Analysis of aqueductal cerebrospinal fluid flow after endoscopic aqueductoplasty by using cine phase-contrast magnetic resonance imaging

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Object. The purpose of this prospective study was to evaluate aqueductal cerebrospinal fluid (CSF) flow after endoscopic aqueductoplasty. In all patients, preoperative magnetic resonance (MR) imaging revealed hydrocephalus caused by aqueductal stenosis and lack of aqueductal CSF flow.

Methods. In 14 healthy volunteers and in eight patients with aqueductal stenosis who had undergone endoscopic aqueductoplasty, aqueductal CSF flow was investigated using cine cardiac-gated phase-contrast MR imaging. For qualitative evaluation of CSF flow, the authors used an in-plane phase-contrast sequence in the midsagittal plane. The MR images were displayed in a closed-loop cine format. Quantitative through-plane measurements were performed in the axial plane perpendicular to the aqueduct. Evaluation revealed no significant difference in aqueductal CSF flow between healthy volunteers and patients with regard to temporal parameters, CSF peak and mean velocities, mean flow, and stroke volume. All restored aqueducts have remained patent 7 to 31 months after surgery.

Conclusions. Aqueductal CSF flow after endoscopic aqueductoplasty is similar to aqueductal CSF flow in healthy volunteers. The data indicate that endoscopic aqueductoplasty seems to restore physiological aqueductal CSF flow.

KEY WORDS • endoscopic aqueductoplasty •
cine phase-contrast magnetic resonance imaging • cerebrospinal fluid flow •
cerebrospinal fluid circulation • aqueduct

CINE phase-contrast MR imaging has been increasingly used during the last decade for evaluating cranial and spinal CSF flow.^{4,7,11,17,18,39,49} The phase-contrast technique is extremely sensitive, even to slow flow, and provides the potential for noninvasive flow quantification.^{3,17,28,60} The results of these measurements have yielded considerable information on the physiology of the normal CSF circulation.^{1,6,7,9,17,23,42,43} In addition, pathological CSF flow dynamics in communicating and obstructive hydrocephalus,^{11,22,32–34,44,54} Chiari malformation,⁸ cystic lesion,¹⁵ and cervical spondylosis⁶⁰ have been analyzed. With the increasing frequency of neuroendoscopic procedures, cine MR imaging has been recommended for evaluating the patency of third ventriculostomies.^{21,37,38,40,48} Aqueductal CSF flow after endoscopic aqueductoplasty, however, has not yet been investigated. We performed a prospective study to compare the aqueductal CSF flow in healthy volunteers and patients who had undergone endoscopic restoration of aqueductal patency.

Abbreviations used in this paper: CSF = cerebrospinal fluid; MR = magnetic resonance; ROI = region of interest.

Clinical Material and Methods

Patients and Healthy Volunteers

Fourteen healthy volunteers and eight patients who underwent endoscopic aqueductoplasty were prospectively investigated using cine phase-contrast MR imaging to evaluate aqueductal CSF flow. All patients had occlusive hydrocephalus caused by aqueductal stenosis and presented with symptoms of increased intracranial pressure or normal-pressure hydrocephalus before surgery. Flow-sensitive sagittal T₂-weighted turbo inversion-recovery spin-echo MR imaging revealed the lack of an aqueductal flow-void sign in all cases. The operative technique of endoscopic aqueductoplasty has been reported elsewhere.⁵⁰ In brief, the aqueduct was approached via a frontal paramedian burr hole. Endoscopic inspection revealed three membranous obstructions, two membranous stenoses with minimal residual lumina, and three short stenoses approximately 2 mm in length. The membranous stenoses were perforated using a steerable 2.5-mm fibroscope. The short stenoses were dilated by inflating the balloon of a No. 3 French Fogarty catheter. The healthy control volunteers exhibited no clinical or radiological signs of CSF circu-

FIG. 1. Quantification of CSF flow. *Left*: Sagittal T₁-weighted scout MR image demonstrating the phase-contrast imaging plane perpendicular to the aqueduct (dotted bar) used to assess aqueductal CSF flow. *Right*: Axial phase-contrast image perpendicular to the aqueduct, demonstrating an annular ROI (arrow) located within the aqueduct. Arrowheads indicate the internal carotid arteries.

lation abnormalities. Both patients (five men and three women) and volunteers (six men and eight women) were normotensive. Their heart rates varied between 55 and 85 beats/minute. The mean age of the patients was 40 years (range 18–56 years) and the mean age of the volunteers was 38 years (range 20–66 years).

