Pleural Manometry*

Technique and Clinical Implications

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Introduction: Pleural manometry during large-volume thoracentesis can prevent the development of excessively negative pleural pressures, which have been associated with re-expansion pulmonary edema; can diagnose an unexpandable lung; and can predict pleurodesis success. We currently perform pleural manometry simultaneously with both a vertical-column water manometer with an interposed resistive element, and a hemodynamic transducer connected to a standard physiologic system. We present the technique as well as the advantages and disadvantages of both systems in measuring pleural liquid pressures.

Technique: A flexible thoracentesis catheter is inserted in the most dependent portion of the pleural effusion. The water manometer consists of two lengths of IV tubing connected through a 22-gauge needle inserted into an injection terminal. The system is connected to the zeroing port of the pressure transducer, and both are carefully purged of air. The electronic system is zeroed at the level the thoracentesis catheter is introduced into the patient. Measurements are performed initially and after each 250 mL of fluid that is withdrawn.

Accuracy of the water manometer: Forty consecutive patients who underwent therapeutic thoracentesis had pressure measurements. Pleural fluid removed ranged from 50 to 4,200 mL (mean, 1,445 mL). A total of 291 pressure measurements were acquired and analyzed. Mean pleural liquid pressure obtained by the water manometer had a strong positive correlation with the values obtained by a standard physiologic system ($r = 0.97$, $p < 0.001$).

Conclusion: An overdamped water manometer is a valid method to measure mean pleural liquid pressure. Coughing invalidates pressure measurements with the water manometer; however, with the electronic method, periods of quiet breathing can be identified, allowing for the measurement of pleural pressure.

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Key words: pleural effusion; pleural manometry; pleural pressure; thoracentesis; trapped lung

Abbreviations: $P_{el}$ = pleural space elastance; RPE = reexpansion pulmonary edema

The monitoring of pleural liquid pressure during large-volume thoracentesis has been advocated to prevent the excessive development of negative pressures that cannot be readily detected by the operator withdrawing the fluid. Excessively negative pleural pressures have been associated with the development of re-expansion pulmonary edema (RPE). The recommendation is not to exceed $–20$ cm H$_2$O. In addition to simple pressure monitoring, pressure change in relation to the volume of fluid withdrawn has been reported as pleural space elastance ($P_{el}$). $P_{el}$ has been found to correlate with the likelihood of successful chemical pleurodesis, and $P_{el}$ may also be helpful for the detection of unexpandable lung.

Previous investigators$^{1–4}$ performed pleural manometry using an underdamped U-shaped water manometer, and they reported pressures as the mean of the oscillating water column. The advantage of water manometers is their conceptual simplicity. The disadvantages are primarily related to the difficulty in reading accurate values from the oscillating water column and the unfavorable physical characteristics of water manometers. It is impossible to construct a water manometer with the frequency response characteristics required for accurate measurement of pleural pressure oscillations.
cultures are primarily related to inertia and flow resistance when water is used as an indicator. However, water manometry may be used to measure mean pressures directly by overdamping the manometer using an interposed resistor. Pressure oscillations may not be measured by such a system. Manometry systems useful for measurement of pressure oscillations require a transducer element with minimal displacement if aqueous solutions are used as a coupling medium. Typical hemodynamic transducers, as used in ICUs, are more than adequate for this purpose, and are conveniently supplied with the appropriate sterile connecting tubing. If only measurement of mean pressures is desired, an overdamped water manometer is all that is required.

If measurement of pressure oscillations is desired, hemodynamic transducers may be connected to a typical physiologic measurement system consisting of a signal conditioner and a display or data acquisition system. Such a system, properly calibrated, is the reference standard, but is not readily available to most clinicians.

Alternatively, standard hemodynamic monitors may be utilized. This circumvents the unfamiliar calibration and zeroing procedures necessary in a reference system but poses other unique problems. In particular, the software of hemodynamic monitors cannot process negative pressures, and numerical values may be erroneous due to software optimized for hemodynamic signals. Transducing negative pressure can be prevented by first zeroing the system, and then creating an offset by moving the transducer by a known distance to a lower level. The fluid column in the tubing between the patient and transducer will create a positive pressure offset proportional to the vertical distance that the transducer is moved. If the transducer is moved downward by a sufficient distance, negative pressures will not be transduced during any part of the respiratory cycle. Obviously, the offset must later be subtracted from the recorded signal if absolute values are needed; changes in pressure are, of course, unaffected by the offset. Hemodynamic pressures are reported in millimeters of mercury, whereas pleural pressure is traditionally reported in centimeters of water, necessitating the use of a correction factor.

