Cerebrospinal fluid outflow resistance as a diagnostic marker of spontaneous cerebrospinal fluid leakage

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OBJECTIVE Spinal CSF leakage causes spontaneous intracranial hypotension (SIH). The aim of this study was to characterize CSF dynamics via lumbar infusion testing in patients with and without proven spinal CSF leakage in order to explore possible discriminators for the presence of an open CSF leak.

METHODS This analysis included all patients with suspected SIH who were treated at the authors' institution between January 2012 and February 2015. The gold standard for “proven” CSF leakage is considered to be extrathecal contrast accumulation after intrathecal contrast injection. To characterize CSF dynamics, the authors performed computerized lumbar infusion testing to measure lumbar pressure at baseline (opening pressure) and at plateau, as well as pulse amplitude, CSF outflow resistance ($R_{CSF}$), craniospinal elastance, and pressure-volume index.

RESULTS Thirty-one patients underwent clinical imaging and lumbar infusion testing and were included in the final analysis. A comparison of the 14 patients with proven CSF leakage with the 17 patients without leakage showed a statistically significantly lower lumbar opening pressure ($p < 0.001$), plateau pressure ($p < 0.001$), and $R_{CSF}$ ($p < 0.001$) in the group with leakage. Sensitivity, specificity, and positive and negative predictive values for an $R_{CSF}$ cutoff of ≤ 5 mm Hg/(ml/min) were 0.86, 1.0, 1.0, and 0.89 (area under the curve of 0.96), respectively. The median pressure-volume index was higher ($p = 0.003$), and baseline ($p = 0.017$) and plateau ($p < 0.001$) pulse amplitudes were lower in patients with a proven leak.

CONCLUSIONS Lumbar infusion testing captures a distinct pattern of CSF dynamics associated with spinal CSF leakage. $R_{CSF}$ assessed by computerized lumbar infusion testing has an excellent diagnostic accuracy and is more accurate than evaluating the lumbar opening pressure. The authors suggest inclusion of $R_{CSF}$ in the diagnostic criteria for SIH.

KEY WORDS CSF outflow resistance; lumbar infusion test; spinal cerebrospinal fluid leak; spontaneous intracranial hypotension; headache; surgical technique

Spontaneous intracranial hypotension (SIH) is an underestimated disease. Rarely diagnosed in the past, it is now recognized as an important cause of headache.\textsuperscript{12,22,24} SIH is caused by spontaneous spinal CSF leakage. Its main symptoms include orthostatic headache, nausea, blurred vision, diplopia, and vestibulocochlear manifestations.\textsuperscript{22,24} The clinical spectrum and radiological manifestations are broad, and diagnostic criteria are hard to establish.\textsuperscript{12,22,23} This is reflected in the evolution of the criteria of the International Classification of Headache Disorders (ICHD) for headache attributed to SIH.\textsuperscript{15,16,21} Schievink et al. proposed a set of diagnostic criteria for spontaneous spinal CSF leaks and intracranial hypotension that aimed to encompass its varied clinical and radiographic manifestations.\textsuperscript{25} However, the key criterion remains the direct proof of a spinal CSF leak.\textsuperscript{16,25}

Pathophysiologically, a CSF leak should alter normal CSF parameters.\textsuperscript{30} Decreased craniospinal pressure causes pathologically low resistance to CSF outflow if sagittal sinus pressure and CSF formation are normal and constant.\textsuperscript{21} The existence of a CSF leak by definition implies a low CSF outflow resistance ($R_{CSF}$), which may occur con-
continuously or intermittently. Lumbar infusion testing qualifies CSF dynamics and quantifies $R_{CSF}$. Here, we describe the results of a computerized constant-rate lumbar infusion test in patients with suspected SIH who underwent a standardized diagnostic protocol that included spinal MRI without or with intrathecal contrast, myelography, and postmyelography CT.

