A Hydrodynamic Study of Pleural Drainage Systems

Some Practical Consequences

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Background: A pleural drainage system must be capable of efficiently evacuating the air or fluids from the pleural cavity so that adequate lung reexpansion can take place. The air flow and negative pressure of the system will depend on the particular design of each model. This experimental study analyzes the specifications and performance of the pleural drainage systems currently on the market.

Methods: Thirteen models of pleural drainage systems connected to wall suction were examined. The models were classified into the following three groups: dry systems; wet systems; and single-chamber systems. We determined the ambient air flow and the negative pressure generated according to the suction level. The components of each model are also described.

Results: Under normal conditions, dry (except for the Sentinel Seal; Sherwood Medical; Tullamore, Ireland), wet, and single-chamber systems reach similar air flow rates (17 to 30, 24 to 27, and 22 to 28 L/min, respectively). With higher wall suction levels, wet systems increase the air flow (26 to 49 L/min) but the negative pressure becomes unstable because of the water loss phenomenon, dry systems increase the air flow (29 to 50 L/min) without modifying the regulator pressure, and single-chamber systems also raise the air flow (45 to 51 L/min) but increase the negative pressure. When there is an air leak, dry systems (except for the Sentinel Seal) lose less negative pressure than the other systems.

Conclusions: The functioning of these systems can be optimized only by applying a suitable wall suction level adjusted to each case. Although the three types of systems are capable of evacuating adequate air flow rates, the negative pressure and the capacity to maintain it in the presence of an air leak are different in each system. Being fitted with valves and not water compartments makes the dry systems the safest and the ideal for use when the patient has to be moved.

Key words: biomedical engineering; flowmeters; laboratory; pleural drainage system; pneumothorax

Abbreviations: mb = millibars; PDS = pleural drainage system

Some of the problems that appear with the use of pleural drainage systems (PDSs) stem from the fact that the drainage flow rate achieved by the system is insufficient, and this in turn leads to the unsatisfactory evacuation of pleural liquids or air. Pleural leaks can have an air flow rate that ranges from <1 to 20 L/min.1–3 The PDS must be capable of evacuating all of this air so as to be able to keep the lung expanded during the distinct phases of respiration.4 An “ideal” PDS must be capable of evacuating at high flow rates (>20 L/min) with low suction levels, and it must also be able to keep the negative pressure applied to the patient constant, despite variations in the air flow through the pleural leakage.2 Each PDS that is available on the market has its own design, and this will have a direct effect on its intrinsic resistance to flow, which in turn determines its maximum absorption capacity.5,6 Some authors3,5,7 have warned of the dangers of some PDSs that limit the flow to very low values. Owing to the space restraints inherent in these compact systems,
together with the assortment of models and the disappearance of some hydraulic compartments, the visual identification of each component and how they work may turn out to be more difficult than with the classical three-bottle system. Nevertheless, the fundamental principles are the same for all of them.\textsuperscript{8}

A review of literature published around the world only produced three articles that compared some PDSs using different methods from the years 1985,\textsuperscript{9} 1988,\textsuperscript{3} and 2003.\textsuperscript{7} The scarcity and age of the literature, in addition to the constant changes in the designs of the different models and the scant technical data supplied by manufacturers, means that there is a lack of objective criteria when it comes to deciding which PDS is most suitable for use in everyday clinical practice. The aim of this experimental study was to analyze the performance of the different PDSs marketed in Spain. This work was carried out in collaboration with the Fluid Mechanics Area of the Department of Technology at Universitat Jaume I in Castellón, Spain.

**Materials and Methods**

**Drainage Systems**

The study was conducted using 13 models of PDSs that are marketed in Spain, which were provided by the four manufacturers that produce them (Table 1). The models were classified into three groups. One group included six models fitted with a dry suction control or mechanical regulator (ie: dry systems), another group was made up of five models equipped with a wet or hydraulic suction control (ie: wet systems), and the third group consisted of two single-chamber models that had no suction control on the device itself and had to be regulated directly at the wall vacuum source (ie: single-chamber systems).

