The measurement of esophageal pressure (Pes) is a practical approach to measuring changes in intrathoracic pressure for the evaluation of respiratory system mechanics in the assessment of pulmonary physiology and pathophysiology. Pes yields an indirect measure of pleural pressure (Ppl), or, more precisely, the changes in Pes (ΔPes) correspond to pleural pressure (Ppl) oscillations (ΔPpl). Thus, the pressures across the lung and chest wall can be measured, and these measurements, together with volume and flow, allow the respiratory system resistance and compliance to be partitioned into their pulmonary and chest wall components. The measurement of Pes has many uses. The changes in Pes reflect the magnitude of the effort to breathe during spontaneous or machine-aided ventilation and can be used to compute the work of breathing across the lung and external circuit or to calculate the product of pressure developed by the inspiratory muscles and the duration of inspiratory effort.

Pes also help in the interpretation of the end-expiratory wedge pressure under conditions of vigorous hyperpnea or elevated alveolar pressures. Transdiaphragmatic pressure and transmural cardiac pressures can also be calculated from Pes. As examples of recent diverse uses of Pes, it has been demonstrated that (1) a Pes-based strategy resulted in faster patient weaning (1.7 days) than when standard clinical parameters were used; (2) it was possible to initiate pressure-support ventilation based on Pes values; (3) assessment of obstructive sleep apnea-hypopnea syndrome by conventional indices may underestimate the risk of highly negative Pes; and (4) ΔPes measured with a water-filled catheter reflects accurately ΔPpl in preterm infants under positive end-expiratory pressure.

The indirect measurement of Ppl through a balloon placed into the esophagus was proposed in 1878 by Luciani and was subsequently popularized by the work of Buytendijk, published in 1949. Several approaches can be used to make measurements, including air-filled balloon catheters, liquid-filled catheters, and small transducers placed in the esophagus. In addition, ΔPpl can also be estimated from measurement of pressure in the vena cava and over the suprasternal fossa. Finally, although relatively simple and well standardized, the technique for measuring Pes requires special attention to avoid errors and artifacts.

**PRINCIPLES OF MEASUREMENT**

Although not difficult to accomplish, the precise measurement of Pes requires full understanding of certain methodological and theoretical concepts.

**FREQUENCY RESPONSE OF THE MEASURING ASSEMBLY**

The dynamic characteristics of measuring instruments may be described by their frequency response. Consider a signal represented by a square wave (Figure 55-1). Under ideal circumstances the recording apparatus should provide a true representation of the original signal. An overdamped recording device modifies the signal, smoothing out sharp corners and delaying the rise and fall of the input wave. On the other hand, for the same input signal an underdamped apparatus generates an output wave that oscillates disproportionately after each transient. When the catheter is connected to a pressure transducer and the input and output signals are compared, the two should follow each other faithfully up to a frequency of at least 15 Hz. Stated otherwise, the entire system should have a flat response up to 15 Hz. The measuring assembly should not delay the pressure signal. In other words, Pes should not lag behind the pressure measured at the airway opening (Pao) and vice versa (Figure 55-2). One should be able to achieve signals that are in phase up to frequencies as high as 32 Hz.

Another important aspect of a pressure measuring device is represented by its common mode rejection ratio. When a differential pressure transducer has both its chambers identically pressurized, the resulting signal should be nil. No pressure transients should be observed when the chambers of the transducer are compressed or decompressed simultaneously to the same degree.

Both the frequency response and common mode rejection characteristics need to be determined in order to ensure that an adequate measuring system is being used to register Pes.

**COMPLIANCE AND RESISTANCE OF THE MEASURING ASSEMBLY**

In addition to the above-mentioned factors, the compliance and resistance of the experimental circuit may also serve to distort the measurements. For instance, a very compliant
A piece of rubber tubing or connection added in series to the esophageal balloon catheter or air bubbles in the liquid-filled catheter will dampen the pressure signal. The tubing and connectors should not be too narrow because the increased resistance may also impair the rapid transmission of pressure at the site of measurement to the recording device.