**Methods**

The Bern University Hospital Ethics Committee granted approval for this study. We included all consecutive patients admitted to the Departments of Neurosurgery and Neurology, Bern University Hospital, with suspected SIH according to ICHD criteria. The criteria are as follows: A) any headache fulfilling criterion C; B) low CSF pressure ($< 60$ mm H$_2$O) and/or evidence of CSF leakage on imaging; C) development of headache in temporal relation to the low CSF pressure or CSF leakage, or has led to its discovery; and D) headache not accounted for by another ICHD 3rd edition (ICHD-3) diagnosis.$^{16}$

In addition, all included patients underwent spinal imaging (myelography and/or spinal MRI) after intrathecal contrast (either iodine or gadolinium) administration.$^{15,16}$ Demographic and clinical data were assessed. Our standardized diagnostic workup was performed as described previously.$^{3}$ We used our current Bern imaging protocol for detection of CSF leakage. The protocol defines Categories 0–5 as a proven CSF leak, in contrast to Categories 0–3 for which there is no proven CSF leak (Table 1).$^{3}$ Spinal imaging consisted of a stepwise protocol using more invasive imaging techniques with increasing suspicion of a spinal leak. First, 1.5-T MR images of the spine, including T2-weighted images in the sagittal orientation (space 0.9 isovoxel, TR 1500 msec, TE 119 msec) with 3D reformats and T1-weighted images in sagittal orientation (TR 670 msec, TE 9.2 msec), were acquired to detect meningeal cysts or extrathecal fluid collection (Categories 1–3). Then, the computerized lumbar infusion test was performed. At the end of the infusion test, intrathecal gadolinium was administered and another spinal MRI study was performed. Postcontrast MRI included T fat saturation acquisition in sagittal and axial orientations (3 mm, TR 520 msec, TE 11 msec). In patients with proven extrathecal contrast media (Category 4) without precise localization of the leak, fluoroscopy was performed. Contrast flow from intra- to extrathecal space observed during fluoroscopy was defined as a Category 5 CSF leak.

**Control Group**

The control group comprised the patients who did not exhibit a spinal CSF leak. These patients had undergone lumbar infusion testing in order to confirm that they did not have a spinal CSF leak. Because of its invasiveness, lumbar infusion testing was not performed in a control group of healthy volunteers.

**Lumbar Infusion Testing**

We used a computerized constant infusion test developed by Czosnyka and colleagues based on the infusion test described by Katzman and Hussey.$^{7,10,17,27,28}$ A lumbar puncture was performed with the patient in the lateral recumbent position with a 20-gauge (0.9-mm outer diameter) needle (Fig. 1). The needle was connected via a 3-way tap to the pressure transducer and the infusion pump. CSF pressure was constantly monitored through the same needle and recorded using ICM+ software (version 7.3, http://www.neurosurg.cam.ac.uk/icmplus). After baseline recording of lumbar CSF pressure, infusion was started at a constant rate of 2 ml/min using Ringer solution (50 ml). The infusion test was terminated prematurely if the patient developed symptoms of increased intracranial pressure (ICP) or if CSF pressure exceeded 50 mm Hg. Computerized analysis was done using the tool provided by the ICM+ software for analyzing lumbar infusion tests. The software recorded and computed lumbar pressure and pulse amplitude (at baseline and plateau, $R_{CSF}$, elastance coefficient, and pressure-volume index (PVI). If a normalized error $> 2\%$ for the $R_{CSF}$ was recorded, we recalculated it manually by calculating the difference between the plateau and the baseline pressures divided by the infusion rate. The lumbar baseline pressure equals the opening pressure.

**Parameters of the Lumbar Infusion Test**

Baseline pressure (in mm Hg) is the mean pressure over a period of 3–5 minutes before the start of the infusion, with the patient relaxed and in the lateral recumbent position. Baseline pressure equals the lumbar opening.

