Fluid flow performance of a new siphon-control device for ventricular shunts

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Most available cerebrospinal fluid diversion systems utilize differential-pressure valves that often induce overshunting, resulting in complications due to the siphoning of fluid from the ventricular system when the patient is in the erect position. A new siphon-control device (SCD) was tested alone and in combination with four types of differential-pressure valves with low, medium, and high opening pressures (namely PS Medical, Heyer-Schulte, Cordis-Hakim, and Codman valves). The valve inlet and outlet pressures were measured at several fluid inflow rates between 2.0 and 50.0 ml/hr. Inlet pressure and valve resistance were determined when the outlet pressures of the differential-pressure valve or SCD were varied between 0 and -60 cm H2O. Of the differential-pressure valves tested, none provided protection against siphoning without the distal connection of the SCD. The SCD allowed all differential-pressure valves tested to maintain atmospheric pressure regardless of the outlet pressure. The SCD performs in a manner similar to the older anti-siphon device, but with some improvements in design and construction. The results of this investigation suggest that the increased resistance due to the inline SCD is not functionally significant when added to the conventional valve systems with low opening pressure.

KEY WORDS • siphon-control device • hydrocephalus • shunt • anti-siphon device

The flow characteristics of the first commercially available anti-siphon valve, designed as an anti-siphon device (ASD) for ventricular shunting, were reported by Portnoy, et al., in 1973. In the present paper, we discuss a similar device that has some advantages over the earlier ASD when used in conjunction with presently available differential-pressure valves for the treatment of hydrocephalus. The necessity for control of cerebrospinal fluid (CSF) outflow from the ventricular system while the patient is in an upright position has been appreciated for some time. This phenomenon of siphoning has been shown to result in excessive drainage of CSF from the ventricular system, expressed in the clinical setting by the development of significant neurological sequelae. These complications of ventriculoperitoneal (VP) or ventriculoatrial (VA) shunting have stimulated the development of anti-siphon valves and the recently introduced variable-resistance-flow regulator that acts as a stage in a differential-pressure valve and controls CSF flow over a wide range of shunt outlet pressures.

The present study compares the in vitro flow and resistance attributes of both the original ASD and the new siphon-control device (SCD). In addition, we explore the anti-siphoning effect of the SCD on the in vitro function of four differential-pressure valves of varying opening pressures.

Materials and Methods

The general experimental arrangement is shown in Figs. 1 and 2. Two anti-siphoning valves, the Heyer-Schulte ASD and PS Medical SCD, were tested with the following four differential-pressure valves: low-, medium-, and high-pressure Codman valves; low-, medium-, and high-pressure PS Medical valves; low-, medium-, and high-pressure Heyer-Schulte valves; and very low-, medium-, and high-pressure Cordis-Hakim valves.* The technique used to evaluate shunt function is similar to that previously reported in the literature and will be only briefly described here. In the anti-siphon valve (ASD or SCD) and anti-siphon valve plus differential-pressure valve experimental systems, the flow of sterile water (25°C) was maintained with a pulsatile

* Heyer-Schulte anti-siphon device and valves manufactured by American V. Mueller, Chicago, Illinois; PS Medical siphon-control device and valves manufactured by PS Medical, Santa Barbara, California; Codman valves manufactured by Codman & Shurtleff, Inc., Randolph, Massachusetts; Cordis-Hakim valves manufactured by Cordis Corp., Miami, Florida.
Constant-speed pump.† The sterile water was delivered at a rate of 2, 5, 10, 20, 30, 40, or 50 ml/hr. Silastic tubing with an inner diameter of approximately 1.5 mm was used to connect all components in the experimental systems. The valve systems were locked onto a vibration-free horizontal bench with the tubing from the distal device (outlet tubing) submerged in a movable reservoir of water. The outlet pressure was varied from the horizontal (0 cm H2O) to subatmospheric pressures (−20, −40, or −60 cm H2O) by changing the relationship of the end of the outlet tubing with the level of the experimental bench. The fluid pressure in the experimental system was measured with fluid-coupled pressure transducers at the various rates of flow defined above. The effect of siphoning (outlet pressure) on the system was determined by lowering the distal end of the submerged outlet table below the level of the test bench to the desired negative pressure as recorded by the outlet transducer. When the anti-siphon valves (ASD or SCD) or differential-pressure valves were tested alone, the proximal (inlet) and distal (outlet) pressures were measured at the inflow rates and outlet pressures described above (Fig. 1). Testing the combination of SCD and various differential-pressure valves required an additional pressure transducer between two devices (Fig. 2). After all air bubbles were cleared from the valves and tubing, the pump was started and allowed to reach a steady-state pressure over a 5-minute period. The fluid pressures were then monitored with a multichannel analyzer‡ for 10 to 15 minutes at each inflow rate and outlet pressure combination. The data were collected on a microcomputer and analyzed with Data Notebook§ hardware and software.