Magnetic Resonance Imaging Techniques

Magnetic resonance imaging was performed using a 1.5-tesla MR imaging unit (Magnetom Symphony; Siemens AG, Erlangen, Germany) with a circular polarized head-array coil and ultra gradients. Standard sagittal (2-mm slice thickness) and axial (5-mm slice thickness) T₁-

weighted images, as well as sagittal T₂-weighted turbo inversion-recovery spin-echo images (TE 4300 msec, TE 60 msec, and 2-mm slice thickness), were obtained before CSF flow measurements were made. For phase-contrast MR imaging, we used a two-dimensional fast low-angle shot sequence from a commercially available flow quantification package (included in the Numaris VA11B software, version 3.5; Siemens AG). Two imaging techniques were applied: one in the axial plane with through-plane velocity encoding in the craniocaudal direction for flow quantification, and one in the sagittal plane with in-plane velocity encoding in the craniocaudal direction for qualitative assessment.⁴⁶

Axial Technique

Cerebrospinal fluid flow dynamics were quantitatively studied by using a prospectively cardiac-gated high-resolution axial phase-contrast protocol with an imaging plane perpendicular to the aqueduct (Fig. 1 *left*). The direction of flow encoding was craniocaudal. The imaging parameters were as follows: TR 46 msec; TE 11 msec; flip angle 10°; number of acquisitions 2; field of view 160 mm; matrix 256 × 512; pixel size 0.63 × 0.31 mm; scan thickness 4 mm; and velocity encoding 20 cm/second. Depending on the patient's heart rate, the measurement time lasted between 10 to 15 minutes, and 14 to 23 phase images were calculated. Once the image data had been acquired, an annular ROI was placed in the aqueduct shown on a magnified image (Fig. 1 *right*) with the aid of a mouse-driven cursor, and a CSF flow waveform was generated (Fig. 2). The time of the cardiac cycle after the R wave was plotted on the x axis and the velocity on the y axis. During CSF diastole, CSF moves in caudocranial direction (positive velocity), whereas during CSF systole, CSF flows in the craniocaudal direction (negative velocity). Mean and peak CSF velocities, as well as mean CSF flow, were calculated at the end of CSF diastole and during CSF systole (solid line in Fig. 2). The early diastole (curved dotted line on right side of Fig. 2) was not evaluated because, in prospec-

FIG. 2. Graph depicting the CSF flow waveform. Positive deflections represent caudocranial flow (CSF diastole) and negative deflection represents craniocaudal flow (CSF systole). Dotted lines indicate a portion of the waveform that was not evaluated because of prospective cardiac gating. R–D = time after R wave to onset of CSF diastole; R–PS = time after R wave to peak CSF systole; R–S = time after R wave to onset of CSF systole; V_{DPeak} = peak end-diastolic CSF velocity; V_{SPeak} = peak systolic CSF velocity.

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tive cardiac gating, the acquisition is stopped within approximately 150 to 200 msec of the next R wave for accurate detection of the next trigger. Hence, the entire diastolic phase is not covered.⁴⁶ Temporal analysis involved determination of the interval from the R wave to the onset of CSF systole (R–S), the interval from the R wave to the peak CSF systole (R–PS), and the interval from the R wave to the onset of CSF diastole (R–D). In addition, duration of the systole and systolic CSF stroke volume were calculated and the aqueductal area measured.

Sagittal Technique

For qualitative assessment of CSF flow, midsagittal phase-contrast images were displayed in a closed-loop cine format. Retrospective cardiac gating was used to cover the whole cardiac cycle.⁴⁶ Thirty-two phase images were calculated. The direction of flow encoding was craniocaudal. The imaging parameters were as follows: TR 70 msec; TE 18 msec; flip angle 15°; number of acquisitions 1; field of view 250 mm; matrix 193 × 256; pixel size 1.13 × 0.98 mm; scan thickness 4 mm; and velocity encoding 2 cm/second. Measurement time was approximately 7 minutes.

