CHAPTER 69  ■ PERIOPERATIVE PULMONARY FUNCTION TESTING AND CONSULTATION

PHILIP BOYSEN

Measurement of pulmonary function is an important adjunct to the symptoms exhibited by a patient, as well as the findings on physical examination. The quantification of pulmonary function has specific applications to clinical medicine in the intensive care unit setting, such as the following:

- Confirming a clinical diagnosis of obstructive versus restrictive ventilatory defects in a patient with respiratory insufficiency or failure
- Following the course of the patient’s disease and the response to treatment
- Enhancing decision making for patients about to undergo thoracoabdominal surgery
- Developing an anesthetic and postoperative plan for a patient with pulmonary disease

This chapter will outline the pulmonary function tests that are now considered routine and will address the interpretation of the tests. The timing and nature of the effects of thoracic and abdominal surgery and the clinical implications of the anesthetic and surgical procedures will also be considered.

The evaluation of a patient who is being considered for resectional lung surgery is an important issue for the anesthesiologist, surgeon, and intensivist. Finally, there are some aspects of pulmonary function measurement that are particularly applicable to practitioners of intensive care medicine.

ROUTINE PULMONARY FUNCTION TESTING

Although it might be argued that no form of testing can be considered routine, when clinicians refer to “routine pulmonary function testing” there are three types of measurement and assessment of lung function that define the pulmonary status of a patient: (i) spirometry, (ii) measurement of lung volumes, and (iii) measurement of lung diffusing capacity.

Spirometry

Spirometry remains the most basic technique to assess lung function, and the most valuable. The concept is simple, but the assessment of the results can be complex. In essence, the patient is asked to inhale to total lung capacity (TLC) and then to forcefully exhale into a device that measures volume versus time. The ability to perform a forceful exhalation is key to obtaining an adequate study. Maximal forced exhalation from TLC to residual volume (RV) results in a spirogram with a smooth and reproducible curve that defines a maximal forced expiratory volume envelope. To ensure that patient effort and cooperation is maximal and approaches the envelope that the patient cannot penetrate, the procedure is repeated three times, and the spirometric curves are superimposed and compared.

Performance of a forced vital capacity maneuver is not problematic for a normal person, but a patient with pulmonary impairment is greatly distressed by this procedure. It may take some time for the technician to achieve the performance needed. Once this occurs, the patient is asked to use a metered dose inhaler (beta2 agonist) and then repeat the forced vital capacity maneuver three more times, as the technician again assesses the results for maximal performance and its response to bronchodilators (Fig. 69.1).

The evaluation of a spirogram is straightforward, compares the results to data provided by examining a normal population of men and women, and seeks to answer two additional questions. From a physiologic standpoint, the spirogram defines patients with an obstructive or a restrictive physiologic defect or impairment. Restrictive defects are associated with a decrease in the forced vital capacity (FVC) of at least 20% of the predicted value. Obstructive ventilatory defects are revealed when the ratio of the forced expiratory volume in 1 second (FEV1) divided by the FVC (the FEV1/FVC ratio) is less than 85%. Other indications of obstructive lung disease available from the spirogram include the peak expiratory flow rate (PEFR), a useful method of following airflow obstruction due to asthma, and the maximal midexpiratory flow rate. With the latter measurement taken at the midpoint of the FVC, the slope of the line between 25% and 75% of the FVC (IFE 25%-75%) is a better indication of obstructive lung disease due to chronic bronchitis (Fig. 69.2).

Another method of representing a maximal forced expiratory maneuver depicts the FVC versus flow rather than versus time (Fig. 69.3).

The forced exhaled volume between TLC and RV is the maximal expiratory flow curve. If the patient is asked to fully inhale back to TLC, once the expiratory maneuver is completed, the flow-volume relationship is referred to as a flow-volume loop. This study is especially useful for diagnosing intrathoracic and extrathoracic upper airway obstruction.