At least two of each type of valve device were tested and the results are given as mean values. The fluid pressures were obtained in cm H2O. Resistance (R) was calculated from the equation \( R = \frac{P}{F} \) (cm H2O/ml/hr), where \( P \) represents the difference in the inlet and outlet pressures and \( F \) is the flow generated by the pulsatile flow pump in ml/hr.‡

**Results**

**Anti-Siphon Valves**

The results of the pressure-flow experiments utilizing the ASD and SCD are presented in a three-dimensional fashion (Fig. 3). Regardless of outlet pressure (0 to −60 cm H2O), both anti-siphon valves demonstrated positive proximal or inlet pressure (> 0 cm H2O) at all rates of fluid inflow. When the outlet tube was horizontal (outlet pressure = 0 cm H2O), the normally open ASD had less internal resistance to flow compared to the normally closed SCD, as evidenced by the lower inlet pressure (Fig. 3).

**PS Medical Valves and SCD**

The results of the pressure-flow experiments with the low-, medium-, and high-pressure PS Medical differential-pressure valves alone and in combination with the SCD are shown in Figs. 4 to 6. The low differential-pressure valve demonstrates the effect of a negative

† LKB 2132 pump manufactured by Micropermex, Bromma, Sweden.
‡ Multichannel analyzer manufactured by Grass Corp., Cambridge, Massachusetts.
§ Data Notebook obtained from Data Translation, Marlboro, Massachusetts.
FIG. 4. The effect of outlet pressure on inlet pressure of the perfused PS Medical low-pressure valve with and without an attached siphon-control device (SCD).  

FIG. 5. The effect of outlet pressure on inlet pressure of the perfused PS Medical medium-pressure valve with and without an attached siphon-control device (SCD).  

FIG. 6. The effect of outlet pressure on inlet pressure of the perfused PS Medical high-pressure valve with and without an attached siphon-control device (SCD).  

The comparisons between the four differential-pressure valves alone and in tandem with the PS Medical SCD are presented by valve model and operating pressure ranges in Tables 1 to 3. For purposes of brevity, comparisons of the various valve types plus SCD are presented at only one rate of inflow, although all of the rates defined above were utilized. The flow rate (20 ml/hr) presented in these tables is approximately that of the normal rate of CSF formation. The mean inlet pressure of the low differential-pressure valve alone varied considerably between different manufacturers, from a low of 1.14 cm H_2O (Codman) to a high of 9.8 cm H_2O (Heyer-Schulte) (Table 1). The use of the SCD outflow pressure (siphoning) on the proximal (inlet) pressure (Fig. 4). As the outlet pressure became negative so did the pressure (inlet pressure) proximal to the low-pressure valve at all inflow rates. When the outlet was horizontal (outlet pressure = 0 cm H_2O), the inlet pressure rose modestly as the rate of perfusion through the valve increased from 2 to 50 ml/hr. The addition of the SCD distal to the low-pressure valve prevented the development of a negative inlet pressure, even when the outlet tube was lowered 60 cm H_2O below the horizontal level of the valve system and SCD (−60 cm H_2O). Qualitatively similar results were obtained in experiments using the PS Medical medium- and high-pressure differential-pressure valves (Figs. 5 and 6). The major difference was that these valves had a higher internal resistance, and therefore the siphoning effect, as indicated by a negative inlet pressure when the outlet pressure was below 0 cm H_2O, was somewhat less than that noted with the low-pressure valve at the same inflow rate. At similar flow rates, these valves with higher opening pressures also generated a higher inlet pressure than the low differential-pressure valve when the pressure at the valve outlet was 0 cm H_2O. It should also be noted that when the SCD was added in series with any of these valves there was an increase in resistance to flow of the total system as shown by the higher pressure recorded proximal to the inlet of the differential-pressure valve.

