In recent years, there has been a proliferation of commercially available pleural drainage units (PDU). The potential advantages of smaller size, lighter weight, and ease of setup, especially for the so-called "waterless systems," have been heavily advertised. On the other hand, it has been suggested that these units are sometimes incapable of resolving pneumothoraces because they cannot handle large bronchopleural air leaks.\textsuperscript{1,2}

In a bench model, we previously demonstrated that the maximal air flow through four commonly used brands of PDU ranged from 5.8 to 35.5 L/min and was directly related to the level of resistance in the unit.\textsuperscript{3} This prompted us to develop an animal model that would simulate the type and amount of bronchopleural air leak commonly seen in clinical practice and to examine the performance of the four PDU in that setting.

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In order to compare the performance of four pleural drainage units (PDU [Emerson Post-Operative Pump, Pleur-Evac, Sentinel Seal, Thora-Klex]), we created an animal model of bronchopleural fistula that simulated the type of air leak seen clinically (mean maximal flow=5 L/min). The PDU were tested at 0 cm (water seal), −20 cm and −40 cmH\textsubscript{2}O suction. Compared to water seal, −20 cmH\textsubscript{2}O suction significantly increased the ability of all four PDU to evacuate air via the chest tube and abolished small differences in chest tube air leak seen among the PDU at water seal. An increase in suction to −40 cmH\textsubscript{2}O did not significantly alter flow via the chest tube. Previously demonstrated differences among the PDU in handling large air flows were not seen in this lower flow model of bronchopleural fistula. However, because of their higher resistance, use of the Sentinel Seal and of the Thora-Klex was technically impractical even at air leaks of 4 to 5 L/min.

**MATERIALS AND METHODS**

Studies were performed on eight healthy mongrel dogs weighing 14 to 31.5 kg. Institutional guidelines for the care and use of laboratory animals were adhered to throughout the experiment. The animals were anesthetized with 30 mg/kg of sodium pentobarbital and paralyzed with succinylcholine. After orotracheal intubation, the animals were mechanically ventilated on a Monaghan 225 ventilator at a P\textsubscript{FIO\textsubscript{2}} of 0.5, a tidal volume of 15 ml/kg, and a respiratory rate adjusted to maintain arterial blood gases. An oxygen analyzer and Bourne L.S.-80 ventilation monitor were inserted into the circuit via a T-shaped connector between the endotracheal tube and the ventilator and used at least hourly to ensure that P\textsubscript{FIO\textsubscript{2}}, tidal volume and minute ventilation remained constant throughout the experiment. An indwelling femoral arterial catheter was placed in order to serially monitor blood pressure and arterial blood gases and ensure that these also remained constant throughout the study.

The left side of the chest was opened via a left lateral thoracotomy incision and a left lower lobectomy was performed in order to create a fixed pleural space. The left lower lobe bronchial stump was oversewn. An alveolar-pleural air leak was created by disrupting the visceral pleum of the left upper lobe over a 6 × 6-cm area using electrosurgery. A No. 32 F chest tube was inserted into the pleural space via a separate inferior stab wound and connected to the PDU with standard 6-foot, ½-inch internal diameter latex tubing. The ribs were approximated with pericostal sutures and the chest wall was closed in layers.

In order to establish a consistent model of bronchopleural air leak from one dog to the next, the chest tube was always initially connected to the Emerson suction pump set at −20 cmH\textsubscript{2}O suction. Positive end-expiratory pressure (PEEP) at 5 to 15 cmH\textsubscript{2}O was then added (mean, 11.3 cmH\textsubscript{2}O) in order to produce an air leak via the chest tube that approximated 60 percent of the total expired tidal volume (endotracheal tube plus chest tube).

The setup for measuring the chest tube air leak (VCT) and the volume exhaled via the endotracheal tube (V\textsubscript{ET}) is illustrated in Figure 1. A Hans Rudolph pneumotachometer was inserted into an

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accessory pathway in the latex tubing between the chest tube and the PDU. This could be included or excluded from the system simply by alternating the position of tubing clamps. The pneumotachometer was in turn connected to a Validyne CD 10 carrier amplifier, a Validyne M 45 Differential Pressure Transducer, and a Validyne FV 156 Respiratory Flow Integrator in order to amplify the flow signal from the pneumotachometer and to derive a volume signal from the flow. Arterial blood pressure, VET and Vct were recorded on a six-channel Gould strip chart recorder model No. 260.