**ANALOG-TO-DIGITAL CONVERSION**

The output of the transducer is in the form of an analog signal, which is usually either a change in voltage or current. With the aid of an analog-to-digital (A-D) converter, a continuous electrical signal can be converted to a discrete digital format in order to be processed by computer. Ideally, the interval between each sample should be as small as possible so that the digital data points closely approximate the analog signal. The faster the changes in the input signal, the higher the sampling frequency needs to be. Likewise, the better the resolution of the A-D converter, the closer the points will be spaced on the y-axis (Figure 55-3). Basically, the resolution improves as the number of bits of the A-D converter increases.

**SETTING UP THE MEASURING SYSTEM**

Once the investigator is assured that the recording system is working properly, there are a number of important considerations related to instrumenting the subject. As is discussed
in detail below, there are three most commonly used methods to determine esophageal pressure—esophageal balloon, liquid-filled catheter, and microtip transducer—and all require adequate positioning within the esophagus. This section reviews the care of the experimental subject and the methods to assess proper positioning of the device. The esophageal balloon catheter is discussed because it is the most frequently used device and is the largest of the three devices.

Preparation for the Test
If infants and children are to be examined, the physical and psychological preparation depends on the age, interests, previous experience, and level of trust. The subject must be told how the test is performed, that is, that a tube will be passed through his or her mouth or nose into the stomach and then pulled slowly back into the esophagus, and that it will remain there for a certain amount of time. Additionally, he or she must be advised that a gagging sensation may be experienced when the tube is inserted. At this point the subject should swallow a mouthful of water through a straw from a glass, as previously instructed. If the gagging sensation is excessive, topical anesthesia should be applied to the oropharynx. Care may need to be taken in some cases to avoid the risk of aspiration of saliva, food, or fluids.

Finally, the common causes of swallowing difficulty may require physician supervision of the balloon placement. Disorders of the mouth and pharynx, such as obstruction to the passage of food or liquid (eg, emotional or anxiety disorder, tumors, cervical spine disease, or pharyngoesophageal diverticulum), and neuromuscular problems (eg, stroke, Parkinson’s disease, Huntington’s disease, multiple sclerosis, myasthenia gravis, muscular dystrophy, polymyositis, or amyotrophic lateral sclerosis) may cause problems. Esophageal pathology, such as to cause obstruction to the passage of food or liquid (eg, tumor, strictures secondary to radiation or chemical burns, medications or ulcers, Schatzki’s ring, or foreign bodies), or neuromuscular problems (eg, achalasia, diffuse esophageal spasm, hypertensive lower esophageal sphincter, or scleroderma) may also make balloon passage difficult.

Introducing the Measuring Device into the Esophagus
When the subject is relaxed and understands the instructions, a rough estimate of the length of the catheter from the nostril to the stomach is taken, and a mark is placed on the catheter with a marker pen. About 3 mL of topical anesthetic is administered with a syringe into the more patent of the two nostrils, and the subject is asked to sniff deeply and pull the catheter with a marker pen. The catheter is then withdrawn slowly until a negative pressure deflection is identified; the upper part of the balloon is now in the thoracic esophagus. The catheter is then withdrawn a further 10 cm, at which point the whole balloon should be in the esophagus, at a distance ranging from 35 to 45 cm from the nares. In this site, the top of the balloon is about midway between the apex and the base of the lung.

Balloon Positioning
Once the empty balloon catheter is in the stomach, 0.5 mL of air should be injected into the system, and the catheter is connected to a pressure transducer. During spontaneous breathing, positive pressure swings during inspiratory efforts confirm that the balloon is located in the stomach. The catheter is then withdrawn slowly until a negative pressure deflection is identified; the upper part of the balloon is now in the thoracic esophagus. The catheter is then withdrawn a further 10 cm, at which point the whole balloon should be in the esophagus, at a distance ranging from 35 to 45 cm from the nares. This site, the top of the balloon is about midway between the apex and the base of the lung.

Balloon volume should be checked again before proceeding further. For such purpose the balloon is emptied either by gently pulling on a glass syringe or more adequately by having the subject perform a Valsalva maneuver or a series of coughs. Five milliliters of air is injected into the balloon via a syringe, and 4.5 mL is subsequently withdrawn. Following maneuvers resulting in large changes in intraesophageal pressure, it is a good idea to recheck balloon volume to ensure that leaks in the system have not allowed the balloon to deflate.