Statistical Analysis

Statistical evaluation was performed using a commercially available computer software package (SAS System for Windows, version 6.12; SAS Institute, Inc., Cary, NC). The range, mean, and standard deviation were calculated for each parameter. The Wilcoxon rank-sum test was used for a comparison of parameters in healthy volunteers and patients. Probability values less than 0.05 were considered significant.

Results

Routine MR Imaging

Standard T₁-weighted images revealed restored aqueducts in all patients (Fig. 3 and Video Clip 1). There was a decrease in the size of the ventricles and reversal of the distortion of the pituitary stalk in six patients. In two patients, ventricular size remained unchanged. Flow-sensitive sagittal inversion-recovery images demonstrated an

FIG. 3. Upper Left and Right: Endoscopic views showing aqueductal stenosis with a minimal residual lumen (left) and restored aqueduct after aqueductoplasty (right). Lower Left: Preoperative sagittal T₁-weighted MR image revealing a short aqueduct stenosis and a dilated third ventricle. Note the wide angle of infundibular recess. Lower Right: Sagittal T₁-weighted MR image obtained 20 months after surgery demonstrating a normal-shaped aqueduct and a slightly decreased third ventricle. Note the small angle of infundibular recess. See Video Clip 1.

aqueductal flow-void sign in all patients. However, in one patient in whom there was a very narrow aqueduct (< 1 mm²) the flow-void sign was very weak. Magnetic resonance imaging of healthy volunteers revealed normal-shaped aqueducts and ventricles and no signs of CSF circulation abnormalities. In two volunteers with narrow aqueducts (< 1 mm²), a flow-void sign was hardly detectable.

TABLE 1
Quantitative assessment of aqueductal CSF flow in 14 healthy volunteers and eight patients who had undergone endoscopic aqueductoplasty

Parameter	Range		Mean ± Standard Deviation	
	Healthy Volunteers	Patients	Healthy Volunteers	Patients
end-diastolic peak velocity (cm/sec)	2.40–9.26	1.74–7.48	4.73 ± 1.73	4.07 ± 1.94
end-diastolic mean velocity (cm/sec)	1.95–6.54	1.24–5.11	3.48 ± 1.22	2.94 ± 1.43
systolic peak velocity (cm/sec)	2.59–8.63	1.5–8.16	5.56 ± 1.87	4.95 ± 1.98
systolic mean velocity (cm/sec)	1.61–4.80	0.76–4.60	3.07 ± 1.09	2.96 ± 1.37
end-diastolic mean flow (cm ³ /sec)	0.01–0.26	<0.01–0.10	0.07 ± 0.06	0.06 ± 0.03
systolic mean flow (cm ³ /sec)	0.01–0.24	0.01–0.13	0.06 ± 0.06	0.06 ± 0.04
onset of CSF systole (R–S; msec)	139–196	123–227	167 ± 18	159 ± 31
time of CSF peak systole (R–PS; msec)	232–414	233–411	326 ± 51	299 ± 59
duration of CSF systole (msec)	303–586	354–555	465 ± 84	441 ± 65
systolic stroke volume (μl)	4–115	4–57	28 ± 28.4	24 ± 16.6
aqueductal area (mm ²)	<1–5	<1–5	1.7 ± 1.4	1.8 ± 1.6

FIG. 4. Axial phase-contrast images obtained perpendicular to the aqueduct. Arrowheads indicate the carotid arteries. *Left:* Hypointense signal within the aqueduct (arrow) indicating cranial flow (CSF diastole). *Right:* Hyperintense signal within the aqueduct (arrow) indicating caudal flow (CSF systole). See Video Clip 2.

Video Clip 1: [6.2 MB] Endoscopic aqueductoplasty. The endoscope is introduced into the posterior part of the third ventricle via the foramen of Monro. Endoscopic inspection reveals a short aqueductal stenosis with a minimal residual lumen. A No. 3 French Fogarty catheter (note the bending of the catheter tip) is carefully inserted into the stenotic aqueduct, and the stenosis is dilated by inflating the balloon. Final inspection with the diagnostic endoscope shows the restored aqueduct.