Once a steady state of bronchopleural air leak had been achieved as demonstrated by measurements obtained 30 min apart, four different PDU were used in random sequence and measurements made of VET and Vct on 0 cm (water seal) and at —20 cmH2O suction. Units studied were the Emerson Post-Operative Pump (J.H. Emerson Co., Cambridge, MA), the Pleur-Evac A-4005 (Deknatel Co., Floral Park, NY), the Thora-Klex (Daval Co., Cranston, RI), and the Sentinel Seal (Argyle Co., St. Louis). The Emerson and the Thora-Klex, which were the two units capable of —40 cmH2O suction, were also tested at that setting. Tidal volume, minute ventilation, inspired oxygen fraction, and PEEP level were kept constant during these measurements. At each level of suction the PDU tested first was retested when measurements on the other three units were completed in order to confirm that the bronchopleural air leak remained stable. Results were analyzed by a two-tailed Student’s t test for paired data. No correction was made for multiple comparisons. A probability value of ≤0.05 was considered significant. In order to determine the relative impact on chest tube air leak of changes in the type of PDU compared with changes in the level of suction, data were also analyzed by the MANOVA routine for repeated measures of the statistical package for Social Sciences for Personal Computer + (SPSS/PC +).

RESULTS

Table 1 summarizes the results of the study, showing $V_{CT}$, $V_{ET}$, and $V_e$ in each PDU at each suction setting tested. There were no statistically significant differences for $V_e$ among any of the PDU at water seal, —20 cmH2O suction or at —40 cmH2O suction. These results also may be examined by expressing the leak via the chest tube as a percentage of the total exhaled volume, i.e.,

$$\%V_{CT} = \left(\frac{V_{CT}}{V_{CT} + V_{ET}}\right) \times 100.$$

This is illustrated in Figure 2. Comparison of the mean percentages of chest tube air leaks ($\%V_{CT}$) showed a significant difference between the Emerson and the Pleur-Evac ($p = 0.03$) on one hand, and Thora-Klex ($p = 0.002$) on the other, but not between the Emerson and Sentinel Seal ($p = 0.12$) on water seal. The addition of —20 cmH2O suction produced a statistically significant increase in $\%V_{CT}$ compared with that at water seal. However, there was no significant change in $\%V_{CT}$ when the suction was raised from —20 cm to —40 cmH2O. At —20 cmH2O suction, there were no
Table 1—Volumes Leaked via Chest Tube, Returned via Endotracheal Tube, and Total Minute Volume for Pleural Drainage Units Tested

<table>
<thead>
<tr>
<th>Suction</th>
<th>Units Tested</th>
<th>Pleural Drainage Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Emerson</td>
</tr>
<tr>
<td>0 cm H$_2$O</td>
<td>$\bar{V}_{CT}$</td>
<td>2.68 ± 0.54</td>
</tr>
<tr>
<td></td>
<td>$\bar{V}_{ET}$</td>
<td>4.46 ± 0.43</td>
</tr>
<tr>
<td></td>
<td>$\bar{V}_{E}$</td>
<td>7.14 ± 0.78</td>
</tr>
<tr>
<td>-20 cm H$_2$O</td>
<td>$\bar{V}_{CT}$</td>
<td>4.49 ± 0.78</td>
</tr>
<tr>
<td></td>
<td>$\bar{V}_{ET}$</td>
<td>2.35 ± 0.46</td>
</tr>
<tr>
<td></td>
<td>$\bar{V}_{E}$</td>
<td>6.84 ± 0.73</td>
</tr>
<tr>
<td>-40 cm H$_2$O</td>
<td>$\bar{V}_{CT}$</td>
<td>4.58 ± 0.97</td>
</tr>
<tr>
<td></td>
<td>$\bar{V}_{ET}$</td>
<td>1.52 ± 0.36</td>
</tr>
<tr>
<td></td>
<td>$\bar{V}_{E}$</td>
<td>6.10 ± 1.03</td>
</tr>
</tbody>
</table>

*Data were obtained during mechanical ventilation of dogs with experimental bronchopleural fistulas (N = 8).

