In vivo intracranial pressure dynamics in patients with hydrocephalus treated by shunt placement

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Object. With the commercial availability of a variety of shunt systems, there is considerable controversy over the choice of the most appropriate shunt valve for each individual with hydrocephalus. Although the performance characteristics of all shunt systems are well documented in the laboratory setting, there is little description of the in vivo dynamics of intracranial pressure (ICP) after implantation of commonly used shunt systems in humans. The authors coupled telemonitoring devices to several different shunt systems to measure the performance characteristics of these valve systems with respect to intraventricular pressure (IVP) at increments of head elevation.

Methods. Twenty-five patients with different shunt systems and three control patients without shunts were studied for IVP at 0˚, 15˚, 30˚, 45˚, 60˚, 75˚, and 90˚ of head elevation, and the resultant curves were analyzed for the best-fit regression coefficient. For purposes of analysis the authors grouped shunt valve systems by design characteristics into three groups: differential-pressure valves ($r = -0.321 \pm 0.061$; 11 patients), nonsiphoning systems ($r = -0.158 \pm 0.027$; 10 patients), and flow-regulated valves ($r = -0.16 \pm 0.056$; four patients); there were three control patients without shunts ($r = -0.112 \pm 0.037$).

Conclusions. The authors found that differential-pressure valves always caused ICP to drop to 0 by 30˚ of head elevation, whereas all other valve systems caused a more gradual drop in ICP, more consistent with pressures observed in the control patients without shunts. Not surprisingly, the differential-pressure valve group was found to have a significant difference in mean regression coefficient when compared with those in whom nonsiphoning shunts ($p < 0.023$) or no shunts were placed ($p < 0.049$). These data provide a basis for evaluating shunt valve performance and for predicting valve appropriateness in patients in whom characteristics such as pressure and flow dynamics are weighed in the choice of a specific valve for implantation.

KEY WORDS • telemetry • ventriculoperitoneal shunt • intracranial pressure monitoring • hydrocephalus

A wide variety of extracranial CSF shunts is currently available for implantation in humans.27,28 Shunt valves for CSF fall into several distinct categories, which include basic differential-pressure valves, those with an integral or inline antisiphoning device,31 and valves that are designed to regulate by flow rather than by pressure differentiation.5 Although hydrocephalus in humans is presumably a multifactorial disease, there are no guidelines as to which specific shunt product might be more appropriate for hydrocephalus of a certain origin. Recent evaluations of various types of shunt valves in which the time from implantation to malfunction was assessed may even be interpreted as suggesting that there is no difference in appropriateness of shunt valves.9 Recommendations of various shunts for specific types of hydrocephalus have generally been based on laboratory data rather than on the in vivo dynamics of shunt systems.12,28

Noninvasive extracranial monitors of CSF shunt pressure have been available for some time but have been used infrequently.4,7,15,17 A telemonitor based on an implanted radiofrequency circuit (TeleSensor) has been used in the past to measure ICP dynamics under a variety of conditions in patients with and without shunts in place.5 We have adopted the use of the TeleSensor as a standard adjunct to the management of patients with hydrocephalus and implanted shunts. In this fashion, we have had the opportunity to couple the telemonitoring device to a large variety of commercially available shunts and have been able to assess their in vivo pressure dynamics while monitoring shunt function. This has allowed us to observe similarities and differences in the in vivo ICPS achieved using these shunts.

Clinical Material and Methods

Clinical Data

Twenty-five shunt systems were implanted in 22 patients (13 male, nine female) over a 3-year period. The median age of these patients at the time of shunt implantation or revision was 27.5 years (range 7–71 years). There were three patients with myelomeningocele-related

Abbreviations used in this paper: CSF = cerebrospinal fluid; ICP = intracranial pressure; NPH = normal-pressure hydrocephalus; OSV = Orbis-Sigma valve.
hydrocephalus, two with NPH, and 17 with either post-
hemorrhagic hydrocephalus or hydrocephalus of un-
known cause at the time of TeleSensor implantation. No
patient was known to have noncommunicating hydro-
cephalus.

