Cerebrospinal fluid hydrodynamics after placement of a shunt with an antisiphon device: a long-term study

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Object. Few studies have been performed to investigate the cerebrospinal fluid (CSF) hydrodynamic profile in patients with idiopathic adult hydrocephalus syndrome (IAHS) before and after shunt implantation. The authors compared the in vivo CSF hydrodynamic properties, including the degree of gravity-induced CSF flow, of a shunt with an antisiphon device with a standard shunt.

Methods. Twelve patients with IAHS underwent insertion of shunts with Delta valves. Clinical testing, magnetic resonance imaging, and CSF hydrodynamic investigations were conducted with intracranial pressure (ICP), gravity effect, and pressure–flow curve of the shunt estimated at baseline and at 3 and 12 months postoperatively. No shunt was revised.

Despite postoperative clinical improvement in all patients who received Delta valves, the mean ICP was only moderately reduced (mean decrease at 3 months 0.3 kPa \( p = 0.02 \), at 12 months 0.2 kPa [not significant]). Patients with the greatest increase in ICP preoperatively had the most pronounced decrease postoperatively. The hydrostatic effect of the Delta valves was significantly lower than with the Hakim shunts (0.1–0.2 kPa compared with 0.6 kPa). The increased conductance (that is, lowered resistance) was up to 14 times higher with the Delta valves compared with preoperative levels.

Conclusions. The function of a CSF shunt may be more complicated than previously thought; the subcutaneous pressure acting on the antisiphon device can modify the shunt characteristics. A compensatory increase in CSF production may counteract the increased outflow through the shunt. The improved CSF outflow conductance may increase the intracranial compliance and thereby dampen a pathological ICP waveform.

Key Words • idiopathic adult hydrocephalus syndrome • differential pressure valve • antisiphon device • cerebrospinal fluid dynamics • cerebrospinal fluid flow

It is generally believed that the essential and sole role of a VP shunt in a patient with hydrocephalus is to increase CSF outflow and normalize ICP. Very little is known about the optimal physiological profile of CSF circulation postoperatively, and there is little agreement among clinicians as to the most efficient and reliable CSF valve system. To date, no CSF shunt has been proven superior to the others.

Technical data about shunt properties are usually described by the manufacturer according to international standards. These guidelines have been criticized for being nonspecific, and it is estimated that 50% of postoperative shunt complications are directly or indirectly caused by inadequate hydrodynamic performance of the devices.

There is a growing body of knowledge, mainly based on laboratory research, about the performance of different types of shunts. The main research involves alterations of the flow into the shunt while the corresponding pressure is registered or vice versa. In only a few studies have researchers evaluated the performance and properties of different shunt systems in an in vivo setting. Recently, we introduced a CSF infusion method to be used preand postoperatively in patients with communicating hydrocephalus. This in vivo technique makes it possible to assess CSF hydrodynamics postoperatively and to determine the properties of the shunt system, including the degree of gravity-induced CSF flow.

The traditional differential pressure valves are sensitive to body posture, which may induce overdrainage due to siphoning. Valves with ASDs may decrease these complications, but inadequate drainage of CSF due to excessive siphon-reducing function has been reported.

Abbreviations used in this paper: ASD = antisiphoning device; CSF = cerebrospinal fluid; \( \Delta P \), \( \Delta P_3 \), \( \Delta P_{12} \) = postoperative decrease in CSF pressure at baseline and at 3 and 12 months postoperatively; \( \Delta P_{post} \) = postoperative decrease in CSF pressure after sitting for 10 minutes at baseline and at 3 and 12 months; \( G_0 \), \( G_3 \), \( G_{12} \) = CSF outflow conductance preoperatively and at 3 and 12 months postoperatively; IAHS = idiopathic adult hydrocephalus syndrome; ICP = intracranial pressure; MMSE = Mini-Mental State Examination; \( P_{post} \) = postoperative CSF pressure after sitting for 10 minutes; \( P_{pre} \) = postoperative pressure; \( P_{pre} \) = preoperative pressure; SD = standard deviation; VP = ventriculoperitoneal.
Our main purpose in this study was to investigate the in vivo function of a standard valve with an ASD in patients with IAHS. In a previous study, we described 28 patients with IAHS preoperatively and 3 months after the implantation of a differential-pressure valve (Hakim valve). Those patients, who were used as controls in this study, fulfilled the same inclusion criteria and had been treated with the same CSF infusion technique that was used in the present study.

