resistance ($R_{RS}$). The patient should be perfectly relaxed for these measurements. Peak inflation pressure (PIP) is the maximum pressure generated following tidal volume inhalation. At the end of the preselected EIP time, usually about 0.3 seconds, PIP decreases to the static elastic recoil pressure or plateau pressure (Pplt) of the respiratory system. PIP is the sum of the resistive (endotracheal tube and physiologic airways series resistance) and elastic pressures (lung and chest wall elastance). $C_{RS}$ and $R_{RS}$ are calculated based on these data (see Table 20.2).
endotracheal tube must be generated by the patient before flow is initiated. This effort results in significant increases in imposed work. By contrast, pressure-triggering at the carinal end of the endotracheal tube effectively decreases the resistance by the endotracheal tube during spontaneous inhalation, thus decreasing the imposed POB.

The sensitivity/trigger setting on the ventilator directly affects the imposed POB. At a higher setting, a greater change in pressure is required to trigger the system on, thereby increasing the POB (35).

**CLINICAL IMPLICATIONS OF RESPIRATORY MUSCLE LOADING**

**Fatigue**

Increased respiratory muscle loading results in increases in the force and duration of diaphragmatic contraction, and leads to an increased tension-time index of the diaphragm (TTdi) (7). TTdi is the product of transdiaphragmatic pressure over the maximum transdiaphragmatic pressure (Pdi max) and the ratio of inspiratory time to total cycle time (TTdi = Pdi/Pdi max × T I/T tot). The TTdi is similar to the tension-time index for the heart and gives a useful approximation of muscle energy demands (6,7). During spontaneous breathing, the change in transdiaphragmatic pressure is normally about 10 cm H2O and the T I/T tot ratio is 0.33, effecting a TTdi of 0.03 (TTdi = 10 cm H2O/100 cm H2O × 0.33). With increased respiratory muscle loading, Pdi may increase to 30 cm H2O and T I/T tot to about 0.5, resulting in a TTdi of 0.15. Breathing patterns with a TTdi of about 0.15 to 0.20 are called fatiguing to indicate that the diaphragm will, in time, fail (6,7). Presumably, when the demand of the diaphragm exceeds 0.15 to 0.20, sufficient energy supplies are not available (6,7). This threshold TTdi is related to the limitation of blood perfusion and oxygen delivery to the muscle (Fig. 20.12).

### TABLE 20.2

<table>
<thead>
<tr>
<th><strong>Calculations of Respiratory System Compliance and Resistance</strong> (See Fig. 20.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Respiratory system compliance</strong> = Tidal volume/Inspiratory plateau pressure − PEEP</td>
</tr>
<tr>
<td>0.051 L/cm H2O = 1 L</td>
</tr>
<tr>
<td>0.051 cm H2O = 20 cm H2O − 0 cm H2O</td>
</tr>
<tr>
<td><strong>Respiratory system resistance</strong> = Peak inflation pressure − Inspiratory plateau pressure</td>
</tr>
<tr>
<td>10 cm H2O/L/sec = 30 cm H2O − 20 cm H2O</td>
</tr>
<tr>
<td>1 L/sec</td>
</tr>
</tbody>
</table>

- Reflects elastic work of spontaneous breathing; that is, the lower the respiratory system compliance, the greater the elastic work of breathing, and vice versa (see Fig. 20.8).
- Reflects resistive work of spontaneous breathing; that is, the greater the respiratory system resistance (physiologic or imposed resistance), the greater the resistive work of breathing, and vice versa.
TABLE 20.3

EFFECT OF INCREASED PHYSIOLOGIC DEAD SPACE VOLUME, AS ASSESSED BY THE DEAD SPACE VOLUME TO TIDAL VOLUME RATIO (Vd/Vt), ON EXHALED MINUTE VENTILATION (V̇E)

\[
\text{PaCO}_2 = \frac{\text{VCO}_2}{V_t(1 - V_d/V_t)} \times 760 \text{ mm Hg}
\]