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**TABLE 1. Categories of spinal imaging findings**

<table>
<thead>
<tr>
<th>Category</th>
<th>Imaging Finding</th>
<th>Imaging Modality</th>
<th>Intrathecal Contrast Material</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No suggestion of CSF loss</td>
<td>MRI, myelography, CT, cisternography</td>
<td>Gd, iodine, radionuclide</td>
<td>No CSF leak</td>
</tr>
<tr>
<td>1</td>
<td>Spinal meningeal cyst, sacral region</td>
<td>MRI, myelography, CT</td>
<td>Gd, iodine</td>
<td>CSF leak unlikely</td>
</tr>
<tr>
<td>2</td>
<td>Spinal meningeal cyst, cervicothoracic region</td>
<td>MRI, myelography, CT</td>
<td>Gd, iodine</td>
<td>CSF leak likely</td>
</tr>
<tr>
<td>3</td>
<td>Extrathecal fluid detection w/o intrathecal contrast</td>
<td>MRI (T2 SPACE)</td>
<td>Gd, iodine</td>
<td>CSF leak very likely</td>
</tr>
<tr>
<td>4</td>
<td>Extrathecal contrast accumulation after intrathecal contrast application</td>
<td>CT/MRI</td>
<td>Gd, iodine</td>
<td>CSF leak proven</td>
</tr>
<tr>
<td>5</td>
<td>Direct visualization of contrast passage from intrathecal to extrathecal space</td>
<td>Fluoroscopy (myelography)</td>
<td>Iodine</td>
<td>CSF leak proven</td>
</tr>
</tbody>
</table>

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Resistance to CSF outflow in diagnosis of spontaneous CSF leakage

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pressure. Plateau pressure (in mm Hg) is the mean pressure over the period of time in which the lumbar pressure reached a steady plateau during infusion. Pulse amplitude (in mm Hg) is a pressure response (AP) to the transient increase in intracranial blood volume during a cardiac cycle (ΔV).² Because of the exponential shape of the pressure-volume curve, pulse amplitude increases with increasing pressure.² Resistance to CSF outflow (in mm Hg/ml/min) measures the impedance to CSF drainage.¹⁹ It is equal to the effective pressure increase (ICP plateau – ICP baseline) divided by the rate of infusion. The elastance coefficient (in ml⁻¹) describes the stiffness of the cerebrospinal system, i.e., the ability to compensate for a cerebrospinal volume increase.³ It reflects the pressure-volume response (ΔP/ΔV) at a certain level, and it shows how fast compliance of the cerebrospinal space decreases when the mean ICP increases.¹³,²⁹ The PVI (in ml) is the volume that has to be added to raise the pressure 10-fold.²⁰,²⁶

Statistical Analysis

Data from the computerized lumbar infusion test were analyzed using descriptive statistics and compared between patients with proven CSF leak and those in whom a leak was not found by using statistical software (SPSS, version 21, IBM). A 2-sided t-test for unpaired variables was performed, with the presence of a CSF leak (Categories 4 and 5) as the dependent variable. A p value < 0.05 was regarded as significant. Discrimination between the occurrence of a leak or no leak was measured by the area under the curve (AUC) of receiver operating characteristic (ROC) curves, which were compared nonparametrically. An AUC of 1 indicates perfect discrimination, and an AUC of 0.5 indicates no better discrimination than would occur by chance.

Results

Between January 2012 and February 2015, 44 patients with suspected SIH in whom spinal imaging had been performed were treated at the Departments of Neurosurgery and Neurology, Bern University Hospital. Thirteen patients were excluded because the myelography study had been performed at an outside institution (n = 2); absence of the investigator who performed all lumbar infusion tests (n = 2); technical problems with data registration (n = 2); missing lumbar infusion test data (n = 2); and previous spinal surgery, clinically unstable patient, previous lumbar puncture, claustrophobia, and symptom resolution after epidural blood patch (n = 1 each) (Fig. 2). Data from lumbar infusion tests in 31 patients (17 females) were suitable for analysis. The median age was 55 years (interquartile range [IQR] 44–69 years). According to spinal imaging findings and our recently established criteria, 14 of the 31 patients had a proven spinal CSF leak.³ Of these 14 patients, 9 were graded as Category 4 and 5 as Category 5; all displayed extrathecal contrast after intrathecal contrast application for spinal MRI, myelography, or CT myelography. In the remaining 17 patients a spinal CSF leak could not be proven; 5 patients were graded as Category 0, 2 as Category 1, 6 as Category 2, and 4 as Category 3 (Table 1).