Each shunt system included a TeleSensor device in se-
ries proximal to the valve within the system’s shunt com-
ponents. All shunt systems were ventriculoperitoneal ex-
cept two: a medium-pressure Radionics contour-flex
valve and a Codman-Medos valve with a PS Medical si-
phon-control device, both of which were ventriculoatrial
shunts. The distribution of valve systems was as follows:
1) differential-pressure systems: two PS Medical high-
pressure contour valves, one PS Medical medium-pres-
sure low-profile valve, one Hakim low-pressure valve, one Ra-
dionics low-pressure contour-flex valve, and five Radion-
cics medium-pressure contour-flex valves; 2) nonsiphoning
systems: two Delta 1.0 and two Delta 1.5 valves, one
Equiflow low-pressure and one Equiflow medium-pres-
sure valve, one PS Medical high-pressure contour valve
with a PS Medical siphon-control device, one Radionics
medium-pressure contour-flex valve with a Radionics si-
phon-limiting device, one Radionics low-pressure contour-flex
valve with a Radionics siphon-limiting device, two Codman-Medos
valves with a PS Medical siphon-control device; and 3) flow-regulated systems: four Cor-
dis OSVs. The group of patients without shunts (controls)
consisted of three individuals with TeleSensors connected
in a blunt-ended fashion to ventricular catheters. Two of
these patients had undergone endoscopic fenestration of
cysts (pinea region and lateral ventricular cysts) with sub-
sequent catheter placement for hydrocephalus that did not
develop. The third patient underwent repair of a fron-
tal leptomeningeal cyst in the setting of ventriculomegaly;
a catheter was placed to treat the expected hydrocepha-
lus, which never developed. All three patients had been
asymptomatic for at least 6 months after the catheter
placement before their ICP values were used as unshunt-
ed control values.

Measurements of ICP

The ICP measurements were obtained as described10,18
by using the TeleSensor device.4,7 Angles of elevation of

Fig. 1. Graph showing postural ICP dynamics in three control
patients without shunts. [Normal (1), (2), and (3)]. deg = degrees of
head elevation.

Fig. 2. Graph showing postural ICP dynamics in 11 patients
with differential-pressure valve shunt systems. Note the steep
curves that intercept the zero pressure axis by 30˚ of head eleva-
tion. H-S = Heyer Schulte LPV valve; Hakim = Cordis-Hakim
valve; Med = medium-pressure valve; PSMed = PS Medical con-
tour valve; Radionics = Radionics contour-flex valve. Numbers in
parentheses represent the case number of the patient in whom the
shunt system was placed, beginning at Case 1 for each system.

the head were estimated from a tilt table or from the angle-
measuring device found in the frames of hospital beds. Mea-
surements were performed two to three times over 20
to 30 seconds at each postural elevation (0˚, 15˚, 30˚, 45˚,
60˚, 75˚, and 90˚). Our system did not include a negative-
pressure generator, as reported in Chapman, et al.5; there-
fore we were unable to assess the magnitude of negative
pressures. Negative pressures were necessarily expressed
as zero values. There were no differences greater than 1
cm H2O among multiple measurements performed at any
head elevation; therefore, results were plotted using the
mean value of these measurements (Figs. 1–5). Intracrani-
al pressures are expressed in centimeters of water, as cali-
brated on the telemonitoring system, measured at the site
of the TeleSensor. Due to a hysteresis effect from head
raising and lowering as reported previously,5 ICP is ex-
pressed only for head-of-bed elevation. Results were plot-
ted directly as pressure against degree of elevation of the
head of the bed.

Statistical Analysis

For control patients without shunts and for each shunt
system, a dynamic-pressure curve was obtained, as shown
in Figs. 1 through 4. These values were subjected to mul-
tiple regression analyses to determine a best-fit regression
coefficient. The regression coefficients were then grouped
by shunt system type: differential-pressure, nonsiphoning,
and flow-regulated valves, and control, and these groups
were subjected to analysis of variance. Significance was
determined using Fisher’s post-hoc analysis at the 5% lev-
el. All statistical analyses were performed using the Stat-
view 4.0 statistics package running on a Macintosh per-
sonal computer.