A. V_d/V_t = 0.30 (normal)
- PaCO_2 = 200 mL/min
- V̇E = 6,000 mL/min (1 - 0.30) \times 760 mm Hg
- PaCO_2 = 36 mm Hg

B. V_d/V_t = 0.50 (increased)
- PaCO_2 = 200 mL/min
- V̇E = 9,000 mL/min (1 - 0.50) \times 760 mm Hg
- PaCO_2 = 34 mm Hg

As physiologic dead space volume to tidal volume ratio increases from 0.30 to 0.50, spontaneous minute ventilation increases from 6,000 mL/min to 9,000 mL/min (50% increase in respiratory muscle loading) to maintain the same alveolar minute ventilation and essentially the same PaCO_2, assuming no change in VCO_2.

\text{VCO}_2, \text{carbon dioxide minute production.}

Energy Supply and Demand

Respiratory muscle fatigue develops for the same reasons that one develops angina pectoris: Demand for energy exceeds the supply of energy (6,36). Energy supply refers to the proportion of cardiac output, blood perfusion, oxygen, and nutrients to the respiratory muscles that directly affect the synthesis of ATP. Respiratory muscle fatigue develops when ATP hydrolysis exceeds ATP synthesis as a result of an imbalance between energy supply and demand. Under conditions of increased muscle loading, respiratory muscle energy demands increase. Increases in muscle blood flow demand and oxygen consumption predispose to the development of muscle ischemia, fatigue, and respiratory failure (36,37). V̇E decreases and increases in dead space to V̇E ratio, and arterial carbon dioxide levels result when the respiratory muscles fail as force generators. Clinically, diaphragmatic fatigue is associated with abdominal paradox (abnormal inward movement of the diaphragm during spontaneous inhalation) and respiratory alternans (Fig. 20.13).

Breathing Pattern

Frequency

When pulmonary mechanics deteriorate, the respiratory muscles are loaded and POB increases. As a result, the breathing pattern changes (Table 20.4). These changes are vagally mediated by afferent or sensory fibers (load sensors) in the lungs and respiratory tract. Three types of afferent fibers modulate the breathing pattern: (a) slowly adapting receptors (SARs); (b) rapidly adapting receptors (RARs) (also termed deflation, cough, or irritant receptors), both of which are pulmonary stretch or mechanoreceptors; and (c) chemosensitive or C-fiber endings (38). SARs are found in the bronchial smooth muscle.
fibers, RARs are situated in the superficial layers of the respiratory tract mucosa, and C fibers are found in the airway epithelium (38).

Central Nervous System Modulation

The mechanoreceptors monitor changes in pulmonary mechanics and thoracic gas volume (functional residual capacity) (39,40). After a decrease in lung compliance (increase in respiratory muscle load), an increase in discharge activity occurs. Similar responses result after increases in total resistance. C-fiber endings are activated by many substances produced in the lungs such as histamine, bradykinin, and some prostaglandins. Some sympathetic afferents also may be activated in response to increases in mechanical loads. Afferent discharge signals from the sensory fibers are directed by the vagus nerve to the central respiratory controllers in the central nervous system (CNS), modifying their output signals, which in turn modify the breathing pattern (3).

Stimulation of these receptors produces patterns of rapid, shallow breathing and an optimal breathing frequency to minimize large changes in intrapleural pressure (41). Patients with loaded respiratory muscles breathe at a faster rate and a smaller $V_T$ to minimize the POB, the so-called “minimal POB” or “least average force” concept, producing the most energy-efficient combination of breathing frequency and $V_T$ (17,41,42). When the frequency is too low, much elastic work is required to produce large $V_T$s; when the frequency is too high, much resistive work is required as well as useless work to ventilate the dead space with each breath (17) (Fig. 20.14). This mechanism also functions to protect the respiratory muscles from exhaustive, fatiguing contractions that can lead to muscle fiber splitting, hemorrhage, and self-destruction (3).