At the Medical University of South Carolina, we routinely use an electronic transducer system and an overdamped water manometer simultaneously. The water manometer is needed for calibration of the electronic system and becomes a convenient device for real-time display of mean pleural liquid pressure when a resistor is interposed. The water manometer may be used alone if an operator experienced with the electronic system is not available. The vast majority of the pleural liquid pressures are acquired with both systems, which provides us with a means to ensure quality and reliability of the measurements.

Materials and Methods

Technique

All patients who are capable are placed in the sitting position. A flexible thoracentesis catheter (Pleura-Seal thoracentesis kit AK-01000; Arrow-Clark; Reading, PA) is inserted using the standard technique; the catheter is inserted in the dependent part of the pleural effusion as determined by thoracic ultrasonography. Safety of access site is the only consideration for catheter placement.

The water manometer consists of two lengths of IV tubing connected through a 22-gauge needle inserted into an injection terminal (Fig 1). The tubing from the thoracentesis catheter to the measuring scale extends 40 to 50 cm below the level of the catheter insertion into the chest similar to a U-shaped water manometer. The system is carefully purged of air with normal saline solution and connected to the zeroing port of the pressure transducer (Vascular Transducer 041576504A; Argon Medical; Athens, TX). The thoracentesis catheter and the transducer assembly are carefully purged of air prior to connection of the water manometer.

A carrier demodulator (model CD 19A; Validyne Engineering; Northridge, CA), in conjunction with a vascular pressure transducer (Argon Medical), is used for electronic signal generation. A personal computer data acquisition system (Biobench 1.0; National Instruments; Austin, TX) is used to obtain and store the electronic pressure signal. The pressure signal is sampled at a rate of 50 times per second (Fig 2).

The electronic pressure signal is calibrated against the water standard. The vertical reference point for a pressure of zero is arbitrarily defined at the level at which the thoracentesis catheter is inserted into the chest.

Measurements are performed initially and for every 250 mL fluid withdrawn thereafter. If unexpandable lung is suspected, smaller aliquots are used at the clinician’s discretion.

Data acquisition is terminated after a satisfactory tracing is obtained and the water manometer has stabilized. The water manometer usually stabilizes in 30 s, and the mean pleural liquid pressure is immediately recorded. The water column usually oscillates with amplitude of 2 to 4 mm H2O around the mean.

Fifteen to 20 respiratory cycles are recorded with the electronic data acquisition system for each aliquot. For the electronic method, a satisfactory tracing is defined by a group of at least four
Clinical Investigations

The pressure measurements were classified into three groups (initial, middle, and terminal). Pressure measurements obtained from the onset to when one third of the volume was removed were considered the initial values. Pressures measured between one third and two thirds of volume removed were analyzed in the middle group. The pressures obtained after two thirds of volume was removed to the conclusion of the thoracentesis were analyzed in the terminal group.

In the initial group, 113 pressure measurements were analyzed by linear regression with a calculated $r$ value of 0.96 ($p < 0.001$). In the middle group, 108 pressure measurements were analyzed with a calculated $r$ value of 0.97 ($p < 0.001$). In the terminal portion of the thoracentesis, 70 pressure measurements were analyzed with a calculated $r$ value of 0.98 ($p < 0.001$) [Table 1]. Figure 3 is a linear plot of the 291 mean pleural liquid pressures acquired by the digital signal compared to the water manometer.

Pressure measurement recording by water manometry was discontinued when patients began coughing. This explains why more pressure measurements were recorded in the initial group compared to the middle and terminal groups.

### Table 1—Pleural Pressure Measurements for the Initial, Middle, and Terminal Portions of the Pleural Pressure/Volume Curve

<table>
<thead>
<tr>
<th>Portions</th>
<th>Measurements, No.</th>
<th>$r$ Value</th>
<th>$p$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>113</td>
<td>0.96</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Middle</td>
<td>108</td>
<td>0.97</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Terminal</td>
<td>70</td>
<td>0.98</td>
<td>&lt; 0.001</td>
</tr>
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**Discussion**

The direct measurement of pleural pressures in the normal pleural space is technically challenging due to the close approximation of the parietal and visceral pleura. Any device, such as a catheter, introduced into the normal pleural space will lead to distortion of the normal pleural space geometry and the resulting deformation forces will result in the measured pressure not being representative of the pressure prior to the introduction of the device.