To validate the measurement of ΔPes as a reflection of ΔPpl, a comparison of changes in Pes (ΔPes) and the changes in airway opening pressure (ΔPao) is made during voluntary static Valsalva and Muller maneuvers while keeping the glottis open. The position of the esophageal catheter is considered acceptable when there is good agreement between the two pressure swings. In many patients and untrained volunteers, this maneuver may be difficult to perform because of glottic closure, poor coordination, and so on. Furthermore, this procedure cannot be used in children, during anesthesia, or in very sick patients. An alternative is to compare ΔPes and ΔPao during spontaneous efforts made against a closed airway. This dynamic “occlusion test” has been validated in normal awake adults in different body positions. The test consists of occluding a subject’s airway at end-expiration while measuring Pes and Pao during three to five spontaneous inspiratory efforts (Figure 55-4). When the balloon is ideally positioned, the ratio between ΔPes and ΔPao should be close to unity throughout the inspiratory efforts, that is, no net change in the transpulmonary pressure should occur since no flow and change in volume are permitted by the closed airway, and hence, pressure losses across the lungs are negligible. In addition, when ΔPes is plotted against ΔPao, a closed loop indicates that there is no phase lag between the two signals (see Figure 55-4). Baydur and colleagues studied 10 healthy seated subjects, each of whom swallowed a balloon 5 cm long positioned in the middle and lower esophagus. The mean ΔPes/ΔPao ratio amounted to 1.04 (range 0.99–1.10). When examined in various postures, the ratio remained close to unity in both right (mean 1.02; range 0.94–1.10) and left (mean 0.98;
range 0.86–1.08) lateral decubitus. In the supine position this was not always the case, although a satisfactory ∆Pes/∆Pao ratio (between 0.86 and 1.10) could be obtained in all supine subjects by repositioning the balloon at different levels of the esophagus (5–15 cm from the cardio-esophageal junction). Similar results have been found in 10 supine patients undergoing general anesthesia, as well as in semirecumbent patients with chronic obstructive pulmonary disease (COPD) in acute respiratory failure. In both of these latter studies the patients were intubated, and hence there were no problems of transmission of alveolar pressure to the airway opening. This is not always the case, and, accordingly, the static Valsalva and Müller maneuvers must substitute for the dynamic occlusion test.

The dynamic occlusion test has also been carried out in neonates. Using a balloon catheter system with an adequate frequency response, Beardsmore and colleagues were able to obtain a satisfactory ∆Pes/∆Pao ratio in the lateral position. However, they emphasized the necessity to use an “ideal” balloon to obtain satisfactory recordings and described the painstaking procedures and difficulties in achieving good performance of their balloon system in neonates. Milner and colleagues found that in the supine position ∆Pes tended to be smaller than ∆Pao by an average of about 20% and showed an intrasubject variability of 20%. However, a 1 mm–wide esophageal catheter was used, which may have made the frequency response of their esophageal balloon catheter system inadequate (overdamping ∆Pes).

The occlusion test can be applied even in paralyzed subjects because, although unable to generate respiratory efforts, they can be subjected to external applied pressure changes around the thorax. As with spontaneously breathing human subjects, the airway is occluded and the body surface pressure is varied while recording Pes and Pao. When studies involving partitioning of respiratory mechanics are envisaged in patients that will necessitate administration of neuromuscular blocking agents, the positioning of an esophageal balloon catheter should be performed before neuromuscular blockade, while the patient is still breathing spontaneously.

In conclusion, since 1982, the dynamic occlusion test has been used in patients requiring mechanical ventilation, in anesthetized patients, in normal volunteers, and in awake and anesthetized animals.

**ESOPHAGEAL BALLOON METHOD**

Air-containing latex balloons sealed over catheters, which, in turn, transmit the balloon pressure to transducers, are the most widely used means for measuring Pes. Details for constructing such balloon catheter systems have been published. Ideally, the balloon perimeter should correspond to that of the esophagus (4–4.8 cm for human adults). In practice, 0.1 mm–thick, 5 to 10 cm–long latex balloons with perimeters varying between 3.2 and 4.8 cm have been found to be adequate. In adult studies, polyethylene catheters with an internal diameter of 1.4 mm (PE-200) and a length of 100 cm are conventionally used. When the speed of pressure changes is very high, such as occurs in the determination of frequency dependence of respiratory compliance, the frequency response of the balloon catheter system can be improved by increasing the internal diameter of the catheter to 1.7 mm or by filling the balloon catheter system with a gas of lower density than air (helium, for instance).