Clinical Findings at Presentation

In the 14 patients with proven CSF leakage, clinical symptoms at presentation consisted of headache (n = 13, of whom 12 presented with orthostatic headache), nausea (n = 5), cochleovestibular manifestations (n = 5), photophobia/visual blurring (n = 3), altered level of consciousness (n = 2), back pain (n = 2), limb numbness/paresthesias (n = 1), and sweating (n = 1).

Patients without a proven CSF leak presented with headache (n = 15, of whom 6 presented with orthostatic headache); cochleovestibular manifestations (n = 5); paresis (n = 3); limb numbness/paresthesias (n = 2); and nausea, altered level of consciousness, facial numbness, per-
sonality change, gait unsteadiness, and speech disturbance (n = 1 each).

**CSF Dynamics Measured by Constant-Rate Lumbar Infusion Test**

Lumbar CSF pressure and pulse amplitude at baseline and plateau were significantly lower in patients with a proven spinal CSF leak (Table 2 and Fig. 3). In addition, $R_{CSF}$ was significantly lower in patients with proven leaks than in those without (Table 2 and Fig. 3). PVI was higher in patients with proven CSF leak (Table 2 and Fig. 3). Elastance was not related to a proven spinal CSF leak. One lumbar infusion test had to be terminated prematurely due to headache. For this patient, we only included the lumbar baseline pressure and $R_{CSF}$ (calculated as [highest pressure - baseline pressure]/2 [ml/min]) in the analysis. The $R_{CSF}$ was 19.5 mm Hg/(ml/min) in this patient.

Lumbar Baseline Pressure (Opening Pressure)

The median pressure in patients with spinal CSF leakage was 5.26 mm Hg, compared with 11.77 mm Hg in patients without proven CSF leakage ($p < 0.001$). Eight (57.1%) of 14 patients with proven leakage had a baseline pressure above 4.4 mm Hg (60 mm Hg (Fig. 3A). IQRs and 95% CIs are provided in Table 2.

Lumbar Plateau Pressure

Patients with spinal CSF leakage had significantly lower median plateau pressures than those without leakage (16.11 mm Hg vs 32.06 mm Hg; $p < 0.001$).

Resistance to CSF Outflow

The median computerized $R_{CSF}$ in patients with spinal CSF leakage was 1.97 mm Hg/(ml/min) versus 11.78 mm Hg/(ml/min) ($p < 0.001$) in the cohort without leakage. Patients without a spinal CSF leak all had an $R_{CSF} > 5$ mm Hg/(ml/min). In contrast, 2 patients with a proven spinal CSF leak had an $R_{CSF} > 5$ mm Hg/(ml/min) (5.15 and 12.45 mm Hg/(ml/min)). Manual recalculation of the $R_{CSF}$ due to a higher normalized error (> 2%) yielded a median $R_{CSF}$ of 4.5 mm Hg/(ml/min) ($p < 0.001$) (Fig. 3C and D).

Amplitude at Baseline

In patients with CSF leakage, the median pulse amplitude at baseline was 0.18 mm Hg versus 0.38 mm Hg in patients without leakage ($p = 0.017$) (Fig. 3E).

Pulse Amplitude at Plateau

In patients with CSF leakage, the median pulse amplitude at plateau was 1.03 mm Hg versus 2.80 mm Hg in patients without leakage ($p < 0.001$) (Fig. 3F).