The conditions differ in the presence of a pleural effusion. An introduced catheter will not result in geometric distortion of the local pleural space and consequently will not result in local deformation forces that influence pressure. Furthermore, an abnormally wide pleural space filled with fluid is characterized by a hydrostatic gradient because in this situation viscous flow resistance is negligible.

Therefore, pressure measured with a catheter residing in a pleural effusion is representative of the actual pressure at that particular level of the effusion; any changes of the pressure during respiration are representative of pressure changes elsewhere in the effusion. Pressure measured in this fashion and referenced to an external vertical level will reflect recoil forces of the lung and chest wall and the vertical extent of the effusion.

Under dynamic conditions, during respiration, pressure changes result from two different mechanisms: forces developed by respiratory muscles attenuated by the inflow of air into the lung, and...
vertical displacement of the fluid collection due to periodical changes in chest geometry. Pressure changes caused by withdrawal of fluid are due to elastic forces originating in the lung and chest wall, altered by changes in the geometry of the pleural space; vertical displacement of the fluid collection caused by the geometrical changes; and diminishing vertical extent of the fluid collection. At the end of drainage, local deformation forces around the catheter or of the catheter system itself dominate any other mechanism.

It is obvious that pressure inside a pleural effusion, especially during thoracentesis, is determined by several factors that cannot readily be separated. Clinically, obtaining information about the elastic characteristics of the pleural space is the objective of pleural space manometry. One solution to obtaining this information would be replacing the fluid with a gas and measuring pneumatic pressure while the gas is removed. Although likely safe, this is impractical in clinical practice.

However, changes in liquid pressure during fluid withdrawal may be an adequate correlate of pressure changes due solely to elastic recoil. Assuming there is a relatively constant quantitative influence of the hydrostatic effects between patients, differences should be a result of differences in pleural space elastic recoil. With this assumption, the measured pressures may be interpreted as if caused by changes in recoil forces alone. Pleural liquid pressure changes due to fluid withdrawal may then be assessed in relation to the amount of fluid withdrawn, and an analog of true elastance may be calculated. Finally, when attempting to use pleural manometry, it must be considered that any pressure in the pleural space without sufficient fluid for a catheter to freely float is representative only of the pressure in the area immediately surrounding the catheter.

We have described the instrumentation and calibration methods for acquiring mean pleural liquid pressure for an overdamped water manometer and an electronic reference system. We currently acquire pleural liquid pressures simultaneously with both systems. This has provided us the opportunity to ensure internal quality and reliability of the data. Each system can be used independently, and both are valid methods of acquiring pleural liquid pressure.

Separation of the pressure measurements into three groups was necessary to establish the accuracy of the water manometer during the terminal portion of the thoracentesis. We have previously reported that the amplitude of the pressure signal increases as pleural fluid is withdrawn. The increase in the signal amplitude is related to a larger change in the end-inspiratory pressures when compared to the change in the end-expiratory pressure as fluid is withdrawn. The improvement in the mechanical efficiency of the diaphragm during thoracentesis is the reason for the increase in the signal amplitude. Therefore, it can be argued that the increase in the pressure amplitude as fluid is withdrawn could affect the accuracy of the mean pressures obtained by the water manometer during the terminal portion of the thoracentesis.

The advantage of the electronic system is that it allows for the acquisition of pleural liquid pressures in patients with intermittent coughing. With the electronic method, periods of quiet breathing can be identified, and mean pleural liquid pressure can be calculated. The major drawbacks of the electronic system center on the complexity of operation and calibration. In addition, the calculation of mean pleural liquid pressure by the electronic signal can only be performed after acquisition. In comparison, the major advantage of the overdamped water manometer is its simplicity in setup and the lack of required calibration. The results of water manometry are immediately available and do not require further analysis. However, coughing renders this system unreliable.

The characterization of the mechanical properties of the diseased pleural space is of clinical value. Characterizing the change in pressure to volume of pleural fluid removed, defined as pleural space elastance, provides diagnostic information relating to the immediate expandability of the lung. When pressure/volume curves are constructed, we have observed that the curves are approximately linear for both an expandable and an unexpandable lung. When minimal amounts of pleural fluid remain, a...
deflection point occurs in all subjects. The deflection is due to shape mismatch between lung and chest wall. The slope of the pressure/volume curve prior to this terminal deflection provides diagnostic information pertaining to the expandability of the lung.