Clinical Material and Methods

Patient Population

Twelve patients with IAHS were included in this prospective study. The mean age of the patients studied was 73 ± 6 years (± SD); eight of the patients were women and four were men. The preoperative patient selection procedure has been summarized previously. Briefly, the presence of a gait disturbance was considered to be the cardinal clinical feature of IAHS and always preceded the development of cognitive decline or urinary symptoms. All patients had communicating hydrocephalus without severe white matter lesions or severe cortical atrophy.

Preoperatively, clinical characteristics were recorded and routine laboratory tests, a magnetic resonance study, and an informed consent form for all aspects of the trial were obtained. A CSF hydrodynamic investigation, which is described later, was used to measure the ICP and the CSF outflow conductance (that is, the inverse of resistance). Each patient’s gait was recorded on videotape and the gait velocity was measured. An MMSE was also performed.

After the baseline investigation was completed, all patients underwent implantation of a differential-pressure valve with an ASD (Delta valve at performance level 1.5). In all cases the procedure was performed by the same senior neurosurgeon. The valve was implanted at the level of the foramen of Monro by using a VP approach.

Neuroradiological and CSF hydrodynamic investigations, as well as tests of gait and cognitive functions, were repeated at follow-up visits 3 and 12 months postoperatively. Surgical complications and adverse events during the follow-up period were recorded.

Investigation of CSF Hydrodynamics

The methodology of the CSF hydrodynamic investigation has been described previously, but the equipment has recently been rebuilt and modernized (Fig. 1). Briefly, at 8 a.m., after 12 hours of bed rest, two needles (outer diameter 1.2 mm) were inserted in the L3–4 interspace while the patient was in the sitting position. Free passage was assessed by aspiration of 2 ml of CSF, which was replaced with artificial CSF. The patient was then placed supine with the zero-pressure reference level at the cranial sagittal center. Drainage of CSF and infusion of artificial CSF were performed with a peristaltic pump. The management of data acquisition and pressure regulation through pump control were performed with software and an electronic control unit developed at Umeå University. Software was programmed in a LabVIEW environment and run on a personal computer with a data acquisition board. Pressure was measured with an ICP monitoring kit calibrated at 0- and 3-kPa levels.

The $P_{c}$ was determined after pressure stabilization for...
at least 10 minutes, usually after 30 to 60 minutes of recording. The conductance of the CSF outflow pathways was determined by applying a pressure level to the CSF space while recording the resulting rate of inflow of artificial CSF into the patient. Equilibria of pressure and flow at six different levels, added in increments of 0.5 kPa and kept at a stable level for approximately 5 minutes, were obtained. There is a straight-line relationship between pressure and flow in a patient without a shunt, and a linear regression analysis was performed and the $r^2$ was calculated. The corresponding slope for the pressure–flow values, that is, the regression coefficient, is equal to the conductance.

Assessment of Shunt Function

At the follow-up visits 3 and 12 months after the shunting procedure $P_{\text{post}}$, the pressure–flow curve, and the $P_{\text{grav}}$ of the shunt were measured.\(^{21}\) To avoid effects from outflow through the shunt caused by body position or physical exercise before the investigation, the postoperative investigation was started with the CSF infusion. From the pressure–flow curve the conductance was calculated in the same way as preoperatively. To identify nonlinear relationships, the curves were visually inspected and the $r^2$ calculated.

After the CSF infusion test, the recorded pressure declined spontaneously. The $P_{\text{post}}$ was determined when the resting recording had been stable for at least 10 minutes, usually after 30 to 60 minutes of postinfusion recording.

The gravity (or siphoning) effect of the shunt was tested at the end of the investigation (Fig. 2). Patients were asked to sit upright for 10 minutes, after which they again lay supine. The corresponding CSF pressure ($P_{\text{grav}}$) was then registered by using the same zero-pressure reference level as mentioned earlier. In a healthy control volunteer or a patient with a VP shunt without a $P_{\text{grav}}$, the $P_{\text{grav}}$ is the same as $P_{\text{post}}$. In a patient with a VP shunt with a $P_{\text{grav}}$, $P_{\text{grav}}$ should be lower than $P_{\text{post}}$. The gravity effect was not measured preoperatively for these patients, but earlier experiences showed that no decrease in pressure occurred.

