A modified slit-valve shunt prototype for the management of hydrocephalus

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The hydraulic properties of a double-slit valve for cerebrospinal fluid (CSF) shunting have been tested in vitro and compared to those of the corresponding standard single-slit valve. The double-valve system proved to compensate better for large transitory increases in CSF pressure than the single valves, without significant variations in the mean pressure levels.

KEY WORDS • cerebrospinal fluid shunt • cerebrospinal fluid pressure • hydrocephalus • instrumentation

PHYSIOLOGICAL as well as artificially induced increases in intrathecal volume may be accompanied in hydrocephalic patients by an abnormally large and persistent increase in the cerebrospinal fluid (CSF) pressure. Both the amplitude of the pressure increase and the time required for its compensation depend on the ability to withdraw an adequate volume of CSF out of the theca. In hydrocephalic patients with a CSF shunt device, variations in intracranial pressure secondary to change in intrathecal volume obviously depend on the characteristics of the shunt valve.

We are describing the draining response of a slit valve, widely used in the surgical management of hydrocephalus, to induced increases in the volume of fluid to be drained from an artificial model system that was devised to study CSF dynamics. We give details of the variations in this response obtained by a simple modification of the draining device.

Materials and Methods

An in vitro model (Fig. 1) was used to investigate the pressure characteristics of 1) a slit valve; 2) a pair of slit valves draining simultaneously from the same reservoir; and 3) a new double valve, devised by one of us (C.D.R.), consisting of two slit valves placed at about 0.5 cm from the end of the same catheter (Fig. 2).*

The following valves were utilized: four unselected Pudenz valves (two low-pressure and two medium-pressure valves); four unselected medium-pressure Pudenz valves, coupled in two sets, draining simultaneously (medium-medium double-valve system); four unselected Pudenz valves, two medium and two low-pressure types, coupled in two sets draining simultaneously (medium-low double-valve system); and two prototypes of the “double valve,” of medium-medium and low-medium pressure types.

The valves were connected to a rubber balloon (Fig. 1, b) containing the fluid (saline) to be drained. The fluid flowing through the valves was collected in calibrated containers and later weighed. The balloon was placed in a glass container to simulate the anatomical relationship of the dural sac to the rigid craniospinal theca. Residual air in the glass container allowed the expansion of the balloon; the elasticity of the balloon itself was appropriately limited by varying the ratio between the air and the fluid in the container. The residual elasticity was thought to serve as a

*Prototypes of the double-valve system manufactured by Codman & Shurtleff, Inc., Randolph Industrial Park, Randolph, Massachusetts.
volumetric compensation response to the induced increases in the fluid content, so simulating the natural compensation provided by dural distension and intrathecal venous-space compression.

The volume of fluid contained in the balloon could be varied by infusions of fluid from a reservoir in order to obtain predetermined pressure values. The inner pressure of the balloon was measured continuously by means of an electromanometer.‡ While the valve was draining, the pressure of the fluid in the balloon was maintained by continuously infusing saline through a constant-infusion pump.¶ Tests were performed to establish the steady-state pressure values in the system allowed by the different valves under study at variable infusion rates (namely, 0.05, 0.1, 0.25, 0.55, 1.1, 2.75, and 5.5 ml/min). An intermittent pump, connected to the balloon, was used to create phasic changes in pressure to simulate the effect of systolic CSF waves.§ Rapidly induced changes in the volume of the fluid contained in the balloon were obtained at a steady-state condition (basal condition) and under two different constant-flow rates (0.55 and 2.75 cc/min), by infusing an additional 0.5 cc of saline over 0.5 seconds.

The increases in pressure that developed in the system and the time required to restore basal pressure were carefully evaluated.

Results

Steady-Flow Conditions

The mean stabilization pressure values observed in our experiment at seven different flow rates, using a single medium-pressure Pudenz valve, a system of two medium-pressure Pudenz valves draining simultaneously, and the medium valve prototype, are illustrated in Fig. 3. The stabilization-pressure values are slightly lower with the two medium Pudenz valves working simultaneously or the medium-medium valve prototype, compared to the values with a single valve. The difference, however, becomes more evident when increasing flow rates are applied, ranging from 0.75 to 2.75 ml/min. At these infusion rates, the slope indicating pressure increase is higher with the simple medium-pressure Pudenz valve. At the highest infusion values, the rate of increase in pressure is substantially similar in all three systems, although the pressure ranges differ.

The mean stabilization-pressure values obtained under the same conditions with a single medium-pressure Pudenz valve, a single low-pressure Pudenz valve, a system of a low- and a medium-pressure Pudenz valve draining simultaneously, and a low-medium double-valve prototype are represented in Fig. 4. The figure shows that the steady-state pressure condition is the same with the low-pressure valve, the low- and medium-pressure valve system, and the low-medium double-valve prototype. However, at the highest infusion rates, the single low-pressure Pudenz valve is less apt to compensate, and the resulting pressure values

†Sanborn 286 pressure transducer manufactured by Hewlett-Packard, 3404 East Harmony Road, Fort Collins, Colorado.
‡Italglass constant-infusion pump manufactured by Sigmamotor, Inc., 3 North Main Street, Middleport, New York.
Modified slit-valve shunt

![Graph 3](image3.png)

**FIG. 3.** Hydraulic characteristics of a medium-pressure slit valve, a pair of medium-pressure slit valves draining simultaneously, and a medium-medium double-valve prototype. Note the increase in pressure in the system at the high infusion rates with the standard valves compared to the satisfactory compensation offered by the two valves draining simultaneously and the double-valve prototype.