**Flow and Pressure Measurement**

In the study, we used patient spirometry equipment (model S/5; Instrumentarium Corporation, Datex-Ohmeda; Helsinki, Finland) that was fitted with a D-lite sensor (Instrumentarium Corporation, Datex-Ohmeda) and was connected in series, with the free end of the tube connecting the patient to the PDS. The maximum negative pressure detected by the device was $-112.6$ cm H$_2$O, the accuracy was ± 1 cm H$_2$O, and the air flow rate ranged from 1.5 to 100 L/min. The spirometry equipment was connected to a computer, and the data were processed using a specific software application (S5 collect 4; Instrumentarium Corporation, Datex Ohmeda). Air flow measurement was performed with the end of the spiroometer open and was expressed in liters per minute. For the pressure measurements, the end of the spirometer was hermetically closed with a rubber stopper, and pressure was expressed in centimeters of water.

**Vacuum System**

The wall vacuum source supplied by the hospital network was employed in our study (flow rate range, 50 to 70 L/min; pressure range, −600 to −760 millibars [mb]). If they are to work properly, dry systems require far higher wall suction levels than wet or single-chamber systems, and for this reason the vacuum was adjusted with two kinds of regulators. For high suction levels, we used a Taema V600 regulator (Air Liquide Sante\textsuperscript{®}; Antony Cedex, France), which allowed a negative pressure of 0 to −600 mb and a maximum flow rate of 70 L/min to be achieved. For low suction levels, a thoracic vacuum regulator (Ohmeda Medical; Columbia, MD) was employed; this allows a negative pressure of 0 to −55 cm H$_2$O and a maximum flow of 62 L/min to be reached. Centimeters of water and millibars were used to measure the vacuum because these are the units employed by the PDSs and the wall regulators. For all practical purposes, 1 cm H$_2$O can be considered to be equal to 1 mb (1.33 mb = 1.36 cm H$_2$O).

**Procedure**

Each PDS was prepared following the manufacturer’s instructions and was tested for leaks. The PDS was connected to the regulator at the wall vacuum source by adding a suction tube (Medi-Vac NEX710; Allegiance Healthcare Corporation; McGaw Park, IL), that was 3 m long and 7 mm in internal diameter. For air measurements, the free end of the PDS-patient connecting tube was connected in series to the D-lite sensor of the spirometer (Fig 1). Atmospheric air flow and pressure were determined (temperature, 22°C; humidity, 50%). Three units of each model of drainage system were tested, except for the Pleuraseal III (Rocket Medical PLC; Watford, UK) [only one unit was available], and the arithmetic mean was then calculated.

**Relation Between Flow and Negative Suction Pressure**

Measurements were performed using a level of suction that was adjusted to the specifications required by manufacturers (normal wall suction levels, −10, −20, −30, −40, and −50 cm H$_2$O in the wet and the single-chamber systems, and −150 mb in the dry systems) and also with a suction that was higher than the recommended level (high wall suction levels, −200, −400 and −600 mb). In dry systems, the air flow obtained was then measured with the suction regulator on the device set to −10, −20, −30, and −40 cm H$_2$O. As the suction regulator on the Sentinel Seal model did not have a scale, this was determined by examining the correlation between the number of times the regulator knob was turned and the pressure as measured by the spirometer. The flow rate obtained when the regulator was fully screwed up was also determined. In wet systems, the air flow obtained was measured with the suction level of the device set at −10 and −20 cm H$_2$O, and −25 cm H$_2$O when available. In single-chamber systems, pressure was regulated directly with the wall suction regulator.