Although respiratory frequencies are higher in newborns than in adults, catheters of smaller internal diameters (1–1.2 mm) have been commonly used in the former which may have led to the underestimation of Pes. At high respiratory frequencies the catheter should have a relatively high internal diameter (1.4–1.7 mm) but be as short as possible.

Finally, spirally arranged holes should be made over the entire portion of the catheter covered by the balloon because the gas in the balloon tends to the site of most negative pressure. If there is no hole in this location, there will be no communication between the gas in the balloon and the

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**FIGURE 55-4**  A, Tracing of volume (V), transpulmonary (Ptp), esophageal (Pes), and mouth pressures (Pm) during a dynamic “occlusion test” in a seated normal subject. B, Plot of ∆Pes versus ∆Pm for the first occluded inspiratory effort in A. Line of identity is indicated by the broken line. Reproduced with permission from Baydur A et al.
catheter-manometer system, and the measurement of Pes will not be correct.

The optimal volume of gas in the esophageal balloon has been determined to be around 0.5 mL of air, but the range of working gas volumes must be determined. For such determination, a three-way stopcock is connected to the distal end of the catheter and left open to the atmosphere. A pressure transducer is attached to the other port of the stopcock. The balloon is emptied by submerging it in water. Thereafter, the stopcock is positioned to connect the pressure transducer to the balloon catheter assembly. With a calibrated syringe gas is introduced into the system in 0.1 mL steps and a volume-pressure curve is constructed. One observes a range of volumes over which balloon pressure does not change appreciably. In most instances the balloon working range encompasses the 0.5 mL volume, the amount of gas generally used.

LIQUID-FILLED CATHETER METHOD

The liquid-filled catheter method has been used for many years, mainly in neonates and small animals, and it has the advantage of a high-frequency response because of rapid pressure transmission through a noncompressible fluid (usually water or saline solution). It thus follows that catheters narrower (internal diameter 1 mm) than those onto which esophageal balloons are mounted can be used without loss of fidelity of measurements. The discomfort for the baby is minimized by such small-bore tubes.

There are some disadvantages associated with liquid-filled catheters, such as the difficulty in obtaining absolute values of Pes because of hydrostatic factors. Additionally, its distal end must be provided with several holes to avoid mucus plugging of the catheter. For the same reason, intermittent flushing of the catheter is required. A constant infusion of liquid at a slow rate (10 mL/h) from a syringe pump can be used, which also serves to keep the catheter free of gas bubbles that might overdamp the recorded pressure.

Validation of the liquid-filled catheter method has been performed using the dynamic occlusion test in healthy full-term newborns. Measurements were made during quiet sleeping or resting wakefulness in right lateral, prone, and supine positions. The group average ΔPao was less than ΔPes by only 1.6% (range 0–3.3%). During the occlusion test, preterm neonates studied with the water-filled catheter system also had a finite region of the esophagus where ΔPes equaled ΔPao. Using an “ideal” balloon catheter system, a decrease in ΔPes relative to ΔPao of up to 6% has been observed. Using the same test, the results of Asher and colleagues were confirmed on supine healthy full-term babies during quiet sleep, whereas during rapid eye movement (REM) sleep, agreement between ΔPes and ΔPao was not assured. The latter applied in all instances to preterm babies. The discrepancies between occluded ΔPes and ΔPao were attributed to uneven distribution of Pes swings as a result of distortion caused by the highly compliant chest wall of newborns. The liquid-filled catheter method also has application in small animals. As predicted, both narrow and wide short (30 cm long) catheters are reliable, and the correct catheter placement can be established using the dynamic occlusion test.

SMALL TRANSDUCER METHOD

Microtransducers placed directly into the esophagus also provide reliable assessments of Pes. A comparison of a 5F catheter-tip pressure transducer in the esophagus and a solid-state pressure transducer measuring Pao, both systems sharing a high-frequency response, has shown close concordance of ΔPes/ΔPao during an occlusion test. The slope of the relationship averaged 0.999, indicating that the microtip transducer was adequately recording Pes up to a frequency of 50 Hz.