Whereas the FVC measures exhaled volume versus time, and therefore gives an index of airflow, the maximum voluntary ventilation (MVV) is a test that involves repeated breaths and vigorous breathing for 10 to 12 seconds. The MVV is reported in L/minute, which means that the 10- or 12-second effort is multiplied by 6 or 5 respectively. Although it is only a rough...
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1.0 2.0 3.0

Time (sec)
Volume (L)

FVC = forced vital capacity
FEV\textsubscript{1.0} = forced expiratory volume 1 second

FIGURE 69.1. Three forced exhalations are performed before and after bronchodilator inhalation to assess immediate response. The maximum measured exhaled volume is FVC. The exhaled volume at 1 second is FEV\textsubscript{1.0}. The FEV\textsubscript{1.0}/FVC ratio is reduced with an obstructive ventilatory defect.

index, the MMV assesses both airway status and respiratory muscle endurance.

Lung Volumes

Whereas spirometry is a simple test and widely available, measurement of lung volumes requires more complex instrumentation. Lung volume determinations add another dimension to spirometry as a means of defining pathophysiologic changes in lung function.

Several methods are available to measure lung volumes, two of which depend on analysis of a specific gas—one physiologic and one inert. The first method, requiring a nitrogen analyzer, is easily performed over a 7- to 10-minute period of spontaneous breathing of 100% oxygen. With each breath, a certain percentage of nitrogen in the lungs is replaced by oxygen until a certain point where very little nitrogen remains in the lungs, although the nitrogen level never reaches absolute zero. The log of the exhaled nitrogen concentration over time is displayed until no further decrement is noted. Since 79% of the resident lung volume is elemental nitrogen (N\textsubscript{2}), measuring the total amount of nitrogen exhaled allows calculation of the volume from which it came. In the lung with significant ventilation perfusion mismatch, the log N\textsubscript{2} versus time is not a straight slope, and it takes longer to reach the equilibration end point.

In the operating room, this phenomenon can be demonstrated in the patient with asthma or chronic bronchitis if the gas analyzer is able to measure nitrogen in addition to the other physiologic or anesthetic gasses. Rather than “wash out” a physiologic gas, the “wash in” of an inert gas can also be used to determine lung volumes, and helium is used for this purpose. Fitted with a nose clip and a one-way valve in the breathing circuit, the patient is asked to breathe quietly with normal tidal volumes and is then connected to the circuit with a reservoir containing a known volume and concentration (10%) of helium. Measuring helium

FIGURE 69.2. Compartmentalization of lung volume is achieved by noting the volume excursion during tidal breathing and repeated inhalation and exhalation. The functional residual capacity is measured using gas wash-in or wash-out techniques. TLC, total lung capacity; VC, vital capacity; FRC, functional residual capacity; RV, residual volume.

FIGURE 69.3. The relationship between a recording of flow and volume during a forced vital capacity (FVC) maneuver. ERV, expiratory reserve; FRC, functional residual capacity; IRV, inspiratory reserve; MMEFR, maximal midexpiratory flow rate; PEFR, peak expiratory flow rate; V\textsubscript{T}, tidal volume.
breath by breath, the technician records the point at which the decline in helium concentration reaches a steady state. Using the formula $V_1C_1 = V_2C_2$, the total volume of the helium black box and the patient's lungs is calculated, and the black box volume is subtracted, yielding the lung volume of the patient. The volume that is measured with either of these techniques depends on the point at which the patient is linked continuously into the breathing circuit. The intent is to begin the measurement at the end of a tidal breath, at functional residual capacity (FRC). Using either a solenoid that detects flow reversal at the end of the tidal breath, or simply using direct observation of tidal breathing, this is usually easily accomplished.

The lung volume study is completed by once again using the spirometer and coaching the patient to a full respiratory maneuver. Then, after quiet tidal breathing, the patient is asked to exhale to residual volume (RV), then inspire fully to total lung capacity (TLC), and after a second interval of quiet tidal breathing, fully inspire to TLC and expire to RV. Knowing the FRC from the dilution studies, all of the lung volume compartments can be calculated (Fig. 69.2).

Residual volume, functional residual capacity, and total lung capacity can be viewed as a system of concentric circles (Fig. 69.4). An obstructive ventilatory defect is characterized by hyperinflation, with a greater effect on RV and FRC than on TLC. A restrictive ventilatory defect can be either intrinsic or extrinsic. An intrinsic restrictive ventilatory defect is characterized by a concentric reduction (each volume decreases by the same percentage). An extrinsic restrictive ventilatory defect shows a disproportionate loss of volume “off the top”; the major change is in TLC. The postoperative patient who has had a surgical procedure in the thorax or upper abdomen shows the latter change in physiology. Though transient, the extrinsic restrictive ventilatory change, especially when superimposed on a patient with obstructive physiology, can be significant.