Sources of Equipment

The TeleSensor and the telemonitoring system (models
ICP-M4 and ICP-M3) were purchased from Radionics,
Burlington, MA, as were the low- and medium-pressure
contour-flex valves, the Equiflow valves, and the siphon-
limiting device. The high- and medium-pressure PS Med-
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Results

Dynamic ICP curves for the shunt systems examined, as well as controls, are shown in Figs. 1 through 4. We observed that in patients with raised ICP in whom differential-pressure valve systems were used (Fig. 2) all curves had crossed the zero intercept by 30° of head elevation. This was in contrast with the controls (Fig. 1), as well as patients with nonsiphoning (Fig. 3) and flow-dependent (Fig. 4) shunt systems. The nonsiphoning shunt systems generated dynamic-pressure curves that were very similar to those found in the controls, both in curve shape and in the zero intercept. The flow-dependent shunt systems were variable in curve shape and had similarities to both differential-valve systems and nonsiphoning systems.

Controls (three patients) were found to have a mean regression coefficient of $r = -0.321 \pm 0.061$, which was significantly different from that of the controls ($p < 0.049$). In the 10 patients with nonsiphoning valve systems a mean regression coefficient of $r = -0.158 \pm 0.027$ was produced, which was also significantly different from that in the differential-valve systems ($p < 0.0226$). There was no difference between the nonsiphoning valve group and the control group. The four flow-regulated valve systems ($r = -0.16 \pm 0.056$) were not found to have a significantly different regression coefficient from the group with differential-pressure valves, those with the nonsiphoning systems, or controls. This may be a function of the small sample size or it may reflect the variability of the pressure dynamics in each of the flow-control valves (Fig. 4).

Three valve systems were revised after initial pressures had been obtained. These revisions consisted of the addition of a nonsiphoning component to an existing differential-pressure (siphoning) valve system (PS Medical high-pressure contour valve with or without a PS Medical siphon-control device, Radionics medium- or low-pressure contour-flex valves with or without a Radionics siphon-limiting device.) The changes produced in these specific shunt systems are highlighted in Fig. 5. Of note, the high- and medium-pressure valve systems appeared to have additional resistance added to the system, as well as changes in the zero intercept. The curves for the low-pressure system crossed the zero intercept at a relatively low head elevation, which did not allow observation of the curve changes, although the pressure in the supine position was elevated by the nonsiphoning component. These changes in the dynamic curve likely explain the effects of the nonsiphoning component on symptomatic low-pressure phenomena.

Within the three groupings of valve type, there appeared to be no consistent differences based on valve manufacturer, although the number of shunt products from each manufacturer was small. As noted, readings in all differential-pressure valves reached a zero intercept by 30° of head elevation, and values for all nonsiphoning valves appeared to have a much flatter curve than in differential-valve systems, regardless of manufacturer. Unfortunately, we were unable to examine the pressure curves in the negative-pressure range to assess the stringency of antisiphoning activity of each specific nonsiphoning valve system. However, these basic observations indicate that as far as delivery of a specific pressure dynamic, overall shunt design differences are much more important than variations in shunt construction among manufacturers.

Discussion

We have examined the in vivo pressure dynamics in 25 variations of CSF shunt systems by using an implanted...
The differential-pressure valve shunt systems produced dynamic ICP curves that were steep and that crossed the zero intercept at 30° of head elevation (Fig. 2). This result was significantly different from the curves seen in controls. The most common functional complications of ventriculoperitoneal shunt placement are related to overdrainage phenomena, 20 subdural hematoma, slit ventricle syndrome, 24 low-pressure headache, and craniosynostosis. 16 Our data readily explain these phenomena by the fundamental difference in ICPs produced by the differential-pressure valve when compared with the control patients. Constant and abnormally low or negative pressure in the nonsupine position theoretically may affect bone growth and cerebral perfusion, and, in young children, brain development. This may explain why, although the overt symptoms of hydrocephalus (such as vomiting, bradycardia, or bulging fontanelle) disappear, in children who undergo shunt placement at birth, long-term deficits in cognition remain. 1,3,23 A detailed study of neurocognitive outcome based on shunt dynamics and ICP would be optimal to determine the best ICP dynamic for higher cortical neural development.

Interestingly, all differential shunt systems examined produced the same type of curve without regard to vendor or specifics of the valve design (for example, Hakim valve ruby ball/metal arm compared with PS Medical Silastic diaphragm). This observation supports the notion that shunt valve dynamics are nearly identical between vendors, although other attributes, such as durability, may be very different. A similar observation was made among the various nonsiphoning valve systems examined in this study.