CONTRAINTS IN MEASURING ESOPHAGEAL PRESSURE

Cardiac Artifacts

Changes in intrathoracic pressure caused by the beating of the heart appear on recordings of esophageal pressure, irrespective of the devices used to make the measurements. The noise, termed “cardiac artifact,” is particularly prominent in normal subjects during resting breathing. Cardiac artifact can be minimized by using balloons shorter than 10 cm and with a large perimeter (4.8 cm) and by choosing a suitable locus in the esophagus. Alternatively, the pressures may be measured at fixed times of the cardiac cycle and ensemble averaged using a personal computer (Figure 55-5). When the artifact results from the use of a catheter-tip pressure transducer it can be markedly reduced by rotating the catheter.

FIGURE 55-5 Left, tracing of flow (V), transpulmonary (PL) and esophageal (Pes) pressures, and volume (V) obtained during three consecutive breaths in an anesthetized paralyzed subject. Right, ensemble average of records form 35 consecutive breaths gathered under the same conditions as in Left. Reproduced with permission from D’Angelo E et al.
UNEVEN DISTRIBUTION OF PLEURAL SURFACE PRESSURE

Pleural pressure is not uniform but has a gradient from top to bottom reflecting gravity and chest wall configuration. Despite this fact, Pes, as sampled at a single site in the esophagus, provides a reasonable estimate of pressure for the assessment of the mechanical properties of the lung and chest wall because swings in pressure are similar over the entire pleural surface. In the upright position, the esophageal balloon technique measures Pes from a site near the midlevel of the lung. This region is close to the point where the changes in regional lung volume are equal to those in overall lung volume. In fact, it has been demonstrated that at lung volumes greater than functional residual capacity (FRC), the regional and overall volume-pressure curves of the lung are virtually superimposed, indicating that at these lung volumes Pes measured with the esophageal balloon closely reflects the static mechanical properties of the lung. Below FRC, where small airway closure is known to occur in dependent lung zones, Pes cannot be interpreted as reflecting the intrinsic elastic properties of the lung. At low lung volumes, compression of the esophagus by the mediastinal structures may cause Pes to deviate from the true Ppl (see below). Although measurement of Pes in body postures other than the upright may be subject to similar problems to the supine, the shape of the V-P curves of the lungs is virtually identical in all postures. Consequently, it can be concluded that independent of body posture, measurements of Pes can provide accurate values of the changes in overall static Ppl with lung volume.

The dynamic occlusion test indicates that in general during spontaneous breathing the dynamic changes of Pes closely reflect the corresponding changes in Ppl, even in different postures. In addition, it has been found that ΔPes reflects ΔPpl after muscle paralysis. Therefore, it is not necessary to repeat the occlusion test after paralysis if its result is acceptable in the nonparalyzed state.

ESOPHAGEAL DISTORTION AND CONTRACTION

If the tissues interposed between the pleural space and the esophageal lumen are flaccid, ΔPpl should be transmitted without attenuation to the esophageal lumen, and ΔPes/ΔPao would equal 1.0 during an occlusion test. Thus, some investigators attribute their difficulty in properly recording Pes in the supine position to esophageal compression by the mediastinal contents. However, if changes in posture alter the pressures acting on the rib cage and distort the esophageal and mediastinal soft tissues, the estimate of ΔPpl may be affected.

Esophageal contraction (peristalsis) may not only affect the baseline value of Pes, but the amplitude of ΔPes may also be altered. However, these contractions are easily detected, and no data should be obtained until Pes returns to its baseline value. Nevertheless, esophageal contractions may occur following the administration of certain drugs, such as methacholine, and may hinder the recording of Pes.

TRANSMISSION OF ALVEOLAR PRESSURE TO THE AIRWAY OPENING

Poor transmission of the changes in alveolar pressure (Palv) to the airway opening is a potential major source of time delay between ΔPpl and ΔPao. The speed with which Palv is conveyed to the airway opening depends on the flow resistance offered by the airways and the compliance of the extrathoracic airways (equipment included). The latter depends partly on the compressibility of the gas in the extrathoracic airways (including mouthpiece, tracheal tube, etc), as well as on the structural (tissue) compliance of the upper airways (cheeks, pharynx, base of the oral cavity, etc). In practice, the compressibility of the gas in the extrathoracic airways causes essentially no problems in terms of transmission of Palv to the airway opening. The tissue compliance of the upper airway is considerably greater than that of gas, especially when cheeks or other structures are not supported, but again essentially no problem of transmission of Palv to the airway opening can be detected.