Pressure Volume Index

In patients with spinal CSF leakage, the median PVI was 26.43 ml versus 20.93 ml in patients without leakage ($p = 0.003$) (Fig. 3G).

Elastance Coefficient

The elastance coefficient in patients with a spinal CSF leak was not significantly different from that in patients.
without a CSF leak (0.09 ml⁻¹ vs 0.11 ml⁻¹; p = 0.237) (Fig. 3H).

The ROC analysis yielded an AUC of 0.958 for computerized R_{CSF}, 0.933 for manually calculated R_{CSF}, 0.942 for lumbar plateau pressure, 0.883 for pulse amplitude plateau, 0.866 for PVI, 0.857 for lumbar baseline pressure, 0.857 for elastance, and 0.752 for pulse amplitude baseline.

### TABLE 2. Results of the computerized lumbar infusion test

<table>
<thead>
<tr>
<th>Variation</th>
<th>No Proven Leak</th>
<th>Proven Leak</th>
<th>95% CI of Difference*</th>
<th>p Value</th>
<th>AUC</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumbar pressure baseline (mm Hg)</td>
<td>11.77</td>
<td>5.26</td>
<td>-0.91/12.80</td>
<td>3.68 to 10.19</td>
<td>&lt;0.001</td>
<td>0.866 0.739–0.992</td>
</tr>
<tr>
<td>Lumbar pressure plateau (mm Hg)</td>
<td>32.06</td>
<td>16.11</td>
<td>10.54/37.60</td>
<td>10.17 to 21.76</td>
<td>&lt;0.001</td>
<td>0.942 0.845–1.0</td>
</tr>
<tr>
<td>AMP baseline (mm Hg)</td>
<td>0.38</td>
<td>0.18</td>
<td>-0.09/0.26</td>
<td>0.08 to 0.72</td>
<td>0.017 0.752 0.557–0.928</td>
<td></td>
</tr>
<tr>
<td>AMP plateau (mm Hg)</td>
<td>2.80</td>
<td>1.03</td>
<td>0.36/3.0</td>
<td>0.96 to 2.90</td>
<td>&lt;0.001</td>
<td>0.893 0.78–1.0</td>
</tr>
<tr>
<td>R_{CSF} computerized (mm Hg/ml/min)</td>
<td>11.78</td>
<td>1.97</td>
<td>0.39/12.45</td>
<td>6.09 to 11.95</td>
<td>&lt;0.001</td>
<td>0.958 0.875–1.0</td>
</tr>
<tr>
<td>R_{CSF} manually (mm Hg/ml/min)</td>
<td>11.78</td>
<td>4.5</td>
<td>3.5/11.0</td>
<td>3.83 to 9.26</td>
<td>&lt;0.001</td>
<td>0.933 0.844–1.0</td>
</tr>
<tr>
<td>Elastance coefficient (ml)</td>
<td>0.11</td>
<td>0.09</td>
<td>-0.03/0.11</td>
<td>0.237 0.857 0.7–1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVI (ml)</td>
<td>20.93</td>
<td>26.43</td>
<td>4.94/51.39</td>
<td>-16.64 to -3.70</td>
<td>0.003</td>
<td>0.888 0.737–1.0</td>
</tr>
</tbody>
</table>

AMP = pulse amplitude.

* Difference between the median values in the no proven leak and proven leak groups.

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**FIG. 3.** Scatterplots displaying the lumbar pressure (A and B), R_{CSF} (C and D), pulse amplitude (AMP) (E and F), PVI (G), and elastance (H) of the lumbar infusion test. Results are dichotomized into patients with or without a proven CSF leak.
Discussion

Lumbar infusion testing is a tool for quantifying CSF dynamics. When applying computerized lumbar infusion tests to patients with suspected SIH, we found a distinct pattern of CSF dynamics associated with spinal CSF leakage. In our patients, an $R_{CSF} \leq 5$ was predictive of a spinal CSF leak that was later proven by imaging, whereas an $R_{CSF} > 5$ predicted a low chance of finding leakage on imaging studies.