### Diffusing Capacity

The third pulmonary function study of importance is aimed at assessing gas transfer at the alveolocapillary membrane. Oxygen is the gas transfer of interest, but making this measurement is difficult because there is always a back pressure or gas tension in the blood that must be compared to alveolar gas. This problem can be overcome by introducing a gas that is not normally in the bloodstream, specifically small amounts of carbon monoxide (CO). Since CO is not a physiologic gas, this measurement is referred to as the diffusing capacity, not diffusional capacity.

The measurement can be made in two ways, and there is controversy over which test gives superior information. The two methods include introducing CO into a breathing circuit and measuring the change in tidal breathing to a steady state, and similarly inhaling CO with a single breath. With the second technique, a further piece of information is obtained by relating the gas transfer to the size of the breath, reported as the KCO.

This is an indication of diffusing capacity “where the gas goes,” and is considered another method of evaluating both restrictive and obstructive changes in physiology.

If the tissue of an adult lung were microdissected and spread out, it would cover the space of a football field. Thus, one of the reasons for a decrease in diffusing capacity (as opposed to a thickened alveolocapillary membrane) is loss of effective surface area for gas transfer. This is a pathognomonic change seen in patients with emphysema.

When spirometry, lung volumes, and diffusing capacity are all evaluated, there is a characteristic pattern of physiologic changes that identifies patient status and diagnosis, which is important in the care of the perioperative patient (Table 69.1).

### Table 69.1

<table>
<thead>
<tr>
<th>Spirometry (FVC, FEV, BD, RV, TLC, DLCO, PaO, PaCO)</th>
<th>OVD&lt;sub&gt;B&lt;/sub&gt;</th>
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OVD<sub>B</sub>, emphysema; OVD<sub>AB</sub>, chronic bronchitis; OVD<sub>A</sub>, asthma; RVD<sub>B</sub>, intrinsic restrictive ventilatory defect; RVD<sub>A</sub>, extrinsic restrictive ventilatory defect.
Arterial Blood Gas Analysis

Arterial blood gas analysis (ABG) is usually included in the panoply of routine pulmonary function testing. In preparing a patient for surgery, ABG analysis is often ordered, but the usefulness is limited to an analysis of trends and diagnosis of underlying chronic disease. Prognostic value is limited, and for resectional lung surgery, postoperative ABGs are often improved. However, there is value in identifying patients with obstructive lung disease who have emphysema, as opposed to chronic bronchitis, in assessing and designing postoperative therapy. Table 69.1 summarizes the findings for the various physiologic states.

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stroke, and acute respiratory failure requiring mechanical ventilation following surgery. Because of the difficulty of making predictions based solely on the measurement of pulmonary function, other strategies for assessment are continually being developed and analyzed. Early studies sought to first identify normal pulmonary function criteria for large populations and then demonstrate changes due to other changes in lung function, such as aging and cigarette smoking (11,12). The next step included identifying risk factors and determining if a preoperative therapeutic regimen would alter outcome, or if alterations in anesthetic technique improved or lessened postoperative pulmonary complications (13,14).

Most studies have been limited by the number of patients entered into the study protocol, but the accumulated evidence would indicate that preoperative testing would identify patients at risk for postoperative pulmonary complications (15–18). The efficacy of strategies to reduce postoperative pulmonary complications is not so well defined (19–24). Recently, the National Veterans Surgical Quality Improvement Program, in developing a multifactorial risk index for predicting postoperative pneumonia and respiratory failure after major noncardiac surgery, has reported large numbers of patients. The consistent risk factors in this population include the following (23):