**Table 1—List of the PDSs Analyzed**

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
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<tbody>
<tr>
<td>Atrium Medical Corporation</td>
<td>Atrium Oasis 3600</td>
</tr>
<tr>
<td>(Hudson, NH)</td>
<td>Atrium Ocean 2002</td>
</tr>
<tr>
<td></td>
<td>Atrium Express</td>
</tr>
<tr>
<td>Genzyme Surgical Products Corp</td>
<td>Pleur-evac A-6000</td>
</tr>
<tr>
<td>(Fall River, MA)</td>
<td>Pleur-evac Sahara S-1100</td>
</tr>
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<td></td>
<td>Pleur-evac A-8000</td>
</tr>
<tr>
<td></td>
<td>Pleur-evac A-7000</td>
</tr>
<tr>
<td>Sherwood Medical (Tullamore,</td>
<td>Argyle Sentinel Seal</td>
</tr>
<tr>
<td>Ireland)</td>
<td>Argyle Sentinel Altitude</td>
</tr>
<tr>
<td></td>
<td>Argyle Aqua-Seal</td>
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<tr>
<td></td>
<td>Thora-Seal I</td>
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<tr>
<td>Rocket Medical PLC (Watford,</td>
<td>Rocket Single Chamber</td>
</tr>
<tr>
<td>UK)</td>
<td>Pleuraseal III</td>
</tr>
</tbody>
</table>
Negative Pressure of the System: The suction regulator that is built into the device must be capable of accurately adjusting the wall suction level to the values required by the system even though the pressure may be too high. To analyze this parameter, we determined the pressure under the same conditions in which flow was established.

Negative Pressure Stability: If the PDS is efficient, it must be capable of maintaining steady negative pressure to the patient, even though there may be pleural leakage. To check the stability of the negative pressure, we carried out a leakage simulation by connecting the end of the patient connecting tube to a stopper with a 2-mm hole in its center so as to allow a certain amount of air to enter the system. To measure pressure in the presence of a flow of air, the measuring equipment must be situated at some distance from where air is entering. This distance must be at least 10 to 15 times the inside diameter of the tube the air is going through. Since the tube connecting the PDS to the patient has an internal diameter of 10 mm, we introduced a 50-cm piece of connecting tubing between the D-lite sensor and the stopper with the hole (Fig 1).

Wall suction levels of −150 and −200 mb were set in the dry PDSs, levels of −30, −40, and −50 cm H₂O were employed in the wet PDS systems, and levels of −10 to −50 were used in the single-chamber PDS system. First, the pressure was measured with the hole in the stopper closed (pressure with no leakage). The hole was then uncovered in order to simulate an air leak, and the pressure (pressure with leakage) and flow (magnitude of the leak) were measured again. The drop in pressure produced by the leakage was calculated by subtracting the leakage pressure from the pressure without leaks. In dry and wet PDSs, measurements were conducted for each level of the regulator that was built into the device.

Components of the Models: We performed a detailed description of each model.

RESULTS

Relation Between Flow and Negative Suction Pressure

Dry PDSs: With the exception of the Sentinel Seal (Sherwood Medical; Tullamore, Ireland), in normal suction conditions (−150 mb) all of the models reached maximum flow rates between 17 and 30 L/min (Fig 2). The Pleur-evac A-6000 (Genzyme Surgical Products Corporation; Fall River, MA) and the Atrium Oasis (Atrium Medical Corporation; Hudson, NH) are the models that achieved the highest flow rates. In almost all of the models, the increase in flow was greater when the regulator on the device was turned up from 10 to 20 L/min (range, 4 to 8 L/min), whereas little difference was seen when flow was changed from 20 to 30 L/min (range, 0 to 3 L/min), and no change was observed on shifting the regulator from 30 to 40 L/min. The Atrium Express (Atrium Medical Corporation) was the only model that increased flow by 5 to 6 L/min each time the regulator was set to a higher position. The flow in the Sentinel Seal ranged from 6 to 15 L/min with the device regulator at the same levels, although if the regulator was fully opened, a maximum flow rate of 11.5 L/min could be obtained with a negative pressure of −88 cm H₂O.

If the wall suction level was stepped up from −150 mb to −200 or −400 mb, the air flow rate rose substantially in all the models except for the Sentinel Seal and the Atrium Express, which hardly varied. On raising suction from −400 to −600 mb, no increase in flow rate was observed. The Atrium Oasis and Pleur-evac A-6000 models achieved the highest flow rates (approximately 50 L/min), while the Sentinel Seal model did not reach 13 L/min despite application of a very high suction level and fully opening the regulator.