![Graph 4](image4.png)

**FIG. 4.** Hydraulic characteristics of a medium-pressure slit valve, a low-pressure slit valve, a pair of slit valves (medium- and low-pressure) draining simultaneously, and a medium-low double-valve prototype. Note the satisfactory control of pressure at the high infusion rate offered by the medium-low pressure valves draining simultaneously, and by the medium-low pressure double-valve prototype.

obviously increase. It is worth noting that the results described above were not altered when the intermittent pump was applied to the system (the amplitude of the resulting pulse waves ranging between 2 and 3 cm H$_2$O).

**Short-Lasting Flow Increases**

The graphs in Fig. 5 show the modifications in pressure obtained throughout rapid infusion of saline at 0.5 cc/0.5 sec with the medium-pressure single Pudenz valve and with the medium-medium double-valve prototype. Tests were performed under steady-state conditions (Fig. 5 left), and with steady-flow infusion at 0.5 ml/min (Fig. 5 center) and 2.75 ml/min (Fig. 5 right).

The responses obtained either with a single valve or the double-valve prototype were not significantly modified by varying the rate of the infusion and by applying the intermittent pump for simulating the CSF systolic pulses (pulse amplitude ranging between 2 and 3 cm H$_2$O).

A comparison of the response obtained in the same experimental conditions with the single medium-pressure Pudenz valve and the double medium-medium valve prototype shows that the time required to return to the basal condition is significantly shorter with the latter. This difference may be better expressed by evaluating the variations in the computed area (an approximated scaloid) of the pressure-time response; in fact, a decrease of approximately 45% has been observed.

Similar differences have been recorded by comparing the response of single medium- and low-pressure Pudenz valves and a low-medium double-valve prototype (Fig. 6). About a 28% decrease of the computed

![Graph 5](image5.png)

**FIG. 5.** Pressure-response curves with rapid infusion of saline (0.5 cc/0.5 sec) from a standard medium-pressure slit valve (dotted line) and a medium-medium pressure double-valve prototype (continuous line). Note the decreased time constant of the double-valve prototype. This test was performed under steady-state conditions (left) and under steady-flow infusion rates of 0.55 ml/min (center), and 2.75 ml/min (right).
area of the pressure-time response was shown by the double-valve prototype.

Discussion

Two main aspects of the behavior of the double-valve prototype in our experiments should be discussed. The first relates to the characteristics of the response at low-infusion rates. This response does not differ significantly from that obtained with the corresponding commercially available valves; in fact, the mean basal pressure remains substantially the same when a single valve replaces the corresponding double-valve prototype.

There is a difference, however, in the response to high rates of steady infusion as well as to rapid increases in flow (Figs. 3–6). The variations in pressure in the system resulting from an increase in volume are reduced with the double-valve prototypes. In other words, a better compensation seems to be assured with our modified draining device. Such an aspect could be easily anticipated as, according to the Navier-Stokes equation for a viscous flow through a slit, \( P = Ka/a^2 \), where the pressure \( P \) is inversely related to the area \( a \) of the slit. The similar behavior of the two valves draining simultaneously can be explained in the same way.

The clinical use of the double-valve system should, in our opinion, be encouraged. Indeed, the basal pressure is approximately the same when the double-valve prototypes are used in place of the corresponding single valves, while compensation for the increases in CSF pressure, such as occur in many physiological conditions, occurs more rapidly.

Even if similar results were obtained in clinical application, the objection could be made that the system might present practical difficulties sufficient to overcome the theoretical advantages. There is no evidence for this. In fact, the clinical use of a double-valve draining device, such as we propose, may conceivably extend the time between shunt revisions required in hydrocephalic children for distal catheter obstruction, since if the more distal valve fails, the proximal one could continue to work for a further period of time.

The proposed modification in the draining device does not increase the number of technical components. The double-valve prototype can be regarded as a system made up of two subsystems (two single-slit valves) with the same functional properties. In such a system, the probability of failure (\( F(t) \)) is given by the following equation:

\[
F(t) = F_1(t) \cdot F_2(t),
\]

where \( F_1 \) and \( F_2 \) are the probability of failure of the single-slit valves (for the medium-medium double-valve prototype, \( F_1 = F_2 \)). As the probability of failure is less than or equal to 1 according to the equation \( F(t) = 1 - R(t) \) (where \( R(t) \) is the reliability of the system), the probability of failure of the double-valve system \( (F_d(t)) \) is equal to or less than the probability of failure of the single valves. Equation 1 might consequently be expressed as follows:

\[
F_d(t) \leq F_1(t) = F_2(t).
\]

Since the reliability of a system is \( R(t) = 1 - F(t) \), the reliability of the double-valve system is greater than that of the single valves.

References


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