Abbreviations and Definitions of Hydrodynamic Variables

The following CSF hydrodynamic variables were measured in each patient: 1) preoperative CSF pressure ($P_{\text{pre}}$); 2) postoperative CSF pressure ($P_{\text{post}}$); 3) postoperative CSF pressure after sitting for 10 minutes ($P_{\text{grav}}$); 4) postopera-
Cerebrospinal fluid dynamics after shunt placement

with a Ppre greater than 2 kPa to have a more pronounced
decrease in CSF pressure (Ppre – Pps = xPpre); 5) gravity
effect (Pgrav – Ppre = xPgrav); 6) preoperative CSF outflow
conductance (Gpre); and 7) CSF outflow conductance 3 and
12 months postoperatively (G3 and G12).

Variables of Surgical Outcome and Statistics

To evaluate postoperative improvement in the study
population, the patients’ gait was classified into two cate-
gories, improved and not improved, according to video-
tape recordings and measurement of gait velocity.23 The
evaluation was made by a physiotherapist who did not
know whether the video recording was made pre- or post-
operatively. An increase of 2 points or more on the MMSE
or a postoperative result of 28 points or more was taken
as an indicator of improvement in the patients’ cognitive
status.23

Comparisons of variables pre- and postoperatively were
evaluated using a paired t-test, and 95% confidence in-
tervals were used to compare patients with the controls.
Linear regression or analysis of variance was performed
when appropriate.

Sources of Supplies and Equipment

The Cordis shunts with Hakim differential-pressure
valves were purchased from Cordis Endovascular, Miami,
FL. The Delta valves were kindly donated by Medtronic
PS Medical Inc., Minneapolis, MN. The peristaltic pump
(model MS-1 REGLO 160) was acquired from Ismatec
SA, Zürich, Switzerland. The LabVIEW equipment was
obtained from National Instruments, Austin, TX, and the
personal computer from Apple Computer, Inc., Cupertino,
CA. The data acquisition board was provided by GW In-
struments, Somerville, NJ. The ICP monitoring kit was
supplied by Becton-Dickinson, Franklin Lakes, NJ.

Results

Preoperative CSF Hydrodynamics

The preoperative CSF hydrodynamics of the patients
who underwent shunt placement had a G3 that was signif-
ificantly increased; G3 was four to 14 times higher than the
Gpre. In three patients (Cases 7–9), the relationship be-
tween pressure and flow was bilinear (Fig. 4).

Three-Month Follow-Up Findings

All 12 patients kept their 3-month follow-up appoint-
ment. The CSF hydrodynamic profiles for each patient are
presented in Table 1. The CSF pressure was significantly
decreased (mean ×Pps, −0.3 kPa; p = 0.02, paired t-test).
As shown in Fig. 3, there was a tendency for the patients
with a Pps greater than 2 kPa to have a more pronounced
decrease of the lumbar pressure postoperatively than pa-
tients with a normal Pps (that is, ≤ 2 kPa).

The difference between the lumbar pressure measured
before and after the patients sat for 10 minutes indicated
a minor ×Pps (p = 0.02, paired t-test). The two patients
(Cases 7 and 10) with the most pronounced ×Pps each
had a reduction of 0.4 kPa.

The patients were mobilized the day after surgery. The

patient in Case 10 suffered from a subdural hematoma 9
months after the operation, but no other serious postsurgi-
cal complications were seen. No shunt infection was ob-
served and no revision was performed.

At the 12-month follow-up visit, three of the 12 pa-
tients (Cases 10–12) could not be evaluated because of
a subdural hematoma, patient refusal, or administrative
reasons. The ×Pps; and ×Pgrav; are presented for each pa-
tient in Table 1. The correlation between ×Pps; and ×Pgrav; was
high (r² = 0.75, p = 0.003; regression analyses). The
decrease of CSF pressure at rest was not significant (mean
×Pps; −0.2 ± 0.4 kPa [± SD]). The ×Pgrav; was not sig-
nificant, indicating a general absence of any ×Pgrav.

The pressure–flow curves at the 12-month follow-up re-
view are presented in Fig. 4. As shown, the results for G1
and G2 are very similar for the patients in Cases 1 through
6, whereas in the patients in Cases 7 through 9 there was
a nonlinear relationship between pressure and flow, as al-
ready described.