Wet PDSs: The air flow rate rose progressively according to the level of wall suction. With normal suction pressures, a flow rate of between 5 and 8 L/min and 22 and 28 L/min, respectively, was ob-
tained, depending on whether the suction applied was \(-10\) or \(-50\) cm H\(_2\)O (Fig 3). The air flow was usually slightly greater with the hydraulic suction level at 20 cm than with the level of 10 cm, with all of the models rising by 0.4 to 3 L/min, except for the Pleuraseal III (Rocket Medical PLC; Watford, UK), in which flow increased more (4.7 and 8.7 L/min, respectively), and the Aqua-Seal (Sherwood Medical), in which flow did not vary. If the water level is increased to 25 cm, the air flow can drop by 0.5 to 1.5 L/min because it loses water from the chamber due to the vigorous bubbling that takes place, a phenomenon that essentially appears with suction levels of \(-50\) cm H\(_2\)O. If suction pressures higher than those recommended are applied, all of the models achieve higher flow rates (range, 26 to 49 L/min).

Single-Chamber PDSs: The air flow rose progressively according to the level of wall suction. With normal suction, a flow of between 5 and 6 L/min and 24 and 27 L/min, respectively, was obtained, depending on whether the suction applied was \(-10\) or \(-50\) cm H\(_2\)O (Fig 3). With high suction rates, flows of almost 50 L/min were reached.

Negative Pressure of the System

Dry PDSs: With a suction level of \(-150\) mb, all the regulators on the units adjust the suction level indicated by the regulator quite accurately, with variations of \(\pm 2\) cm H\(_2\)O. If the wall suction level is increased to values above those recommended by the manufacturer, the negative pressure applied with the device regulator remains fairly stable with all the models and the variation does not exceed 5 cm H\(_2\)O. In the Atrium and Pleur-evac models, the pressure becomes more negative whereas with the Sentinel models the pressure becomes less negative.

The pressure regulator of the Sentinel Seal does not maintain the negative pressure steady in the
presence of high suction rates when the regulator is set to –10 cm, since a loss of negative pressure of 8 cm H$_2$O is produced. If it is set between –20 and –40 (between two and three and three quarter turns of the knob), it does maintain adequate negative pressures, but if it is opened completely it generates excessively high negative pressures (above –112.6 cm H$_2$O).

Wet PDSs: With suction levels of –10 to –50 cm H$_2$O, all the models are capable of adjusting the wall suction pressure to that indicated in the suction control chamber with precision (a variation of ±2 cm H$_2$O), provided that the wall suction level is higher than that selected on the device. The higher the wall suction level is, the more bubbling is produced in the suction control chamber. With a suction level of –10 cm, there is either no or very little bubbling, with –30 cm moderate bubbling takes place which does not lead to any loss of water in the chamber, but with –50 cm bubbling is more vigorous and can give rise loss of water if the level of the water in the chamber is 25 cm; this in turn leads to a loss of negative pressure.

When high wall suction levels are used, the flows obtained are also high but water is lost from the suction control chamber via two routes (Fig 4). On the one hand, water is sucked by the hospital vacuum source and drops of water can be seen moving along the suction tube toward the filter on the air regulator, which becomes wet. On the other hand, part of the water from the suction control chamber spills over into the water seal chamber until it is completely full. The higher the level of water in the suction control chamber is, the earlier this phenom-
Enon will appear. If the wall suction level is increased to very high values (–600 mb) at first, the negative pressure in the device rises, but does not exceed –40 cm H₂O in any models studied. Later, as the water level drops in the suction control chamber and the level of the water seal increases, negative pressure is gradually lost.

**Single-Chamber PDSs:** Since these PDSs have no suction regulator, the negative pressure is similar to that applied by the wall regulator. Pressure values above –112.6 cm H₂O could not be determined due to the restricted scale of the spirometry equipment.

**Stability of the Negative Pressure**

**Dry PDSs:** Depending on the position the regulator is set to, with a suction level of –150 mb the leakage gives rise to a loss of negative pressure of between 3 and 15 cm H₂O in all the models except the Sentinel Seal (Fig 5). An air flow rate of 7.5 to 17.5 L/min was registered for the leakage, although in the case of the Sentinel Altitude with the regulator set at 10 or 20 the leakage rate was lower (2 to 8 L/min). In the Sentinel Seal, despite air leakage being much lower (1.7 to 6.6 L/min), the loss of negative pressure was two or three times higher than in the other models. If the wall suction level is increased to –200 mb, the leakage rises by 1 to 2 L/min and the pressures with and without leakages become somewhat more negative; negative pressure loss, however, is the same as with –150 mb. Maintaining a wall suction level of –200 mb and setting the device regulator to 40, the dry PDS (except Sentinel Seal) is capable of tolerating air leaks of 15 to 18 L/min while maintaining negative pressures of –30 cm H₂O.