A diagnosis of SIH is usually difficult to establish. Particularly in patients with chronic SIH, the clinical presentation might not match the stereotypical description, and orthostatic headache may be variable or even nonexistent. Obtaining proof of a spinal CSF leak and its precise localization is cumbersome and often requires multiple and invasive diagnostic procedures. Many patients with SIH show only subtle signs of extrathecal fluid accumulation on spinal MRI. Depending on the patient’s symptoms, imaging often needs to be repeated and other modalities such as intrathecal contrast media must be used. The recently revised guidelines of the ICHD reflect these diagnostic issues. As a result, the diagnostic criteria are rather unspecific, and an additional diagnostic technique to corroborate the diagnosis of SIH would be helpful. A test that can differentiate patients with a CSF leak from patients without one is crucial.

From the pathophysiological point of view, if a leak leads to high outflow of CSF, i.e., low resistance to outflow, it should be possible to diagnose its existence with a lumbar infusion test.

Typical Pattern of CSF Dynamics for Patients With a Spinal CSF Leak

We observed all features of CSF dynamics that were derived theoretically from the assumption of a dural defect. Mathematically, such pathology would represent a very low CSF outflow resistance. The reduced CSF volume would lead to reduced pressure, increased craniospinal compliance, and reduced pulse pressure amplitude. When loaded with a constant rate of volume, patients with leakage, i.e., reduced $R_{CSF}$, would show less pressure increase, less pulse pressure increase, and greater compliance (Figs. 4 and 5).

The key parameter, however, is the pathologically decreased $R_{CSF}$, on which the other parameters are dependent. Unfortunately, few studies in the literature have measured $R_{CSF}$ in healthy individuals. Most studies of $R_{CSF}$ were performed to establish the upper threshold of normal $R_{CSF}$ for diagnosing malfunction of CSF shunts or normal pressure hydrocephalus.

Resistance to CSF outflow in young, healthy patients ranges from 5 to 10 mm Hg/(ml/min) and increases with age. $R_{CSF}$ values are well studied in hydrocephalus, and $R_{CSF}$ above 13 to 18 mm Hg/(ml/min)—depending on the age of the patient—is used as definition of a disturbed CSF circulation. Due to the SIH pathophysiology resulting from a spinal CSF leak, $R_{CSF}$ values should be lower than normal, but no studies in the literature have investigated the lower limit of the normal value of outflow resistance, and we are not aware of any study reporting $R_{CSF}$ outflow in patients with SIH. In our cohort, the existence of a spinal CSF leak was associated with lower $R_{CSF}$ values. When using 5 mm Hg/(ml/min) as the cutoff, our results yield a sensitivity of 86% and a specificity of 100% for the computerized $R_{CSF}$ for the presence of a spinal CSF leak. Because of the small patient numbers, these results have to be interpreted with caution. The fact that $R_{CSF}$ can also be calculated from a noncomputerized lumbar infusion test (difference between the plateau and the baseline pressure divided by the infusion rate) makes it an easy-to-measure additional parameter in the evaluation of SIH. However, the use of a computerized test enables a quick and reliable assessment of CSF dynamics, eliminates unwanted pressure fluctuations and artifacts, and permits calculation of $R_{CSF}$ even if no steady pressure level is obtained.