Inferred Work of Breathing

Spontaneous breathing frequency and tidal volume are used as inferences of the POB (43). An abnormal adult respiratory muscle workload is inferred when the spontaneous respiratory rate is greater than 25 to 30 breaths/minute; a breathing rate of 15 to 25 breaths/minute is inferred to mean that work-load is tolerable and in a more normal range. These inferences,

\[
\begin{align*}
\text{BREATH} & \quad \text{WOB}_\text{v} & \quad \text{WOB}_\text{i} \\
A & 0.92 & 0.00 \\
B & 2.10 & 0.05 \\
C & 3.71 & 0.18
\end{align*}
\]

FIGURE 20.11. Operation of the tracheal pressure control (TPC) system as shown in Figure 20.10 illustrates the automatic and variable inspiratory pressure assist to minimize imposed resistive work of breathing (WOBi). Data for work of breathing by the ventilator assisting inhalation (WOBv) are also shown. Peak inspiratory flow rate demands for breath “A,” “B,” and “C” are 0.5, 1.0, and 2 L/second, respectively. TPC responds automatically by providing inspiratory assist in proportion with the demands at 15, 30, and 50 cm H$_2$O, respectively, to decrease WOBi to nearly zero for all conditions. Breathing circuit pressure measured at the Y piece ($P_Y$), not pulmonary airway pressure as reflected by tracheal pressure ($P_T$), is increased. The greater the patient’s inspiratory flow rate demand is, the greater the inspiratory pressure assist to minimize WOBv, and vice versa.
FIGURE 20.12. Increased respiratory muscle loading and the subsequent effects leading to fatigue are shown. Fatigue is defined as loss of the force-generating capacity of the respiratory muscles.

however, seem to be inaccurate and misleading with regard to the POB (44,45). Although patients breathing between 15 and 25 breaths/minute often demonstrate an apparently acceptable breathing pattern, the respiratory muscle workloads may vary from fatiguing to normal to zero (44,45).

INAPPROPRIATE RESPIRATORY MUSCLE UNLOADING WHEN USING CONVENTIONAL METHOD FOR SETTING PRESSURE SUPPORT VENTILATION

A primary goal of mechanical ventilatory support for spontaneously breathing patients with respiratory failure is reduction of excessive POB. Appropriate respiratory muscle unloading to decrease power of breathing is thought to be achieved by setting PSV using the following conventional method:

- Spontaneous breathing frequency 15 to 25 breaths/minute
- Tidal volume 6 to 8 mL/kg ideal body weight
- Absence of SCM contraction
- Appearance of breathing comfortably and no apparent anxiety or adverse cardiovascular effects

We evaluated the effects on respiratory muscle workloads using this method of applying PSV in 115 adults (35 males, 60 females, weight 81 ± 18 kg, age 55 ± 11 years) with varying degrees of respiratory failure from various etiologies (e.g., pneumonia, sepsis, trauma, congestive heart failure) (institutional review board [IRB] approved). A combined

TABLE 20.4

MANIFESTATIONS OF LOADED RESPIRATORY MUSCLES AND FATIGUE

- Increased breathing frequency
- Discordant respiratory movements, that is, abdominal paradox (abnormal inward abdominal displacement during spontaneous inhalation, characteristic of a fatigued diaphragm) and respiratory alternans (alternating between abdominal paradox and normal breathing, which is characterized by an outward displacement of the abdominal wall during inhalation) (see Fig. 20.13)
- Hypercapnia and respiratory academia
- Terminal fall in breathing frequency and minute ventilation

a Fatigue is defined as loss of the force-generating capacity of the muscles.
Therapeutic Objectives

Objectives of therapy for loaded or fatigued muscles include the following: (a) decrease energy demand (POB), and (b) increase energy supply (oxygen, blood flow, and nutrient delivery) to the respiratory muscles. PSV is advocated to unload the respiratory muscles, decrease the POB, and decrease the energy demands of patients with decreased compliance and increased resistance (47,48). It also augments spontaneous breathing by potentially decreasing the work imposed by the resistance of the breathing apparatus to zero (10,28).