Quantitative Assessment

An overview of the measured and calculated parameters of aqueductal CSF flow are presented in Table 1. Axial phase-contrast images revealed aqueductal cranial flow during CSF diastole (hypointense signal) and caudal flow during CSF systole (hyperintense signal; Fig. 4 and Video Clip 2). The CSF waveforms generated were similar in patients and healthy volunteers (Fig. 5). There were no significant differences between patients and healthy volunteers regarding aqueductal area, velocity, flow, and temporal parameters. The high variability of end-diastolic (1.74–9.26 cm/second) and systolic (1.5–8.63 cm/second) peak CSF velocities in both patients and healthy volunteers is striking. Mean CSF flows at the end of CSF diastole (0.06–0.07 ml/second) and during CSF systole (0.06 ml/second) were nearly equivalent in patients and volunteers. Caudal flow (CSF systole) started approximately 165 msec after the R wave and lasted approximately 450 msec. The calculated volume of CSF that flows caudally through the aqueduct during CSF systole was 24 μ l in patients and 28 μ l in healthy volunteers. The aqueductal area varied from less than 1 to 5 mm² in both patients and volunteers.

Video Clip 2: [4 MB] Cine MR imaging CSF flow quantification. For quantitative assessment (velocity and flow measurements), cine MR imaging is performed in an imaging plane perpendicular to the aqueduct with through-plane velocity encoding in the craniocaudal di-

rection. Cerebrospinal fluid flow dynamics are studied by using a prospectively cardiac-gated high-resolution axial phase-contrast protocol. The imaging parameters are as follows: TR 46 msec; TE 11 msec; flip angle 10°; number of acquisitions 2; field of view 160 mm; matrix 256 $\times$ 512; pixel size 0.63 mm $\times$ 0.31 mm; scan thickness 4 mm; velocity encoding 20 cm/second. Depending on the heart rate, measurement time is between 10 and 15 minutes and 14 to 23 phase images are calculated. The early diastole is not evaluated, because in prospective cardiac gating the acquisition is stopped within approximately 150 to 200 msec of the next R wave for accurate detection of the next trigger. Therefore, the entire diastolic phase is not covered. The phase-contrast images are displayed in a closed cine loop format. Aqueductal cranial flow in CSF diastole is indicated as a hypointense signal and caudal flow in CSF systole as a hyperintense signal.

Qualitative Assessment

Sagittal phase-contrast images revealed aqueductal CSF flow in all patients and healthy volunteers. However, in one volunteer with a narrow aqueduct (aqueduct area < 1 mm²), the sign of flow was weak. Caudal CSF flow during CSF systole was indicated as a hypointense signal, whereas cranial flow during CSF diastole was shown as a hyperintense signal (Fig. 6 and Video Clip 3). The general CSF flow pattern was similar in patients and healthy volunteers. At the end of CSF diastole, immediately after the R wave, CSF flow in the upper cervical subarachnoid space, prepontine cistern, and aqueduct was directed cranially (Fig. 6A). Cerebrospinal fluid systole started in the upper cervical subarachnoid space and preceded caudal flow in the prepontine cistern and aqueduct (Fig. 6B). During midsystole, CSF motion proceeded in a caudal direction in all CSF pathways (Fig. 6C). Onset of CSF diastole occurred first in the upper cervical subarachnoid space followed by flow reversal in the prepontine cistern and aqueduct. During the middle of diastole, flow again

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was directed cranially in the cervical subarachnoid space, prepontine cistern, and aqueduct (Fig. 6D).

Video Clip 3: [5.2 MB] Cine MR imaging CSF flow visualization. For qualitative assessment (flow visualization), cine MR imaging is performed in the midsagittal plane with in-plane velocity encoding in the craniocaudal direction. Retrospective cardiac gating is used to cover the whole cardiac cycle. Thirty-two phase images are calculated. The imaging parameters are as follows: TR 70 msec; TE 18 msec; flip angle 15°; number of acquisitions 1; field of view 250 mm; matrix 193 × 256; pixel size 1.13 mm × 0.98 mm; scan thickness 4 mm; velocity encoding 2 cm/second. Measurement time is approximately 7 minutes. The phase-contrast images are displayed in a continuously repeating cine loop format. Caudal CSF flow in CSF systole is indicated as a hypointense signal, whereas cranial flow during CSF diastole is shown as a hyperintense signal. In CSF end diastole immediately after the R wave, CSF flow in the upper cervical subarachnoid space, prepontine cistern, and aqueduct is directed cranially. Cerebrospinal fluid systole started in the upper cervical subarachnoid space and preceded caudal flow in the prepontine cistern and aqueduct. In late systole, CSF motion is in caudal direction in all CSF pathways. In mid diastole, flow is again directed cranially in cervical subarachnoid space, prepontine cistern, and aqueduct.