The pressure/volume curve of a normally expandable lung is characterized by a gradual decrease in pressure. The slope steepens only at the very end of drainage, and the PEL is $< 19 \text{ cm H}_2\text{O/L.}^2$

For practical purposes, we subdivide unexpandable lung due to pleural disease into two categories. The first category is trapped lung, which we consider a diagnosis. The pathogenesis of a trapped lung is related to a remote inflammatory process resulting in the formation of an irreducible pleural space due to the formation of a fibrous visceral pleural peel.\(^{19,20}\) The inflammation itself must have resolved in order to make the diagnosis of trapped lung. Consequently, the clinical presentation of trapped lung is a chronic, undiagnosed pleural effusion that most often is asymptomatic but may result in dyspnea. Pleural fluid formation in trapped lung results from an imbalance of hydrostatic forces. Pleural fluid analysis reveals a transudate. The chest radiograph shows no contralateral shift of the mediastinum. The initial mean pleural liquid pressure is always negative. The pressure/volume curve of trapped lung is linear but with a steep slope over all intervals of fluid removal. Initial PEL, where elastance is defined as the change in pressure to volume removed, is high and usually $> 25 \text{ cm H}_2\text{O/L.}^1,^3$

The second category includes any active inflammatory or malignant pleural disease leading to visceral pleural restriction preventing normal lung expansion. We use the terms lung entrapment or entrapped lung to describe this category. Entrapped lung, in our definition, is a mechanical complication of active pleural disease. In our experience, lung entrapment due to active pleural disease, especially malignancy, is far more common than trapped lung. Lung entrapment may resolve with specific therapy directed at the underlying pleural disease. The clinical presentation is often dominated by the active pleural process itself, and entrapment is usually appreciated only with fluid removal. The chest radiograph may show contralateral mediastinal shift. Initial mean pleural liquid pressure is usually positive, and initial PEL may be normal or high. The initial slope of the pressure/volume curve may be normal; however, once a critical volume is removed, the slope of the curve becomes steeper, reflecting a restricted pleural space at lower volumes. Figure 4 illustrates the pressure/volume curves of a normally expanding lung, a trapped lung, and an entrapped lung with a biphasic pressure/volume curve.

By demonstrating lung entrapment, pleural manometry can assist in the management of malignant pleural effusion and predict the success of pleurodesis.\(^2\) Patients with malignant pleural effusions with a PEL $\geq 19 \text{ cm H}_2\text{O/L had poor pleurodesis success with bleomycin administered through a thoracostomy tube.}^2$ This group, however, can be successfully palliated with the placement of a chronic indwelling catheter, where the patient intermittently removes a volume of fluid to relieve dyspnea.

We also use pleural manometry as a guide to terminate the removal of pleural fluid. One of the complications of removing large amounts of pleural fluid is RPE.\(^{21-23}\) RPE is correlated with increasing negative pleural pressure. Previous studies\(^{24,25}\) in animal models found that $-20 \text{ cm H}_2\text{O was safe, and } -40 \text{ cm H}_2\text{O was associated with a high risk in the development of RPE.}$ We arbitrarily terminate fluid removal when the mean pleural liquid pressure exceeds $-20 \text{ cm H}_2\text{O.}$ In addition, the development of chest pain is a criterion that we use to terminate fluid removal. Using this criterion, the development of clinically significant RPE has not occurred in $> 200$ patients.

Currently, pleural manometry is not used by practicing pulmonologists. Water manometry with an overdamped system is simple, and provides accurate estimates of mean pleural liquid pressure. In addition, the incorporation of the resistor eliminates concerns such as aspiration of air into the pleural space and spillage during coughing.
In summary, a vertical column water manometer with a 22-gauge needle acting as a resistor is a simple method to acquire mean pleural liquid pressures during any phase of the thoracentesis. Pleural manometry is useful for monitoring and diagnostic purposes during large-volume thoracentesis. Not only does pleural manometry help avoid excessively negative pleural pressures, which may contribute to the development of RPE, it may also serve as a diagnostic tool for identification of an expandable lung and as a predictor of pleurodesis success.

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