A classic diagnostic criterion attributed to SIH is low opening pressure, although it is reported that up to 25% of patients may exhibit a normal opening pressure. The suggested cutoff for SIH diagnosis is 60 mm H2O (4.4 mm Hg). In our cohort of patients with a proven spinal CSF leak, the median opening pressure was 5.26 mm Hg and was therefore higher than the cutoff for diagnosis of SIH according to the ICHD-3. A higher opening pressure

FIG. 4. Graph showing the pressure response of a computerized lumbar infusion test in a patient without a spinal CSF leak. Note the high opening pressure (about 14 mm Hg), with steep incline of pressure, which corresponds to the resistance of the needle after the start of the infusion. Thereafter, the graph shows a rather quick increase in pressure up to a plateau at about 38 mm Hg.
than the suggested cutoff was measured in 8 of 14 patients (57.1%). Therefore, opening pressure by itself might not suffice as the sole parameter of CSF dynamics for confirming the diagnosis of SIH.

In the current series, the plateau pressure was also a specific parameter indicating a spinal CSF leak. However, plateau pressure is not an accurate physiological parameter and does not represent a measure of outflow resistance. Baseline and plateau pulse amplitudes were also associated with the existence of a spinal CSF leak, probably because these parameters are well correlated with the pressure. Unlike elastance or its inverse, compliance, the PVI describes pressure-independent steepness of the entire craniospinal pressure-volume relationship. It is measured as the volume that has to be added to raise the pressure 10-fold. In occlusive hydrocephalus assessed using intraventricular infusion, the PVI is low (<13 ml), indicating poor compensatory reserve. In our study, the median PVI in patients without proven CSF leakage was 20.93 ml, compared with 26.43 ml in patients with proven spinal CSF leakage. The higher PVI is in line with the pathophysiological concept of SIH. Because of the spinal CSF leak, there is a relative volume depletion, and compliance is greater than in patients without a proven spinal CSF leak.

The lumbar infusion test has the potential to guide management of patients suspected of having a spinal CSF leak. Lumbar infusion testing is superior to opening pressure and can prevent unnecessary imaging studies.

Limitations of the Study

From a pathophysiological point of view, the diagnostic accuracy of lumbar infusion testing hinges on the assumption of open leakage rather than a valve-like intermittent opening of the dural defect. If such a valve mechanism or position-dependent mechanism exists, lumbar infusion testing might still be negative. Despite the sound pathophysiological concept of diagnosing a CSF leak by measuring the resistance to CSF outflow, a defect in the dura mater can be small and covered by the arachnoid or spinal venous plexus, as often observed during surgery. Therefore, some CSF leaks may open only intermittently and may be position dependent, like a valve mechanism. Further limitations of the study are the single-center setting, the limited number of patients, and that lumbar infusion tests were not performed in healthy volunteers. Yet these preliminary results are promising, and large multicenter studies are warranted.

Conclusions

Lumbar infusion testing seems to capture a specific pattern of CSF dynamics associated with spinal CSF leaks in patients with SIH. Lumbar infusion tests are useful tools in the diagnostic workup of SIH. The key parameter is a pathologically reduced CSF outflow resistance.

References


FIG. 5. Graph showing a pressure response of a computerized lumbar infusion test in a patient with a spinal CSF leak. Note the low opening pressure (about 4 mm Hg), with a steep incline of pressure, which corresponds to the resistance of the needle after start of the infusion. Thereafter, the graph shows a slow increase in pressure, without reaching a plateau. The maximum pressure is about 22 mm Hg.


Disclosures
Dr. Fiechter states that he is a consultant for Brainlab AG.

Author Contributions
Conception and design: Beck, Fung, Ulrich, Raabe. Acquisition of data: Fung, Fiechter, Mordasini, Gralla. Analysis and interpretation of data: Beck, Fung, Ulrich, Fiechter, Z’Graggen, Gralla. Drafting the article: Beck, Fung. Critically revising the article: Beck, Fung, Ulrich, Raabe. Reviewed submitted version of manuscript: Beck, Fung, Mattle, Mono, Meier, Mordasini, Z’Graggen, Gralla, Raabe. Approved the final version of the manuscript on behalf of all authors: Beck. Statistical analysis: Fung. Administrative/technical/material support: Fung, Raabe. Study supervision: Beck, Raabe.

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