However, in patients with severe airways obstruction there is often a considerable delay in the transmission of Palv to the mouth. Under these circumstances ΔPao underestimates ΔPalv, and dynamic occluded ΔPao underestimates the concomitant ΔPes.

The delay in the transmission of Palv to the mouth resulting from incorrect assembly setup is a different entity from the difference between Palv and Pao caused by “intrinsic” or “auto positive end-expiratory pressure” (PEEPi). The latter condition is most likely to occur in clinical situations of increased resistance or compliance (less elastic recoil) and short expiratory times. Thus, airflow does not cease at the end of expiration but continues slowly as increased alveolar pressure decompresses through dynamically narrowed airways, and hence there is not enough time for the equilibration between Palv and Pao. Under these conditions, the initiation of a spontaneous breath requires the patient to generate sufficient inspiratory force to counterbalance dynamic PEEPi. Under these circumstances, if the dynamic occlusion test fails one can ask the patient to slow down his or her breathing frequency and repeat the test. If the occlusion test is still inaccurate, the static Valsalva and Müller maneuvers should be used, as discussed above.

COMPARISON BETWEEN PLEURAL AND ESOPHAGEAL PRESSURES

Studies comparing Ppl and Pes have produced conflicting results. Some of these discrepancies may result from differences between the pleural and esophageal catheters used, adequate placement of the esophageal balloon, or the measurements of Ppl in regions distant from the periesophageal pleural space.

Several studies using air-filled needles introduced into the lateral pleural space found significant differences between absolute Pes and Ppl. Cherniack and colleagues found more negative pressures in the pleural space than in the esophagus, although inspiratory ΔPpl and ΔPes were similar. Daly and Bondurant reported that ΔPpl in most regions of the rib cage were not equal to ΔPes until a small
amount of air was introduced intrapleurally.\textsuperscript{71} When Ppl was recorded directly from an air-filled catheter system, it was higher than Pes in the lateral decubitus, but no significant difference was found in either prone or supine dogs.\textsuperscript{72} However, when air-filled catheters or needles are used, recorded Ppl may be distorted by the presence of an air–liquid interface between the measuring device and the pleural liquid.\textsuperscript{73} In addition, pressures measured by means of liquid-filled catheters may represent liquid rather than surface pressures.\textsuperscript{74,75}

An assortment of liquid- and air-filled balloon-like devices have been used to measure Ppl in a manner approximating the esophageal balloon technique.\textsuperscript{76–79} Hurewitz and colleagues used perfectly matched pleural and esophageal latex balloons and were able to demonstrate an excellent correlation between Pes and Ppl, as well as between $\Delta$Pes and $\Delta$Ppl.\textsuperscript{77} Wohl and colleagues employed mushroom catheters in paralyzed ventilated dogs and reported only a small difference between Pes and Ppl.\textsuperscript{79} Nevertheless, the discrepancies between direct determinations of pleural and esophageal pressures have not been as yet completely resolved. On the other hand, there is good evidence that $\Delta$Ppl is accurately tracked by $\Delta$Pes.\textsuperscript{20,21–24,42,48}

**CONCLUSIONS**

The indirect determination of changes in pleural pressure via the esophageal pressure forms the basis for the assessment of respiratory system mechanics in the pulmonary function laboratory and in experimental physiology. Several methods for measuring changes in esophageal pressure can be safely employed in both human subjects of all ages and experimental animals. Although the assessment of respiratory mechanics in patients is usually accomplished by noninvasive means, the evaluation of certain pathologies, in particular those associated with restrictive ventilatory impairment and mixed restrictive and obstructive impairment as well as suspected occupational lung disease, may still require direct assessment of the mechanical properties of the lungs. A thorough knowledge of the methodology involved is essential so that reliable measurements are obtained.

**REFERENCES**