- **Smoking status**: The duration of smoking cessation to achieve benefit appears to be at least 4 weeks, possibly as long as 8 weeks.
- **Chronic obstructive lung disease**, as defined by history and physical examination (spirometry has not been shown to be useful in prognosis)
- **Measures of general health status**: includes the presence of comorbid conditions, functional status, recent weight loss.
- **Cognitive impairment, for whatever reason**
- **Previous stroke**
- **Type and location of the anticipated surgical procedure**
- **Age**: a risk factor when controlled for comorbid conditions
- **Long-term steroid therapy**
- **Recent moderate-to-heavy alcohol intake**
- **Impaired renal function**
- **Large transfusion: generally >6 units of packed red blood cells, plus other blood products**

In this study, the authors were not able to analyze the importance of serum albumin, spirometry, use of prophylactic antibiotics, and body mass index or obesity. Other studies have suggested that a low serum albumin carries a higher risk for PPCs, and the outcome is not changed by administering intravenous hyperalimentation, but risk is possibly lessened by feeding through the gut. As mentioned, spirometry is diagnostically accurate, but is not useful for prognosis; and obesity in the absence of comorbid conditions is not a significant risk factor for PPCs.

The use of general anesthesia for surgical procedures, and the duration of the anesthetic and surgical procedures (greater than 4 hours) were reported to increase the risk of PPCs. A common consultant comment has been, “OK for spinal, avoid general anesthesia,” implying that the volatile anesthetic agent had some negative impact on postoperative pulmonary function. Advances in anesthesia technology and skills have allowed investigators to reframe the question. Does the presence of adequate neuroaxial blockade during a surgical procedure reduce risk? The anesthetic plan can include spinal anesthesia, epidural anesthesia, combined spinal-epidural anesthesia, and these can also be combined with light levels of general anesthesia (the “epigeneral”). Further, neuroaxial blockade can be continued into the postoperative period for pain management. Postoperative pain management is an important goal that also enables a patient to complete deep breathing maneuvers. It does appear that the presence of neuroaxial blockade, either alone or in combination with general anesthesia, is associated with fewer deaths and complications.

### STRATEGIES TO REDUCE PPCs AFTER NONCARDIOTHORACIC SURGERY

The general approach to the patient with impaired pulmonary function has included cessation of smoking and an attempt to maximize pulmonary function with the use of bronchodilators, both beta-2-agonists and parasympatholytic agents, treatment of underlying infections or purulent sputum, and coaching to learn deep-breathing exercises. Bronchodilators are continued throughout the anesthetic and surgical procedure.

A recent publication reviewed the available literature on interventions to prevent PPCs after noncardiotoracic surgery. A synthesis of the evidence indicates the following:

- **Studies with good evidence**: The evidence indicates that lung expansion interventions are useful in preventing PPCs. This includes incentive spirometry, deep breathing exercises, and continuous positive airway pressure.
- **Studies with fair evidence**: The evidence indicates that selective rather than routine use of nasogastric tubes after abdominal surgery is beneficial, given that it decompresses the stomach, allowing for better diaphragmatic excursion. The use of short-acting, intraoperative neuromuscular blocking agents (e.g., vecuronium vs. pancuronium) is associated with improved outcomes.
- **Studies with conflicting evidence**: The evidence is conflicting or insufficient for cessation of smoking, epidural anesthesia, epidural analgesia, and laparoscopic versus open abdominal surgery. As noted above, the presence or absence of neuroaxial blockade—not the anesthetic choice—may be the determining factor. Also, laparoscopic procedures result in less pain and a lesser reduction in the FVC. Finally, although malnutrition is associated with increased risk, routine total enteral or parenteral nutrition does not reduce risk.

In summary, for noncardiotoracic surgery, there has been substantial investigation for decades aimed at performing a preoperative assessment to identify risk (24) early with invasive techniques (27). The value of preoperative pulmonary function testing has been repeatedly called into question (28,29) owing to the added time and expense. Preoperative pulmonary function testing is safe and noninvasive, but should not be routinely performed; rather, it should be limited to a specific indication supported by changes in the anesthetic or surgical procedure (30). Furthermore, the incidence of postoperative pulmonary dysfunction is influenced by the surgical site and the propensity to cause diaphragmatic dysfunction (31,32).
ADDITIONAL PULMONARY FUNCTION TESTS PERTINENT TO THE INTENSIVE CARE UNIT