**Wet PDSs:** With a wall suction level of –30 cm H₂O the leaking air flows at 3 to 15 L/min and gives rise to a loss of negative pressure of 3 to 15 cm H₂O, depending on the level of water in the suction control chamber (Fig 6). If the wall suction level is increased to –40 or –50 cm H₂O the air leakage rate rises by 1 to 2 L/min, but the loss of negative pressure is the same or even two or three times lower, depending on whether the water level is at 10 or 20 cm, respectively. This is due to the fact that with a higher level of suction the pressure without leakage is not modified, but the pressure with leakage does become more negative. Maintaining a wall suction level of –50 cm H₂O and a device suction level of 20 cm, the wet PDS can tolerate air leaks of 10 to 12 L/min while maintaining negative pressures of –10 to –12 cm H₂O.

**Single-Chamber PDSs:** Air leakage rate was 2 to 7 L/min and halved the negative pressure without leakage, with losses of between 6 and 24 cm H₂O depending on the wall suction level (Fig 5).

**Components of the Models**

**Compartments:** The single-chamber PDSs consist in just one chamber that is used for collection and as a water seal, and has no vacuum regulator (Table 2). In wet PDSs first there is a collection chamber, the second chamber with water in it acts as a one-way system (water seal) and the third chamber, also with water in it, regulates the suction level of the unit, keeping it at 0 to –20 or –25 cm H₂O. To work properly, two of their chambers must be filled with water. In dry PDSs, the water in the third chamber is replaced by a mechanical regulator that allows a higher level of suction to be achieved and can be graduated from 0 to –40 cm H₂O or nongraduated.
Additionally, in the Pleur-evac Sahara and the Atrium Express, the water in the seal chamber is replaced by a one-way mechanism (valve), but it is also possible to fill this chamber with water in order to view the bubbling caused by the leak.

**Accessories:** Table 2 offers a detailed description of the characteristics of each PDS. Moreover, some models include other accessories. The Aqua-Seal has a wall suction inlet-outlet stopcock to allow regulation of the bubbling inside the device. It also has an auxiliary cap that can be fitted over the air vent of the suction control chamber in order to bypass this chamber and achieve a higher level of suction applied directly from the wall regulator. In the Sentinel Seal, the water seal has no graduated scale for measuring pressure and, similarly, the suction regulator is not graduated either. To make up for these limitations it is fitted with a fourth chamber, called a patient assessment chamber, which consists of a hydraulic manometer with a scale from 0 to 25 cm and which must be filled with 30 mL of water. To set a level of suction between 0 and –20 cm H₂O the suction regulator is turned until the water in the fourth chamber rises to the prescribed vacuum level, while keeping the patient connecting tube closed. The Atrium Express is equipped with two short tubes in series inside the unit which impede the passage of water from one chamber to another should the device be upset.

The patient connecting tube of dry and wet PDSs (except the Pleuraseal III) is similar because they are the same compliance and the same internal diameter (10 mm). In the Pleuraseal III and single-chamber PDS the patient connecting tube has another compliance and a lower internal diameter (9 mm in the Pleuraseal III, 8 mm in the Rocket and 7 mm in the Thora-Seal). The length of patient connecting tube ranges from 181 to 220 cm depending on the models.
although in the case of the Rocket the length was much lower (152 cm).

**Discussion**

One crucial factor to be borne in mind when assessing the performance characteristics of a PDS is the wall suction level that is applied to the PDS. We believe that the wall suction level must be unified in all studies comparing PDSs. Generally speaking, the greater the wall suction level, the higher the flow rate and the negative pressure achieved by a PDS will be. To date, no study has been published that takes this factor into account; in addition, if PDSs are compared while the different wall suction levels recommended by the manufacturer are applied to each model, then results are not comparable. For example, in a study by Baumann et al., the Pleur-evac Sahara achieved a flow rate of 12.5 L/min with the regulator set at 10. Nevertheless, in our study, with a wall suction level of -150 or -200 mb, the flow rate for the same model is 16.5 and 19.1 L/min respectively. It is also worth noting that wet PDS such as the Atrium Ocean or the Aqua-Seal reach flow rates of 40 L/min, which, according to the findings of our study, can only be achieved if a very high wall suction level is applied, although this is not recommended if the device is to operate properly because of the appearance of the water loss phenomenon. With a normal suction level that does not exceed -50 cm H₂O, the maximum flow rate of wet PDSs is never > 26 L/min.