In the PSV mode, the ventilator is patient-triggered on, and an abrupt rise in airway pressure to a preselected positive pressure limit results from a variable flow rate of gas from the ventilator. As long as the patient maintains an inspiratory effort, airway pressure is held constant at the preselected level. Gas flow rate from the ventilator ceases when the patient's inspiratory flow rate demand decreases to a predetermined percentage of the initial peak mechanical inspiratory flow rate (e.g., 25%). The ventilator is thus flow-cycled "off" in the PSV mode.

Once the preselected inspiratory pressure limit is set, the patient interacts with the pressure-assisted breath and retains
control over inspiratory time and flow rate, expiratory time, breathing rate, VT, and minute volume (Fig. 20.16). Patient work decreases, and ventilator work increases at incremental levels of PSV (21,27). Decreasing the load on a muscle to an appropriate level decreases the force and duration of muscle contraction (tension-time index) (6), energy demand, muscle ischemia, and fatigue. For a patient with increased respiratory muscle load or POB (e.g., 15 joules/minute), a clinician may also unload the respiratory muscles to a more appropriate range, which appears to be about 5 to 10 joules/minute using PSV. This range is based on studying over 500 adults treated with PSV.

**Partial and Total Respiratory Muscle Unloading**

The level of PSV may be set to partially or totally unload the respiratory muscles (21,48,49). During partial unloading, PSV is increased until the patient’s POB is decreased to a tolerable range. My goal usually is 5 to 10 joules/minute, an appropriate range for physiologic POB. During inhalation with PSV, positive pressure actively assists lung inflation. A portion of the POB is provided, relieving and unloading the respiratory muscles of the increased workload, and decreasing the force and duration of muscle contraction. Work is performed in part by the patient and in part by the ventilator (i.e., a work-sharing approach). Partial respiratory muscle unloading is appropriate to provide a nonfatiguing workload and promote muscle conditioning.

**Titration of Pressure Support Ventilation**

The level of PSV may be set to provide appropriate, or optimal, respiratory muscle loads. The exact level of this load is not known, but some authorities suggest that near-normal workloads are well tolerated (21,50). In a carefully done study, Brochard et al. (50) report that at a PSV of approximately 15 cm H2O, an optimal muscle load corresponded to a...
patient work of breathing of 0.52 ± 0.12 joules/L. (This is proportional to a POB range of 5–10 joules/minute.) An optimal load was defined as that which maintained maximal diaphragmatic electrical activity without fatigue (specifically, the lowest level of PSV at which no reduction in the ratio of high-to low-frequency components of the diaphragm's electromyographic signal occurred). A reduction of 80% or less of the initial high/low ratio is defined as incipient diaphragmatic fatigue (51).

**Patient Characteristics**

Physiologic patient characteristics should also be considered. Weak, malnourished, and chronically ill patients will not tolerate normal workloads as well as physically powerful individuals with short-term illness. The latter patients may be able to generate twice the normal work range without developing fatigue. Because the tolerance may vary, setting the level of PSV so that the POB is in an appropriate range of 5 to 10 joules/minute is a reasonable initial guideline (24).

Available evidence suggests that total unloading, allowing fatigue respiratory muscles to rest and recover, is appropriate (4,6,52). The time for respiratory muscle recovery after chronic fatigue is estimated to be at least 24 hours (6). A reasonable approach is to totally unload the respiratory muscles of such patients for approximately 24 hours by using high levels of PSV (e.g., >30 cm H₂O). Subsequently, when appropriate, PSV may be decreased so that the patient POB is in a normal, tolerable range and the respiratory muscles are partially unloaded (27).