Clinical Outcome

Clinical improvements in the 12 patients with the Delta
valves are summarized in Table 2. At the 3-month follow-
up review gait was considered improved in the majority of
patients, and after 1 year gait was still improved in half of
them. The improvement in cognitive status was less pro-
ounced.
Discussion

The usual way to assess shunt hydrodynamic properties is in vitro testing in bench-test systems according to the guidelines described in laboratory manuals. The main finding in the present study is that it was possible to evaluate hydrodynamic shunt characteristics in vivo by using a new CSF hydrodynamic method that allowed us to compare the patients’ CSF hydrodynamic profiles before and after shunt implantation. This new method allows us to perform the investigations under standardized conditions and to ascertain gravity effects, with pressure and flow measurements obtained in patients who are in a relaxed, supine position with a well-defined zero-pressure level. Furthermore, this constant-pressure method makes it possible to induce the number of ICP levels required for a pressure–flow curve with a high degree of precision, by a rapid infusion of artificial CSF and in a short time interval.

As can be seen in Fig. 4 we found good reproducibility for the patients in Cases 1 to 6 when comparing the pressure–flow curves at 3 and 12 months. There is also a linear relationship between pressure and flow, although pressure–flow curves for the patients in Cases 7 to 9 diverge from the others. These curves seem to be bilinear, probably because the valves were not completely open at low pressure.

Conventional differential-pressure valves like that in the Hakim shunt are the most commonly used in clinical practice. In a previous study we found that the Hakim shunt lowered ICP, mainly because of the siphoning of CSF from the ventricular system when the patient was in an upright position. This effect may cause problems with overdrainage. The Delta valve, in which an ASD is incorporated with a differential-pressure valve, was developed to overcome this problem of uncontrolled drainage in patients who are sitting upright. In supine patients the Delta shunt, like the Hakim shunt, functions as an ordinary differential-pressure shunt; however, malfunction of shunt systems with ASDs has also been reported (for example, inadequate drainage of CSF secondary to an excessive siphon-reducing function).

In the patients with the Hakim valves, there were no differences when the preoperative mean CSF lumbar pressures were compared with the postoperative levels. The differences between the gravity effects in the Hakim and Delta valves were highly significant (Fig. 5).

The cardinal clinical feature of IAHS is gait disorder, and the typical CSF hydrodynamic characteristics are a

Fig. 4. Graph showing pressure–flow curves preoperatively (triangles), at 3 months (squares), and at 12 months (circles) postoperatively, respectively. Units for the abscissa are kilopascals and for the ordinate the units are cubic millimeters per second. Numbers 1 through 12 = case numbers.
Cerebrospinal fluid dynamics after shunt placement

### TABLE 2
Postoperative improvement in gait and cognition in 12 patients who received shunts with ASDs*

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Gait 3 Mos</th>
<th>MMSE 3 Mos</th>
<th>Gait 12 Mos</th>
<th>MMSE 12 Mos</th>
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<tbody>
<tr>
<td>1</td>
<td>70, F</td>
<td>+</td>
<td>ND</td>
<td>–</td>
<td>ND</td>
</tr>
<tr>
<td>2</td>
<td>66, F</td>
<td>+</td>
<td>ND</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>65, F</td>
<td>–</td>
<td>ND</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>81, M</td>
<td>+</td>
<td>ND</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
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<td>77, M</td>
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</tr>
<tr>
<td>6</td>
<td>72, F</td>
<td>+</td>
<td>ND</td>
<td>–</td>
<td>ND</td>
</tr>
<tr>
<td>7</td>
<td>83, F</td>
<td>NA</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>8</td>
<td>76, M</td>
<td>+</td>
<td>+</td>
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<td>–</td>
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<tr>
<td>10</td>
<td>75, F</td>
<td>+</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>11</td>
<td>73, F</td>
<td>+</td>
<td>ND</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>12</td>
<td>64, F</td>
<td>+</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
</tbody>
</table>

*NA = not applicable (unable to estimate because preoperative video recording was not available); ND = not done; + = improvement; – = no improvement.

slight to moderate increase in ICP and a low conductance (that is, increased resistance). Therefore, a successful shunting procedure should improve gait function and the CSF hydrodynamic disturbances, that is, decrease ICP and increase conductance.