For a PDS to work properly, each of the three systems will require an adequate wall suction level. Dry PDSs must be connected to high suction wall regulators because they require a higher level of suction (150 mb) to be able to work properly. It is judicious to connect wet PDSs to low suction regulators (-30 to -50 cm H₂O) in order to prevent excessively high negative pressures due to oscillations.

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<thead>
<tr>
<th>Model</th>
<th>OC</th>
<th>P8</th>
<th>P7</th>
<th>PL</th>
<th>AS</th>
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<td>Negative pressure (cm H₂O)</td>
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<td>24.8</td>
<td>23.3</td>
<td>18.5</td>
<td>18.1</td>
</tr>
<tr>
<td>Device suction level (mb)</td>
<td>10,4</td>
<td>10.4</td>
<td>12.2</td>
<td>12.1</td>
<td>10.8</td>
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</table>

**Figure 6.** Loss of pressure caused by an air leak. Wet systems (wall suction level set to -30 cm H₂O). See legends of Figures 2 and 3 for abbreviations not used in the text.
tions in the wall vacuum system or to erroneous use of the wall regulator. Excessively high suction levels (>−50 cm H2O) produce vigorous bubbling, suck up the water from the suction control chamber, alter the negative pressure in the system and, theoretically, can favor the transmission of germs in the fluid that is drained through the tubing in the hospital’s suction network. One situation that frequently occurs in clinical practice is that the wall suction level is often reduced until bubbling is lowered to an absolute minimum so as to diminish the annoying sound of the bubbling through the water. Nevertheless, it must be borne in mind that when dealing with an air leak from the pleural cavity, this practice lowers the flow rate of the unit and, in turn, the efficiency with which air is evacuated. Like wet PDSs, it is wise to connect single-chamber PDSs to low suction regulators so as to prevent excessively high intrapleural negative pressures.

In this study dry and single-chamber PDSs achieve higher flows than wet systems because they work with higher wall suction levels. In dry PDSs the flow can be raised to a notable degree by increasing the suction level on the wall regulator (−200 to −400 mb) or by increasing the level on the regulator of the PDSs (−10 to −40 cm H2O). In the case of the Atrium Express the flow can only be adjusted at the regulator on the device and does not increase even though the wall suction level is raised. Like other authors,3,7 we believe that the Sentinel Seal is not the most appropriate model to treat pleural leaks, since its regulator limits the air flow to an excessive extent even with high suction levels. When a wall suction that is much higher than the level recommended by the manufacturer is applied to wet PDSs, air flows similar to those achieved by dry PDSs can also be obtained. However, the appearance of the phenomenon of loss from the hydraulic control chamber restricts the performance of this type of PDS. A greater increase in flow rate is achieved by adjusting the wall regulator than with the hydraulic regulator because, except in the case of the Pleuraseal III, the air flow only varies a little or not at all (Aqua-Seal) when the suction level is changed from −10 to −20 or −25 cm H2O. A greater rate of air flow is achieved with a wall suction value of −40 cm H2O and a water level of 10 cm (14 to 22 L/min) than with a suction of −20 and a water level of 20 cm (11 to 14 L/min). The air flow of single-chamber PDSs can also be increased by incrementing the wall suction level but, unlike the dry PDSs, the negative pressure would also be raised because they have no regulator. For example, both systems reach flow rates >35 L/min but single-chamber PDSs would apply a high negative pressure (−200 mb) in the pleural cavity whereas dry PDSs would apply less negative pressures (−30 or −40 cm H2O).