Discussion

Magnetic resonance imaging has provided considerable information regarding CSF dynamics.^{4,42,43} Initially, CSF flow was only qualitatively described as the flow-void sign that is best appreciated in areas of narrowing within the ventricular system such as the aqueduct.^{2,10,53–55,62} The visualization of this effect on routine T₁- or T₂-weighted MR images is not consistent. However, on sagittal T₂-weighted turbo inversion-recovery MR images, an aqueductal flow-void sign can be detected in most healthy volunteers. If the aqueduct is very narrow (aqueduct area < 1 mm²), the sign may be very weak or even absent. In all patients in this series, a flow-void sign indicating patency of the restored aqueduct could be detected. For routine follow-up examination after endoscopic third ventriculostomy or aqueductoplasty, we use this turbo inversion recovery sequence. If no flow void can be seen, cine phase-contrast MR imaging is performed.

During the last decade, flow-sensitive cardiac-gated phase-contrast MR imaging techniques have been increasingly applied to study CSF flow dynamics both qualitatively and quantitatively.^{9,11,14,18,46} The results of our study support the current opinion on physiological CSF circulation. Early during the cardiac cycle, immediately after the R wave, there is still CSF motion in the caudocranial direction, which is referred to as CSF diastole in all CSF spaces. The CSF systole (motion in the craniocaudal direction) starts in the upper cervical subarachnoid space and then in the basal cisterns. Systolic flow within ventricles and aqueduct is slightly delayed compared with that of the cisterns. The CSF diastole starts in the upper cervical subarachnoid space and then in the basal cisterns, followed by the aqueduct and ventricles.^{7,18,24,46,49}

Cerebrospinal fluid flow within the aqueduct is best

FIG. 5. Graphs showing CSF velocity profiles in a healthy volunteer (upper) and a patient 20 months after aqueductoplasty (lower). (Data were obtained in the same patient represented in Figs. 3 and 4).

described as a to-and-fro motion with a very small net flow.⁴⁹ The wide physiological range of the temporal, velocity, and flow parameters is striking.^{6,7,28,34,59} This normal variation is mainly related to the size and anatomy of CSF spaces, size of blood vessels, systolic and diastolic arterial blood pressure, heart rate, jugular venous flow, compliance of surrounding brain tissue,^{1,6,12,49} and respiration.^{41,52}

FIG. 6. Midsagittal phase-contrast images obtained in a patient 20 months after aqueductoplasty (same patient as shown in Figs. 3–5). A: Early during the cardiac cycle, there is a hyperintense signal in all CSF spaces indicating cranial flow (end of CSF diastole). B: Caudal flow (hypointense signal, CSF systole) started in the cervical subarachnoid space, whereas in the aqueduct there is still cranial flow. C: During CSF midsystole, there is caudal flow in all CSF spaces. D: During CSF diastole, there is cranial flow in all CSF spaces. See Video Clip 3.

The systolic temporal parameters are less variable than the diastolic parameters because variations in the R–R interval mainly influence the diastole.^{7,24,39,42} The peak CSF velocities (mean 4–5 cm/second), flow rates (mean 0.06 ml/second), and stroke volumes (mean 26 μ l) measured in our investigation compare favorably with results recently reported in the literature.^{3,23,25,28,35,44} Earlier investigations using in-plane measurements often found lower velocities.^{18,49} Because of the small size of the aqueduct relative to the sagittal slice thickness, accurate velocity calculations are difficult to obtain when quantifying in-plane phase-flow images. Partial volume effects contributed by static structures introduce severe phase diminution. This results in significant underestimation of CSF velocity.^{3,36} Nevertheless, even with the through-plane sequences and the use of high-resolution imaging units, there remains a considerable inaccuracy in the velocity data caused by nonlinearity of the gradients, eddy currents, partial volume effects, and placement of the ROI.^{3,28,33} The error is estimated to be approximately 10 to 15%.^{3,58} With very narrow aqueducts, the error may be even higher because noise and poor contrast make placement of the ROI difficult (unpublished data). Velocity measurements obtained in the basal cistern and cervical subarachnoid space are more reliable than velocity measurements obtained in smaller spaces such as the aqueduct.