My experience and that of others (14) suggests that all intubated, spontaneously breathing patients in respiratory failure should receive a minimal level PSV that reduces imposed POB to zero (Figs. 20.2 and 20.2A) (10). Additional PSV may be required to decrease the abnormally high physiologic work associated with the disease process to a normal level (21). Subsequently, as the patient's respiratory status improves, PSV may be decreased while ensuring that the POB is in a nonfattiguing range. PSV should not be decreased to zero or below the level required to decrease imposed work to zero. To do so functionally reloads the respiratory muscles and risks fatigue. Extubation at the level of PSV results in zero imposed POB; that is, about 10 cm H₂O for most adults seems reasonable.

**POWERS OF BREATHING AS A CRITERION FOR EXTUBATION**

POB, the rate at which work is done per minute, is a better assessment of respiratory muscle workload than work of breathing per breath because it is a measure over time, not for an individual breath. Spontaneous breathing f, V, ḞV₁ ratio, minute ventilation (MV), PaO₂/FIO₂ ratio, PaCO₂, and SCM use are used typically when evaluating a patient's readiness for extubation. We hypothesized that POB may be another parameter for predicting successful extubation. To test this hypothesis, we studied adults with respiratory failure who were candidates for extubation.

We evaluated 25 adults (15 males, 10 females, age 56 ± 19 years, weight 80 ± 25 kg) in an IRB-approved study where POB was measured in real time and noninvasively (POBn), without the need of an esophageal balloon, using a monitor (NICO, Respironics, Convergent Engineering) (1). Data from a combined pressure/flow sensor, positioned between the endotracheal tube (sizes ranged from 6–8 mm internal diameter) and ventilator circuit, were directed to the monitor. All patients were studied immediately prior to extubation using minimal ventilator settings (intermittent mandatory ventilation 0 per minute, pressure support ventilation 10 cm H₂O, continuous positive airway pressure 5 cm H₂O and FIO₂ 0.4). An arterial blood gas was obtained. Data were analyzed using a Mann–Whitney U test; α was set at 0.05 for statistical significance.

It was found that POBn ranged from 2 to 10 joules/minute for patients successfully extubated (N = 20) and 10 to 23 joules/minute for those failing extubation (N = 5), requiring reintubation and ventilatory support. POBn was significantly lower, and related breathing parameters were significantly different for patients successfully extubated (Table 20.5). POBn values >10 joules/minute were associated with failed extubation. A critical value for POBn to predict successful extubation may be about 10 joules/minute (53). A larger sample size is needed to thoroughly evaluate these pilot data findings for determining a critical value. POBn data coincided with typically used breathing parameters for assessing readiness for extubation; that is, when f, V, ḞV₁ ratio, PaO₂/FIO₂ ratio, and PaCO₂ data were clinically acceptable, and in the absence of SCM activity, patients were successfully extubated. It appears that POBn may be a parameter to consider for predicting extubation from ventilatory support.

**TABLE 20.5**

<table>
<thead>
<tr>
<th>POBn (joules/minute)</th>
<th>f (breaths/min)</th>
<th>V (L)</th>
<th>ḞV₁ (L/min)</th>
<th>MV (L/min)</th>
<th>PaO₂/FIO₂</th>
<th>PaCO₂</th>
<th>SCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Successful extubation</td>
<td>6.1±2.9</td>
<td>16±5</td>
<td>0.53±0.1</td>
<td>34±12</td>
<td>8.5±5</td>
<td>300±78</td>
<td>40±6</td>
</tr>
<tr>
<td>Failed extubation</td>
<td>14.8±4.9</td>
<td>33±5</td>
<td>0.35±0.1</td>
<td>109±25</td>
<td>11±2.5</td>
<td>225±70</td>
<td>45±6</td>
</tr>
</tbody>
</table>

*p = 0.05.