### TABLE 1

<table>
<thead>
<tr>
<th>Valve Type</th>
<th>Siphon = 0 cm H_2O</th>
<th>Siphon = −60 cm H_2O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IP (cm H_2O)</td>
<td>Resistance (cm H_2O/ml hr)</td>
</tr>
<tr>
<td>PS Medical</td>
<td>2.90</td>
<td>0.15</td>
</tr>
<tr>
<td>PS Medical + SCD</td>
<td>7.70</td>
<td>0.39</td>
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<tr>
<td>Codman</td>
<td>1.14</td>
<td>0.06</td>
</tr>
<tr>
<td>Codman + SCD</td>
<td>7.27</td>
<td>0.36</td>
</tr>
<tr>
<td>Cordis</td>
<td>4.20</td>
<td>0.21</td>
</tr>
<tr>
<td>Cordis + SCD</td>
<td>7.80</td>
<td>0.39</td>
</tr>
<tr>
<td>Heyer-Schulte</td>
<td>9.80</td>
<td>0.49</td>
</tr>
<tr>
<td>Heyer-Schulte + SCD</td>
<td>14.20</td>
<td>0.71</td>
</tr>
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</table>

*SCD = siphon-control device. Flow rate = 20 ml/hr.
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TABLE 2
Inlet pressure (IP) with resistance in medium-pressure differential pressure valve with and without an SCD*

<table>
<thead>
<tr>
<th>Valve Type</th>
<th>Siphon = 0 cm</th>
<th>Siphon = -60 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IP (cm H2O)</td>
<td>Resistance (cm H2O/ml hr)</td>
</tr>
<tr>
<td>PS Medical</td>
<td>7.60</td>
<td>0.38</td>
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<tr>
<td>PS Medical + SCD</td>
<td>11.90</td>
<td>0.59</td>
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<tr>
<td>Codman</td>
<td>3.22</td>
<td>0.16</td>
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<tr>
<td>Codman + SCD</td>
<td>11.00</td>
<td>0.55</td>
</tr>
<tr>
<td>Cordis</td>
<td>10.17</td>
<td>0.51</td>
</tr>
<tr>
<td>Cordis + SCD</td>
<td>13.03</td>
<td>0.65</td>
</tr>
<tr>
<td>Heyer-Schulte</td>
<td>10.80</td>
<td>0.54</td>
</tr>
<tr>
<td>Heyer-Schulte + SCD</td>
<td>13.80</td>
<td>0.69</td>
</tr>
</tbody>
</table>

* SCD = siphon-control device. Flow rate = 20 ml/hr.

TABLE 3
Inlet pressure (IP) and resistance in high-pressure differential pressure valve with and without an SCD*

<table>
<thead>
<tr>
<th>Valve Type</th>
<th>Siphon = 0 cm</th>
<th>Siphon = -60 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IP (cm H2O)</td>
<td>Resistance (cm H2O/ml hr)</td>
</tr>
<tr>
<td>PS Medical</td>
<td>14.50</td>
<td>0.73</td>
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<tr>
<td>PS Medical + SCD</td>
<td>18.80</td>
<td>0.94</td>
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<tr>
<td>Codman</td>
<td>7.50</td>
<td>0.38</td>
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<tr>
<td>Codman + SCD</td>
<td>13.80</td>
<td>0.69</td>
</tr>
<tr>
<td>Cordis</td>
<td>24.90</td>
<td>1.25</td>
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<tr>
<td>Cordis + SCD</td>
<td>28.70</td>
<td>1.44</td>
</tr>
<tr>
<td>Heyer-Schulte</td>
<td>24.10</td>
<td>1.21</td>
</tr>
<tr>
<td>Heyer-Schulte + SCD</td>
<td>28.40</td>
<td>1.42</td>
</tr>
</tbody>
</table>

* SCD = siphon-control device. Flow rate = 20 ml/hr.

added about 4.5 to 6.0 cm H2O to the inlet pressure and approximately 0.20 to 0.30 cm H2O/ml/hr resistance to the combined differential-pressure valve and SCD shunt systems when outlet pressure was 0 cm H2O and the rate of inflow 20 ml/hr. Lowering the pressure at the valve outlet to -60 cm H2O led to a negative inlet pressure in all valve systems when not connected to an SCD. This siphoning effect was reversed when the SCD was attached distally to the differential-pressure valve. Not surprisingly, there was a 7- to 30-fold increase in the internal resistance of the valve plus SCD system under these conditions. The experiments utilizing a medium- (Table 2) or high-pressure (Table 3) differential-pressure valve also demonstrated results qualitatively similar to those obtained with the low-pressure differential-pressure valve (Table 1). The inlet pressure and intrinsic resistance of the differential-pressure valve were always substantially greater in the differential-pressure valve with higher opening pressures (high > medium > low), and the SCD was again noted to add resistance and inlet pressure to the system when the flow rate was 20 ml/hr and the pressure at the valve outlet was 0 cm H2O. Even in the medium- and high-pressure differential-pressure valves, siphoning was still present when the outlet pressure was -60 cm H2O without the SCD, but was of a lower magnitude in the high-pressure (and higher resistance) differential-pressure valve (Table 3). The siphoning was inhibited with the SCD connected in tandem with the medium- and high-pressure differential-pressure valves but with progressively greater system resistance and inlet pressure (high > medium).