Nonsiphoning Valve Shunt Systems

The dynamic intraventricular pressure curves observed in patients with nonsiphoning shunt systems (Fig. 3) were much closer in shape and zero intercept to the controls than what was observed in patients with differential valve shunts. This observation is predicted by the design of the system, which should not allow negative pressure (relative to atmospheric pressure) as the patient’s head is elevated. Pressure in the supine position still appeared to be mostly controlled by the differential pressure portion of the valve system.

Several aspects of this type of pressure curve deserve discussion. The nonsiphoning valve appears to restore relatively normal ICP dynamics. This result is depicted most directly in Fig. 5, which shows ICPs from the same patients before and after addition of a nonsiphoning component to the shunt system. Although only three patients are depicted, there is clearly more resistance in the nonsiphoning system, and the zero intercept is much higher in two of the patients. These observations lead us to conclude that the consequences of overshunting, such as headache, slit ventricle syndrome, and premature closure of the sutures, will be reduced by the use of nonsiphoning valves.

There are some situations such as the NPH syndrome that may require subnormal ICPs, 25 in which restoring normal pressures may not affect the disease. Normal-pressure hydrocephalus, analogous to low-pressure hydrocephalus, 30 may require subnormal ICPs for effective treatment. Although low-pressure hydrocephalus may require...
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the negative pressures associated with ventriculopleural shunting, it would seem that NPH may not always be adequately treated by a nonsiphoning system shunting to the peritoneum. Previous bench test observations have prompted the prediction that Delta valves may not adequately treat NPH caused by undershunting.12 This conclusion was based on possible technical failure of the antishunting component rather than pressure mismatch.

Because newborns tend to have lower ICPs than children or adults, brain injury from hydrocephalus in a newborn may require decreased ICP for brain recovery and development. This group may benefit more from a differential-pressure system than from the relatively normal pressures predicted according to observations of nonsiphoning valves; previous observations of differential-pressure valve systems have indeed found elevations in cerebral perfusion.13

Flow-Regulated Valves

Our study of flow-regulated valves consisted of a group of only four implanted OSVs.14 We have not yet encountered a Diamond valve that has been coupled to a Tele-Sensor device. Although it is difficult to generalize from such a small sample size, the ICP curves generated in patients with OSVs appeared to conform to an intermediate area between nonsiphoning shunt system curves and those from the differential-pressure valve systems. This would be predicted from the tendency of the valve not to allow very negative pressures, due to the increased impedance to flow with relative differential pressure from head to belly, yet no set differential opening and closing pressure. The dynamics of the shunt in the negative pressure range cannot be addressed in our study. However, they may be very negative in that the OSV has been linked to a high rate of subdural hematoma in patients with NPH, when compared with differential-pressure valve systems.32

Comparison Among Valve Systems

The results of the Pediatric Valve Design Trial have led to predictions of a similar rate of malfunction between differential-pressure valves, nonsiphoning valves, and OSVs. Because the majority of malfunctions are caused by ventricular catheter occlusion and not valve malfunction, this is not unexpected. However, our study clearly shows that shunt systems of fundamentally different design produce significantly different dynamic ICPs in vivo (Figs. 2–4). The significance of this finding is important for choosing a shunt system in the context of the multifactorial origins of hydrocephalus. It may be that certain types of hydrocephalus (for example, communicating compared with noncommunicating) or hydrocephalus associated with certain types of brain injury (for example, prenatal infarct) may respond better to a specific pressure dynamic. This dynamic may not change the rate of shunt malfunction but may only be reflected by improved symptoms or better performance on neurocognitive testing. The introduction of a programmable differential-pressure valve will allow fine-tuning of ICP in the patient with hydrocephalus who undergoes shunt placement. We hope the knowledge of the in vivo ICP dynamics of a variety of shunt systems, coupled with detailed studies linking pressure dynamics and outcome, will allow implantation of the most effective shunt system possible in each individual with hydrocephalus.

Disclosure

The authors have no financial, proprietary, or other interest in the Radionics company or any of its products.

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