Lung–Thorax Compliance and Airway Resistance

Physiologists described lung–thorax pressure relationships in normal subjects by defining elastic recoil pressure. With a nose clip and mouthpiece in place, the subject inhaled deeply to TLC and, with an open glottis and no airflow, relaxed against a pressure monitor. The process was repeated in decrements of 200 mL to record the pressure–volume curve of the lung and thorax. The same process can be adapted to the mechanically ventilated patient. In the ventilated patient who is not breathing spontaneously, changes in transpulmonary pressure—and thus lung volume—are achieved by positive pressure applied at the airway by the ventilator. Although some clinicians have suggested the construction of the pressure–volume relationship throughout the tidal breath, the common approach is to deliver a tidal breath—under positive pressure in the range of 8 mL/kg body weight—and measure the resulting airway pressure at two points: the peak inspiratory pressure (flow) and the relaxation pressure with the tidal breath held in the lungs with no airflow. Measurement of these two pressures, the second measurement accomplished with a short inspiratory hold, allows the calculation of lung–thorax compliance and airway resistance (33).

\[ Clt = \frac{P - P_o}{\Delta V} \]  
\[ P = P_{raw} + P_{aw} \]

where \( V \) = tidal volume and \( P = \) relaxation pressure

\[ P_{raw} = P_{IP} - P_{aw} \]  
\[ P_{aw} = P_{inspiratory\,flow} \]

Since \( P_{raw} \) is measured in cm \( H_2O/cm\) and \( P_{aw} \) is constant during lung inflation

\[ Clt (mL/cm\,H_2O) = \frac{P_{raw} (cm\,H_2O/ml/second)}{\Delta V (mL)} \]  
\[ = \text{seconds or time constant for the lung} \]

Tests of Respiratory Muscle Endurance

From the standpoint of a working muscle, endurance is defined as the ability of a muscle to develop tension and sustain it over time; the time–tension index is, therefore, the physiologic manifestation of muscle endurance. For the respiratory muscles, pressure is a manifestation of the ability to generate tension, and the pressure–time product, therefore, correlates with respiratory muscle endurance in the normal subject breathing against a resistive load. Measurement of tidal volume, mean inspiratory mouth pressure, and the duty cycle determine the pressure–time product. Similarly, in the intubated patient, pressures can be measured at the proximal end of the endotracheal tube as an index of the energy necessary to move the lung to a higher volume during positive pressure ventilation (35).

Breathing Patterns

Normal tidal breathing begins at FRC, a point where the tendency for the chest wall to spring outward is balanced by the tendency of the lung to collapse. The balance of these two forces occurs when there is complete apposition of the pleural surfaces. A tidal breath is an energy-transferring mechanism, the reason why expiration is usually a passive phenomenon returning the lung volume to the normal FRC. Tidal excursions occur within the TL-to-RV envelope, and both an inspiratory reserve volume and an expiratory reserve volume are maintained. Patients in respiratory distress alter their tidal breathing patterns according to the added load placed on the respiratory system. Patients with a resistive load will slow inspiratory or expiratory flows and diminish the respiratory rate, in an effort to attain searching for the best combination of rate and tidal volume/flow to work against the imposed load. Patients with alterations in compliance, in a similar manner, reach the best combination of rate and tidal volume, which results in a rapid respiratory rate and smaller tidal volumes.

In the latter patients, tracheal intubation, mechanical ventilation, and the addition of positive end expiratory pressure (PEEP) are used to support the patient. This is often instituted with the observation of rapid, shallow breathing patterns, owing to the propensity to respiratory failure and collapse, a high oxygen cost of breathing, and, finally, hypoxemia and carbon dioxide retention.

The reoccurrence of rapid, shallow breathing is used to assess the ability to wean a patient from positive pressure ventilation. The so-called spontaneous breathing trial involves watching the patient breathe with very low levels of positive pressure support, presumably enough to overcome the endotracheal tube resistance prior to extubation. Thus, rapid shallow breathing patterns, which can be measured by the rapid shallow breathing index (RSBI), are used to assess the feasibility of weaning from ventilatory support (36,37).

SUMMARY

Pulmonary evaluation is a critical step in managing patients with lung disease who are undergoing elective surgeries or are admitted to the ICU for respiratory insufficiency or failure. A few examples of this evaluation are indicated below:
Chapter 69: Perioperative Pulmonary Function Testing and Consultation


References