As early as 1943, O’Connell⁴⁷ suggested that intracranial arterial pulsations are the main source of CSF pulsations. Bering⁵ proposed that choroid plexus pulsations are

responsible for CSF motion. Du Boulay’s¹³ cineventriculographic investigations seemed to confirm O’Connell’s theory. He claimed that the third ventricle is the site of the CSF pump. Recent phase-contrast MR imaging studies of CSF flow confirm the concept of a cardiac-driven CSF pump. There is an expansion of the brain caused by arterial blood inflow during systole and relaxation of the brain caused by blood outflow during diastole.^{10,24,49} These pulsatile changes in intracranial arterial blood volume shift the CSF.¹⁹ Furthermore, brain parenchyma motion contributes to CSF flow.^{16,19,20} Systolic downward movement of the brain has been deemed responsible for a piston action of the brain.²⁴ Brainstem velocities of approximately 1.5 mm/second have been measured.^{16,20,26} The CSF and brain motions represent responses to vascular pulsations as the primary driving force.¹

Retrospective cardiac gating has been proposed as the preferred triggering method for CSF flow quantification.^{6,7,46} This technique enables continuous measurement throughout the cardiac cycle. As the R wave is recorded, the data are sorted retrospectively. Advantages compared with prospective gating are use of the averaging approach to define the zero-velocity point and fewer shifts within the phase background caused by eddy currents.⁴⁶ Nevertheless, we used prospective cardiac gating for flow quantification because, in our experience (unpublished data) and in the experience of others,⁵⁶ prospective gating has been less sensitive to disturbances such as irregular electrocardiographic signals. Furthermore, with prospec-

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tive cardiac gating, two acquisitions could be performed, which is not possible using our retrospective cardiac-gating technique. With the use of retrospective cardiac gating, the relative signal-to-noise ratio of 1 would decrease to 0.71, which is particularly relevant in small anatomical structures such as the aqueduct.¹⁷ The partial volume effects would increase, because the placement of the ROI within the aqueduct would be less accurate. The main disadvantage of prospective cardiac gating is that the whole cardiac cycle is not covered and, hence, the diastolic flow cannot be completely evaluated. However, our intention was primarily to obtain as accurate quantitative CSF flow data as possible by using an acceptable imaging time.

Endoscopic third ventriculostomy has become the preferred treatment for hydrocephalus caused by aqueductal stenosis.^{29–31,57} The procedure is considered to be straightforward and safe. Although complications are rare, near-fatal and even fatal vascular injuries have been reported.^{27,45,51} Furthermore, sometimes the floor of the third ventricle is very tough, requiring considerable force to perforate it, which may traumatize surrounding structures such as the hypothalamus or pituitary stalk. Finally, the anatomy of the floor may be very distorted and lack landmarks, which makes orientation difficult. Therefore, endoscopic aqueductoplasty offers a reasonable alternative for the treatment of membranous or short aqueductal stenoses. Compared with third ventriculostomy, aqueductoplasty has some advantages: 1) aqueductoplasty restores the physiological CSF pathway; 2) aqueductoplasty carries no risk of major vessel injury; 3) arachnoid adhesions, which might interfere with CSF circulation, do not occur around the aqueduct but are occasionally found below the floor of the third ventricle; and 4) strictures of the aqueduct are easily perforated. In our opinion, an aqueductoplasty of a membranous stenosis is less traumatic than a third ventriculostomy.⁵⁰ However, endoscopic aqueductoplasty is indicated only in a select group of patients (16% of our endoscopically treated patients with hydrocephalus).

Conclusions

The limitation of net CSF flow as well as pulsatile CSF flow through the aqueduct, as a cause of hydrocephalus,⁶¹ can effectively be treated using endoscopic aqueductoplasty.

The results of our investigation show that endoscopic aqueductoplasty restores the anatomical patency of the aqueduct and also seems to restore physiological CSF flow through the aqueduct. Therefore, we currently consider endoscopic aqueductoplasty to be the therapy of first choice in the treatment of membranous and short stenoses.

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