Discussion

Patient Position

The pressure of the fluid within the cerebral ventricular cavity and the subarachnoid space is normally positive when measured with the individual in a horizontal position.19 The resting pressure within the ventricular cavity varies considerably with age, body activity, respiratory phase, and body position.18,19 It has been shown that in the sitting or standing position, the intraventricular pressure (IVP) and hydrostatic pressure (HP) were measured distal to the valve outlet to the atrium or peritoneal cavity. CP = closing pressure of the differential-pressure valve; AP = atrial pressure; PP = peritoneal pressure.

FIG. 7. Diagram showing the origin of the pressure (P) operating across a differential-pressure valve. The intraventricular pressure (IVP) and hydrostatic pressure (HP) were measured distal to the valve outlet to the atrium or peritoneal cavity. CP = closing pressure of the differential-pressure valve; AP = atrial pressure; PP = peritoneal pressure.
FIG. 8. Cross-sectional diagram of the Heyer-Schulte anti-siphon device. Arrows represent the direction and route of fluid flow.

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From Shunt

OPEN

To Distal Catheter

Anterior Chamber

Silicone Diaphragm

Outlet Port

Outlet Tubing

Outlet Connector

Inlet Connector

Inlet Tubing

Inlet Port

In this figure that the perfusion pressure developed across the differential-pressure valve is equal to the sum of both the IVP and the hydrostatic pressure within the distal drainage cavity and the closing pressure of the valve.\(^4,15\) The valve will open and flow will occur when the pressure at the valve inlet exceeds the opening pressure of the valve regardless of whether the IVP is positive at the inlet or the hydrostatic pressure is negative at the outlet due to siphoning with the patient in the erect position.\(^15\) As shown by Portnoy, et al.,\(^15\) and others,\(^4,16\) hydrostatic pressure is 0 cm H\(_2\)O when the individual is in the supine position because the inlet to the ventricular catheter and the outlet in the heart or peritoneal cavity is approximately 0 cm H\(_2\)O. Fluid flow through the differential-pressure valve continues until the IVP falls to a value equal to the atrial or peritoneal pressure plus the closing pressure of the valve, but IVP does not become subatmospheric (negative). With the patient in the sitting or erect position, the hydrostatic pressure is equal to the length of the vertical column of CSF contained in the outflow tube attached to the distal outlet of the valve.\(^13\) Under these circumstances, hydrostatic pressure exceeds the sum of the atrial or peritoneal pressure plus the closing pressure, the IVP becomes negative (subatmospheric), and the ventricular cavity may collapse with the possible development of neurological complications. These include ventricular catheter obstruction, subdural collections of fluid (hematoma or hygroma), low intracranial pressure syndrome, premature closure of the cranial sutures, induction of aqueductal occlusion, and slit ventricle syndrome.\(^1,3,8,9\) The addition of an anti-siphon valve to the outlet of a differential-pressure valve eliminates the siphoning phenomenon in the upright position and allows the valve to operate in response to a positive inlet pressure, thereby regulating the IVP within a more normal range of pressure values. This regulation of inlet pressure has been shown to substantially but not completely eliminate the complications that are associated with siphoning or overdrainage of the ventricular CSF.\(^4,15\) In this study, we evaluated the Heyer-Schulte ASD and the PS Medical SCD. Both of these anti-siphon valves were designed to be used with commercially available pressure-regulated valves. The in vitro and in vivo testing of the Heyer-Schulte ASD has been reported previously in detail.\(^3,15\)

Description of Anti-Siphon Devices

In the present study, both the ASD and the SCD demonstrated the ability to prevent development of a negative pressure at the inlet of these devices, even when the outlet pressure was in the range of -60 cm H\(_2\)O (Fig. 3). The design of each device is different although both function in a similar manner. The Heyer-Schulte ASD is 0.94 cm in diameter and maximally 0.38 cm high (Fig. 8). It is a normally open ASD in which the orientation of the valve is critical to its proper operation (the radiopaque arrow marker must be placed posterior and the diaphragm anterior). When properly positioned, there is an offset between the single diaphragm and the overlying skin. The PS Medical SCD is 0.94 cm in diameter and maximally 0.38 cm high (Fig. 8). It has a single Dacron-mesh reinforced silicone diaphragm and single outlet port. It is a normally open ASD in which the orientation of the valve is critical to its proper operation (the radiopaque arrow marker must be placed posterior and the diaphragm anterior). When properly positioned, there is an offset between the single diaphragm and the overlying skin. The PS Medical SCD is 0.94 cm in diameter and its maximum profile height is 0.43 cm (Fig. 9). It is a normally closed ASD in which the orientation of the device is not as critical because there are two silicone diaphragms that inhibit flow into the twin outlet ports. There is also an offset ring exterior to both diaphragms.
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FIG. 9. Cross-sectional diagram of the PS Medical siphon-control device. Arrows represent the direction and route of fluid flow.

in order to prevent the overlying scalp from occluding the apparatus.