Volumes measured in liters per minute; mean ± SEM. Abbreviations follow: $V_{CT}$, volume leaked via chest tube; $V_{ET}$, volume returned via endotracheal tube; $V_{E}$, total minute volume.

Water seal.

significant differences for $\%V_{CT}$ among the four PDU. Comparison of all four PDUs was not possible at -40 cm H$_2$O suction, since two of the units are not capable of reaching that setting. While there was no significant difference in $\%V_{CT}$ between the Emerson pump and the Thora-Klex at -40 cm H$_2$O suction, the Thora-Klex required constant attention and adjustments in order to consistently maintain that setting. Likewise, the Sentinel Seal required maximal wall suction in order to achieve a setting of -20 cm H$_2$O suction on its manometer. Analysis of the interaction of type of PDU and changes in level of suction indicated that the increase in suction to -20 cm H$_2$O was the most important factor responsible for changes in $\%V_{CT}$ (p = 0.001).

DISCUSSION

Closed drainage of the pleural space has been used since Hewett introduced it in 1876 for the management of empyema. Its importance was not recognized, however, until 1918, when the Empyema Commission documented the prohibitive mortality associated with open pneumothorax in the treatment of post-influenzal empyemas. Chest tubes and pleural drainage systems became a standard part of post-thoracotomy care during the 1920s, but there were few commercially available systems until about 20 years ago. Now clinicians are confronted with an increasing array of pleural drainage systems, each alleged to be superior to the next. Critical evaluation of these units has been lacking. We believe that the performance of PDU should be assessed in relationship to (1) the physiologic principles that determine adequate drainage of the pleural space; (2) their maximal capacity to evacuate the pleural space as demonstrated by the maximal flow rate through each unit; and (3) their ability to handle the size of bronchopleural air leak commonly seen in the clinical setting.

Adequate drainage of the pleural space depends on the intrapleural pressure changes that occur with respiration and the physical properties of the pleural drainage system. Under normal circumstances, the slightly positive intrapleural pressure that occurs with expiration is sufficient to evacuate air from the pleural space. Several factors can alter or even reverse this gradient, including the size of the chest tube and of the connecting tubing to the PDU. Laminar flow through any tube is governed by Poiseuille's equation and has a linear relationship to the length, but varies exponentially to the fourth power of the radius of the tube. It has been suggested that a tube with an internal diameter of 6 mm is the smallest acceptable size because it allows a maximum possible flow rate of 15.1 L/min at -10 cm H$_2$O suction. All of our measurements were obtained using a No. 32 F chest tube (internal diameter of 9 mm) and commercially availa-
Evacuation of the pleural space also is affected by the hydrostatic pressure in the connecting tubing. If the tubing is completely filled with fluid, it can establish up to 100 cm of negative pressure, and can compound the normal tendency to evacuate the pleural space on expiration. Air in the tubing, ascending loops of tubing between the patient and the PDU, and the amount of fluid in the water seal chamber of the PDU counteract this hydrostatic pressure. In practice, therefore, it usually is necessary to add suction to the system. 4

The level of suction required to achieve effective evacuation of the pleural space depends on the size of the air leak from the lung. 9 Air leaks measured in the situations commonly seen by clinicians, namely, patients who have had thoracotomy, patients with chest trauma, and patients with barotrauma secondary to acute respiratory distress syndrome (ARDS), range from <1 to 16 L/min. 9, 10 Thus, the PDU must be capable of achieving not only a significant level of pressure, but also relatively high flow rates.