Data are mean ± standard deviation. POBn (joules/minute), spontaneous breathing frequency (f) (per minute), tidal volume (V) (L), ḞV₁ (breaths/minL), minute ventilation (MV) (L/min), sternocleidomastial contraction (SCM).
Noninvasive Power of Breathing for Weaning

Maintaining patients in a normal POB (normal range may be approximated when the decision to “wean to extubation” is not contemplated and spontaneous ventilation is allowed. Under this ventilatory support condition, PSV can be applied to maintain POB, in a normal range and low IMV rates are applied, assuming the patient is hemodynamically stable. Still others may need to have their respiratory muscles totally unloaded, requiring high levels of PSV (> 20 cm H2O).

When the decision is made to “wean to extubation,” a patient’s respiratory muscle endurance and ventilatory reserve need to be probed. The PSV level may be set to maintain POB at about 5 to 10 joules/minute so as to assess the patient’s workload tolerance. It is not so much the amount of POB performed; rather, a patient’s ability to tolerate a specific respiratory muscle workload is the important concept. When assessing workload tolerance, it has been reported that breathing pattern parameters (i.e., V1, SV, r, ratio, MV, accessory respiratory muscle use) do not always correlate, and are not good predictors of work of breathing. It is not implied that breathing pattern parameters should be ignored. On the contrary, these parameters provide useful diagnostic information and should be used. POB and breathing pattern data should be used in a complementary manner when assessing respiratory muscle workload tolerance (18).

The aforementioned range of POB levels appears appropriate for patients with acute forms of respiratory failure and need to be evaluated in patients with chronic forms of respiratory failure, as in chronic obstructive pulmonary disease (COPD).

Multiple Noninvasive Power of Breathing Range Concept

1. Initial phases of ventilatory support

A. Maintain POB in a low range (0–2 joules/minute) for patients whose respiratory muscles are fatigued—total unloading (about 24 hours) promotes respiratory muscle rest and recovery.

B. Maintain POB in a normal range (5–10 joules/minute), when allowing spontaneous breathing—use when the patient is weak and still has substantial pulmonary disorder.

2. Weaning phase of ventilatory support

Probe the patient’s reserve by maintaining POB at a higher range (up to 12 joules/minute). This allows for a relatively prolonged assessment of a patient’s respiratory muscle tolerance and endurance.

SUMMARY

Respiratory muscle loads of intubated patients receiving ventilatory support may be visualized as a continuum; muscles at one end are highly loaded and at the other end are totally unloaded, predisposing to fatigue and atrophy, respectively. The terms, moscovial respiratory failure and iatrogenic ventilator dependency (14), describe the inappropriate prolongation of ventilatory support. This problem may result from respiratory muscle fatigue (caused by increased muscle loading from breathing through a highly resistive apparatus, increased physiologic work, or inefficient ventilatory support) or muscle atrophy (as a result of total unloading of respiratory muscles by too high levels of PSV) (14).

With either fatigue or atrophy, the respiratory muscles become weak, failing as force generators. Hypoventilation, hypocapnia, and failure to wean often result, thus prolonging the need for ventilatory support. Fatigue or atrophy can occur; in fact, from lack of assessing and adjusting respiratory muscle afterload, thereby failing to perceive their often subtle onset. Measurement of the POB provides objective and tested data that can be used to set ventilator modes such as PSV to prevent either occurrence, and may expedite eventual weaning and extubation.

References

24. Banner MJ, Eklof NR, Brunnim V, et al. Power of breathing determined...

23. Macklem NR, Leatham NE. Mechanical loads on the ventilatory mus-


45. Kirton O, Banner MJ, DeHaven CB, et al. Respiratory rate and related as-


49. Macklem NR, Ohmura M, Usada Y. The Nogoya conference on system design and sensor-ventilator interactions during pressure support ventilat-

50. Bretschad L, Had A, Lotton H. Inspiratory pressure support provides di-


52. Mencurra D, Aubert M, Lecqur E, et al. Effects of theophylline on di-
aphragmatic strength and fatigue in patients with chronic obstructive pul-


54. Gabrielli A, Leon AJ, Eukin NE, et al. Respiratory monitor recommends ap-