Although the negative pressure that should be applied in the pleural space has historically been a controversial issue, it is currently agreed that the

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Table 2—Characteristics of the Different Models of PDSs*

<table>
<thead>
<tr>
<th>PDSs</th>
<th>One-way System</th>
<th>Suction Indicator</th>
<th>Suction Control</th>
<th>Suction Level</th>
<th>Air Flow Rate,† L/min</th>
<th>Negative Pressure Relief Valve</th>
<th>Positive Pressure Relief Valve</th>
<th>Collection Chamber Capacity, mL</th>
<th>Chamber Access Ports</th>
<th>Graded Leak Monitor</th>
<th>Autoflush Connection</th>
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<tbody>
<tr>
<td>Dry systems</td>
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<td>D</td>
<td>0–40</td>
<td>29.4</td>
<td>A + M</td>
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<td>2.000</td>
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<td>2.500</td>
<td>Ws</td>
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<td>Pleur-evac Sahara</td>
<td>V F + 1</td>
<td>D</td>
<td>0–40</td>
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<td>A + M</td>
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<td>2.000</td>
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<td>A + M</td>
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<td>2.100</td>
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<td>0–40</td>
<td>8.1</td>
<td>M§</td>
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<td>Atrium Ocean</td>
<td>Ws B</td>
<td>W</td>
<td>0–20</td>
<td>17.2</td>
<td>A + M</td>
<td>A</td>
<td>2.100</td>
<td>Co,Ws,Su</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Pleur-evac A-8000</td>
<td>Ws B</td>
<td>W</td>
<td>0–25</td>
<td>18.3</td>
<td>A + M</td>
<td>A</td>
<td>2.500</td>
<td>Co,Ws,Su</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Pleur-evac A-7000</td>
<td>Ws B</td>
<td>W</td>
<td>0–25</td>
<td>17.7</td>
<td>A + M</td>
<td>A</td>
<td>2.500</td>
<td>Co,Ws,Su</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
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<tr>
<td>Pleuraseal III</td>
<td>Ws B</td>
<td>W</td>
<td>0–25</td>
<td>16.1</td>
<td>A + M</td>
<td>A</td>
<td>2.400</td>
<td>Co,Ws,Su</td>
<td>No</td>
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<tr>
<td>Aqua-Seal</td>
<td>Ws B</td>
<td>W</td>
<td>0–25</td>
<td>16.5</td>
<td>M§</td>
<td>A</td>
<td>2.300</td>
<td>Co,Ws</td>
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</tr>
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*Ws = water seal; V = mechanical valve; B = bubbling; U = unfolding bellows; F = float; M = hydraulic manometer; I = image; W = wet; D = dry; A = automatic; M = manual; Co = collection chamber; Su = suction control chamber.
†Air flow under normal operating conditions: dry systems, wall regulator set at −150 mb and device regulator set at 40 cm H2O; wet systems, wall regulator set at −30 cm H2O and device level set at 20 cm; single-chamber systems, wall regulator set at −30 cm H2O.
‡Leak monitor.
§Fitted with an automatic valve that prevents the water seal from being suctioned.
recommended value is the minimum required to keep the lung expanded. Most authors do not recommend the use of a high suction because it could increase or perpetuate a pleural leak, augment air steal, which may lead to hypoxia, or even unexpectedly trap lung parenchyma in chest tube holes. Occasionally, the best treatment of a pleural leak is to stop suction, not increase it.

Nevertheless, there are situations in which the lung has become rigid and a higher negative pressure may be required to re-expand it. Dry PDSs allow pressures of up to –40 cm H₂O to be applied and, despite increasing the wall suction level, the pressure hardly varies because of the high efficiency of the dry regulator. Wet PDSs attain negative pressures of –20 or –25 cm H₂O, which can reach higher values if the air vent is closed (the Aqua-Seal has a cap) and the pressure is adjusted directly with the wall regulator, because the hydraulic suction control chamber is bypassed. Nevertheless, we believe that to apply a negative pressure above –40 cm H₂O it is better to utilize a single-chamber PDS than a wet bypassed system because it is more economical and does not have an automatic negative pressure relief valve.