In a bench model, we have previously recorded the maximal flow capability of the four PDU evaluated in this study. 3, 11 With the wall suction regulator set to entrain 40 L/min, the flows varied from 5.8 L/min for the Sentinel Seal to 35.5 L/min for the Emerson. The Emerson is the only unit on which suction can be set independent of a wall regulator. When it was set at −20 cmH 2 O, the flow was even higher. It entrained 59 L/min. As shown in that study the flow through each PDU was directly linked to the resistance in the system.

Since differences in the capabilities of these four PDU at −40 L/min wall suction did not necessarily imply significant clinical differences, we sought to compare the performance of the PDU in an animal model that would mimic the type and size of air leak seen in the clinical setting. We created a true alveolar-pleural air leak with mean maximal flow rates of 5 L/min. This differs from previous animal models in which a bronchopleural air leak has been produced by direct injury to a bronchus, frequently resulting in high flow rates through the fistula. 12-15

On water seal there were small differences in the %Vct among the four PDU. The addition of −20 cm H 2 O suction significantly increased %Vct and equalized the ability of the PDU to evacuate air. When the effects of the level of suction and the type of PDU are analyzed together, it is clearly the addition of −20 cm H 2 O suction rather than the type of PDU that is the most important factor in evacuating air via the chest tube. A further increase in the level of suction for the two units that could be set at −40 cmH 2 O did not significantly increase the flow via the chest tube. Moreover, use of the Sentinel Seal at −20 cmH 2 O suction and of the Thora-Klex at −40 cmH 2 O suction for air leaks of this size was impractical. The Thora-Klex is a "waterless" system. Its suction port incorporates a rubber diaphragm that acts as a one-way valve in place of a water seal chamber. The Sentinel Seal is designed according to the traditional water-filled three-chamber system, but has a very narrow connector off of its suction chamber to the wall suction. Since all of the other components of the drainage system (chest tube, connectors and connecting tubing) were held constant throughout the study, the limiting factor for both the Thora-Klex and the Sentinel Seal seems to be the caliper of the suction port.

We conclude that any of the four PDU tested are adequate for the management of small air leaks such as occur with a spontaneous pneumothorax or after an uncomplicated pulmonary resection, particularly when the PDU are placed on −20 cmH 2 O suction. Increasing the suction further to −40 cmH 2 O does not appear to alter significantly the flow via the chest tube. When the air leak reaches 4 to 5 L/min, use of the Thora-Klex or the Sentinel Seal remains theoretically possible but becomes clinically impractical. Our previous bench studies indicate that the Pleur-Evac can handle flow rates up to 34 L/min, but that its use with rates more than 28 L/min is impractical due to intense bubbling in the suction control chamber. Bronchopleural air leaks of this level are infrequent in the clinical setting and are likely to be associated with either major airway disruption or diffuse parenchymal leak secondary to ARDS with severe barotrauma. 16, 10-17

The low-pressure high-volume Emerson suction pump remains the only PDU capable of handling this situation. The choice of a PDU should be influenced by its physiologic capabilities and the types of bronchopleural air leak that the clinician is likely to encounter in practice.

REFERENCES
1 Van Way CW. Persisting pneumothorax as a complication of chest suction. Chest 1980; 77:815-16
3 Capps JS, Tyler ML, Rusch VW, Pierson D. Potential of chest drainage units to evacuate broncho-pleural air leaks. Chest 1985; 88:575
5 Lillenthal H. Pulmonary resection for bronchiectasis. Ann Surg 1922; 75:357
6 Munwell ER, Thomas KK. Current concepts in thoracic drainage systems. Am Thorac Surg 1975; 19:261-68
8 Batchelder TL, Morris KA. Critical factors in determining adequate pleural drainage in both the operated and nonoperated chest. Am Surgeon 1962; 28:296-302
9 Powner DJ, Cline CD, Bodman GH. Effect of chest-tube suction on gas flow through a bronchopleural fistula. Crit Care Med
12 Pace R, Bankin RN, Finley RJ. Detachable balloon occlusion of bronchopleural fistulae in dogs. Invest Radiol 1983; 18:504-06
17 Pierson DJ. Persistent bronchopleural air leak during mechanical ventilation: a review. Respiratory Care 1982; 27:408-16

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