In this study the Delta shunt provided an effective antisiphoning mechanism and a high conductance or low resistance. The ICP was mainly reduced in the patients who had increased ICP preoperatively; however, in all patients the ICP levels were higher than the opening pressure of the shunt (0.6–1.2 kPa according to the manufacturers’ technical data) both at 3 months and 12 months after shunt placement. This indicates possible underdrainage. The unequivocally improved clinical status of all patients speaks against this mechanism as the sole explanation for these findings.

The common opinion is that shunts remove excess CSF, resulting in a decrease in CSF pressure. The opening pressure of a CSF shunt is the pressure at which the valve opens. For all differential pressures lower than the opening pressure, the shunt is inactive and will not affect the hydrodynamic system of the patient. For pressures exceeding the opening pressure by a certain amount there will be a net flow through the shunt. After placement of a differential-pressure CSF shunt the outflow will occur both through the normal pathways and through the shunt. The pressure will depend on the CSF production and on the outflow conductance of the whole system. Because the design of the Delta shunt includes an ASD, there will be a dependence on the subcutaneous pressure and that pressure will simply add to the opening pressure of the shunt.

In this study we found that CSF pressure was not lowered by implantation of a CSF shunt; however, the device did increase the conductance of the system significantly. Because CSF pressure was unchanged or only slightly reduced, other aspects of the changed CSF dynamics induced by the shunt insertion must be considered to explain the clinical improvement. Strictly hydrodynamically speaking, there are two possible options to explain the unchanged ICP level after Delta shunt implantation.

### Explanation 1: Subcutaneous Pressure

One explanation assumes an unchanged rate of CSF production. The shunt valve remains closed below the CSF resting pressure. Because the ICP does not decrease, the opening plus the subcutaneous pressure must be equal to or greater than the corresponding $P_{\text{pre}}$, otherwise there would be flow through the shunt and the CSF pressure would decrease. Furthermore, because we found an increased conductance for pressures above the CSF resting pressure, as well as clinical improvement, the valves were functioning. This indicates that the subcutaneous pressure contributes substantially to the shunt opening pressure, because the opening pressure of the valve is specified as 0.6 to 1.2 kPa. The bilinear pressure–flow relationship in the patients in Cases 7, 8, and 9 even indicates a shunt opening pressure higher than $P_{\text{pre}}$. In previous experimental studies it has been suggested that although the subcutaneous pressure around the ASD of the Delta valve may vary in individual patients, it may significantly affect the opening pressure of the valve. A gradual rise was observed in the opening pressure as the magnitude of the external pressure was increased. Because of the subcutaneous pressure effect, it is therefore possible to develop shunt adequacy or insufficiency when using valves with ASDs.

### Explanation 2: Rate of CSF Formation

Perhaps the body adjusts to the increased outflow conductance of the CSF system by an increase in CSF production to maintain the CSF resting pressure as it was before the shunt insertion. The effect of shunting procedures on CSF production must be further investigated.

Some investigators believe that shunts are effective primarily because the outflow conductance is increased. A reduced CSF outflow conductance is often an important pathogenic factor in IAHS and may cause a hyperdynamic CSF state, defined by high-amplitude CSF pulse pressure waves when compared with normal individuals. This undamped waveform may reflect a reduction in intracranial compliance caused both by a diminished cerebral...
venous venting capability and by a maximal CSF space distension. Furthermore, a correlation between the clinical response to shunt surgery on one hand and intracranial compliance, pulse pressure, and the presence of a high time percentage of B waves on the other has been shown in patients with IAH. In a series of eight patients with IAHs in whom shunts were placed, the postoperative ICP did not decline but the B waves disappeared. Patients with IAHS in whom shunts were placed, the postoperative device was at a high opening pressure. During that period baseline pressure remained unchanged, indicating that the improvement had resulted from a reduction in resistance. Thus, the important effect of a shunt insertion could be an increase of conductance leading to elimination of pressure waves, or the presence of a shunt may ameliorate the potentially adverse effects of pressure waves.

Conclusions

Our results support the concept that normalization of the CSF outflow conductance is a very important factor in the clinical improvement observed after shunt insertion. One possible mechanism could be the elimination or amelioration of pressure waves due to an increase of the intracranial compliance. Further studies are needed to elucidate this particular aspect of CSF dynamics and the effect of shunt placement on CSF production.

Disclosure

Medtronic PS Medical, Inc., contributed the Delta valves. The company did not claim any service in return. The authors have no financial interest in the company.

References