Wet PDSs maintain a steady pressure inside the device when a normal wall suction level is applied but become less effective if a very high suction level that produces excessively vigorous bubbling is used. Despite the fact that the work of Bar-El et al.11 describes the appearance of excessively high negative pressures when the level of bubbling becomes too high, we could not confirm this finding with the PDSs used in this study. We were able to observe that, in this situation, the air flow increases but negative pressure is gradually lost as the level of water in the suction control chamber drops and the level of the water seal rises; however, the pressure in the PDS never exceeds –40 cm H₂O. The purpose of the atmospheric vent is to allow outside air to enter the system so that the hydraulic suction control chamber is bypassed. Nevertheless, we believe that to apply a negative pressure above –40 cm H₂O it is better to utilize a single-chamber PDS than a wet bypassed system because it is more economical and does not have an automatic negative pressure relief valve.

With regard to the magnitude of a leak, theoretically any of the 13 PDSs under study could evacuate a small pleural leak (< 5 L/min), but if the leak is large (> 10 L/min) the Sentinel Seal is not recommended and the other systems have to be adjusted so as to be able to work under the best conditions. If a dry system is being used, the regulator of the device will have to be set to at least 20 to 30 cm and a wall suction level of –150 mb (for the Pleur-evac or Atrium model) or –200 mb (in the case of the Sentinel Altitude) will have to be applied. If a wet system is used, the water chamber must be filled to 20 cm and a wall suction level of –40 or –50 cm H₂O must be applied to ensure a moderate amount of bubbling. The chamber must not be filled to –25 cm and the PDS must not be connected to higher wall suction levels because the water loss phenomenon will take place. In the presence of a leak, if the clinician increases the wall suction level until bubbling appears in the suction control chamber (for example, at –100 cm H₂O), the moment the pleural leak is decreased or stopped (due to breathing, pleural leakage, kinking of the tube, and so on), bubbling would become excessive and the water loss phenomenon would occur because the recommended value of –50 cm have been exceeded. If a single-chamber PDS is used, a wall suction level of at least –40 cm H₂O has to be applied.

Our study was designed to test the maximal air flow a system could provide using a large, fixed leak (with the patient connection tube open). In this situation, the flow is so large that it will probably overwhelm the capacity to maintain an adequate negative pressure in most systems. This study was not designed to test the maximal air leak that could be handled by a system without loss of pressure, since to do so it would be necessary to deliver different, but known, flow rates. Despite this limitation, it can be seen that the dry PDSs (except the Sentinel Seal) can handle leaks of 15 to 18 L/min while maintaining adequate negative pressures, but the wet PDSs do not support air leaks so well.

Another limitation of our study is that the air leak is simulated, fixed and constant, unlike a pleural leak which is dynamic and may be associated to an effusion. Moreover, the measurements have been performed at room temperature and 50% humidity, that is no physiologic. Pleural leaks can have an air flow rate that ranges from < 1 to 20 L/min, this value being higher in patients submitted to mechanical ventilation. They are modified by breathing and the expiratory leak is the most frequent type, although in ventilated patients leaks are usually inspiratory or continuous. Cerfolio et al.12 used the graduated air leak monitor, included in some PDSs, to monitor the progress of the leak and to predict which pleural leaks will require suction in order to keep the lung expanded and which will not require suction. Using a two-bottle PDS, Batchelder and Morris1 measured postoperative pleural air leaks by inserting an American gas meter between the fluid trap bottle and the water seal bottle. Powner et al.13 assembled standard measuring instruments and introduced them into the connecting tubing to titrate optimal level suction. In a similar manner, by connecting a spirometer at some point along the patient connecting tube, it becomes possible to monitor pleural air leaks. If the suction is momentarily
cannot reproduce human physiologic conditions. It can, however, provide a scientific basis on which to determine the performance of the PDSs currently on the market, while allowing users to optimize their functioning and to help them choose the most suitable model. Wall suction level affects the air flow and the negative pressure in each PDS. Under normal conditions dry (except the Sentinel Seal), wet and single-chamber systems reach similar air flow rates. With higher wall suction levels, wet systems increase the air flow but the negative pressure becomes unstable because of water loss phenomenon, dry systems increase the air flow without modifying the regulator pressure, and single-chamber systems also raise the air flow but increase the negative pressure. When there is an air leak, dry systems (except the Sentinel Seal) lose less negative pressure than the other systems.

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REFERENCES