At less negative outlet pressures, the bench tests demonstrated that the normally open ASD had a lower internal resistance and inlet pressure than the normally closed SCD (Fig. 3). As the siphoning pressure (more negative outlet pressure) increased, the SCD intrinsic resistance and inlet pressure was less that that of the ASD for the same inflow rate. This suggests that the SCD would add less resistance to fluid flow for any anti-siphon valve plus differential-pressure valve combination when the patient is in the upright position.

When attached to the distal end of the four differential-pressure valves evaluated in this study, the SCD eliminated any observable siphoning (negative inlet pressure) induced by a negative pressure at the outlet of the device when the inflow rate was approximately that of CSF formation (Tables 1 to 3). Even when the SCD was used with the PS Medical differential-pressure valve with a medium or high opening pressure (Figs. 5 and 6), the inlet pressure to the valve system rose modestly at all flow rates up to twice the normal rate of CSF production; however, the rise in pressure was significantly greater than in the SCD plus the low-pressure valve (Fig. 4).

The ASD and SCD were substantially equivalent in their performance characteristics and surgical implantation techniques. However, the SCD could be oriented to the skin surface without concern, and the operating resistance to fluid flow was somewhat less at lower subatmospheric pressures than the ASD. Both devices were designed to be used immediately distal and in tandem with a differential-pressure valve. It is important to note that the internal resistance of both devices is added to that of the attached differential-pressure valve and therefore a higher IVP is needed to actuate flow through the shunt system. A medium-pressure valve in combination with either the ASD or SCD can be converted to function as a high-pressure device, which may not be appropriate in certain cases. Our experience and that of Foltz (personal communication, 1989) is that the SCD should only be combined with a differential-pressure valve using a low opening pressure. It has previously been suggested that this is also the best combination with ASD. As with the ASD, the SCD is best placed in a loose subgaleal pocket and not in tissues of the neck, chest, or abdomen. In an infant, the use of a frontal catheter placement will keep the SCD away from the tight compressive tissues of the skull base. Based on laboratory experiments and clinical observations, Foltz (personal communication, 1989) suggested that the SCD be placed in tandem immediately distal to the differential-pressure valve and on the same level as the tip of the ventricular catheter. The SCD normally serves as the atmospheric reference point and, when the distance between it and the site of CSF inflow is approximately 0 mm, the differential-pressure valve and SCD shunt system function as a "zero pressure valve" (personal communication, 1989). Under these conditions, the
IVP cannot fall below zero on the upstream side of the shunt system. It has been suggested these anti-siphon valves be used cautiously with the high-resistance distal slit valves of the Holter type, since this type of valve may actually require siphoning for proper fluid drainage. In the present study, the SCD worked satisfactorily with the low-resistance differential-pressure valves of the diaphragm or ball type manufactured by PS Medical, Heyer-Schulte, and Cordis-Hakim, although similar results were obtained with the proximal-slit design of the Codman differential-pressure valve. The performance of the SCD with all of the differential-pressure valve systems tested in this study implies its usefulness with commercially available shunt systems for the prevention of overdrainage of ventricular CSF in the treatment of hydrocephalus.

Conclusions

In view of the increased incidence and clinical severity of subdural hematomas seen in older children and adults following VP or VA shunting, as compared to infants, it would appear that the former group is the most likely to benefit from an SCD. It is our view that there is also an advantage in using the SCD with a low-pressure valve system in the infant since it is reasonable to assume that some if not most ventricular catheter obstructions in this age group are secondary to siphoning and ventricular wall collapse. In our clinical experience, the small amount of additional resistance added to a shunting system with low opening pressure by an inline PS Medical SCD does not adversely affect intraventricular fluid drainage, as measured by isotope clearance from the reservoir of the differential-pressure valve. Only time and experience will allow comparison of the favorable in vitro flow performance of the SCD in association with presently available shunt valves to its function in a clinical setting.

Acknowledgments

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References