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Fluids and Barriers of the CNS

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Longitudinal changes in ventricular volume after treating aqueduct stenosis through endoscopic third ventriculostomy in adults

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Abstract

Background Assessment of ventricular size following endoscopic third ventriculostomy (ETV) often relies on linear measurements and indexes such as the Evans index (EI) and frontal and occipital horn ratio (FOHR). Long-term data on ventricular volume following ETV is scarce, which leads to uncertainties regarding optimal follow-up duration and whether ventricular size correlates with clinical outcomes. This study aims to analyze the longitudinal changes of ventricular volume following ETV for aqueduct stenosis (AS) in adults.

Methods We retrospectively analyzed radiological images and clinical records of adult patients who underwent ETV for AS between the years 2010 and 2020. The primary endpoint was the change in lateral and third ventricular (LTV) volume at various follow-up periods in patients who did not require revision surgery (successful ETV group). Cluster analysis was performed to identify distinct volumetric patterns, and logistic regression was used to analyze the correlation between ventricular volume changes and clinical symptom improvement.

Results A total of 238 radiological images with 197 (82.8%) MRI and 41 (17.2%) CT scans from 46 patients were analyzed. Thirty-nine (84.8%) patients did not require revision surgery (successful ETV group). In the successful ETV group, LTV volume decreased by 19.6% within 3 months, 31% after 3–6 months, and 47.5% after 6–12 months. Two main clusters were identified: one with a mean LTV volume decrease of 56% and the other of 18.9% after 1 year. The presence of a pineal or tectal lesion (OR 3.94, $p = 0.074$) tended to be predictive of the former cluster, and the presence of a membrane in the aqueduct (OR 5.1, $p = 0.036$) was predictive of the latter. Volumetric changes were significantly greater than those measured by EI and FOHR postoperatively ($p < 0.001$) and at the last follow-up ($p = 0.002$). There was no association between LTV volume reduction and clinical improvement during the follow-up period (OR 1.03, [95% CI 0.99–1.06]; $p = 0.195$).

Conclusion Volumetric analysis provides a more accurate representation of ventricular size changes following ETV for AS. It demonstrates a continuous reduction in LTV volume during the first year after surgery, whereafter LTV volume appears to stabilize with a cumulative reduction of 38.7%, suggesting that lifelong imaging may be unnecessary in these patients. However, it does not predict the clinical outcome.

Keywords Endoscopic third ventriculostomy, Aqueduct stenosis, Volumetry

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Introduction

Aqueduct stenosis (AS) is the most common type of non-communicating hydrocephalus in adult patients [1]. AS is caused by obstructions within the aqueduct due to brain lesions, such as cysts or tumors in the mesencephalic or pineal region, or due to thin membranous webs [2–4]. Endoscopic third ventriculostomy (ETV) is recognized as an effective, minimal-invasive procedure treating patients suffering from AS [5–13]. To evaluate the effect of ETV, radiological measurements such as ventricular size and the presence of flow void, as well as clinical assessments, are usually assessed. However, it is still unclear how the ventricular volume is affected after ETV and whether it is associated with the treatment success. Traditionally, ventricular size is measured using linear measurements, with the Evans index (EI) and frontal and occipital horn ratio (FOHR) being the most established measures [14–17]. However, due to the reliance on only two or three linear measures for EI and FOHR calculation, respectively, it provides only an estimate and does not reflect the actual size of the ventricles. Recent studies have indicated that volumetric analysis of the ventricles might offer a more precise representation of ventricular size [18–20]. Despite this, data on longitudinal ventricular volume changes following ETV are scarce, and the potential inaccuracies of linear measurements in capturing these changes remain a significant concern [21–23]. Moreover, the lack of data leads to uncertainties regarding the optimal follow-up duration and whether ventricular size correlates with ETV success and clinical outcome. The aim of our study is to analyze the longitudinal changes in ventricular volume after ETV in adult patients with aqueduct stenosis correlated to their impact on clinical outcomes and surgical revision rates, and finally compare the efficacy of volumetric measurements against traditional linear metrics.

Methods

Patient selection

We retrospectively analyzed data from a consecutive series of adult patients diagnosed with AS who underwent ETV alone or ETV combined with endoscopic biopsy or cyst fenestration at the Department of Neurosurgery, University Hospital Basel, between the years 2010 and 2020. To be included in the study, pre- and postoperative imaging data had to be available in our institutional radiology system (Sectra Workstation IDS7, Sectra, Linköping, Sweden), suitable for qualitative and quantitative analyses. Patients with a history of cerebrospinal fluid (CSF) diversion through ventriculoperitoneal or ventriculoatrial shunts or previously performed ETV were excluded.

Data collection and outcome measures

Data were extracted from our surgical logbook and the patient's medical files. Baseline characteristics, including age, gender, etiology for AS, type of endoscopic procedure, and modified Rankin Scale (mRS) at admission, were collected. Radiological parameters, such as the EI, FOHR, and the volume (cm^3) of the lateral, third, and fourth ventricles and the presence of a flow void through the stoma, were assessed at all available time points. Using a T2-weighted MRI sequence, the presence of a flow void after ETV was defined as a corresponding signal reduction at the floor of the third ventricle through the stoma, serving as an indirect indicator of high CSF flow velocity through an open stoma. Considering that AS is localized between the third and fourth ventricles, we primarily report the combined volume of the lateral and third ventricles, referred to as the lateral-third ventricle (LTV) volume.

The primary endpoint was the postoperative longitudinal relative change in the LTV volume compared to the preoperative LTV volume. Secondary endpoints included longitudinal changes in linear ventricular measurements such as EI and FOHR, mRS scores, and clinical improvement at discharge and at last follow-up (mean 2.6 ± 2.5 years) compared to the preoperative condition. The mRS was dichotomized into 2 groups (favorable ≤ 2; unfavorable > 2), and clinical symptom improvement was categorized into 3 groups (improved; same; worsened) and referred to the leading clinical symptom documented at baseline. Furthermore, subsequent revision surgeries were assessed. To ensure a homogeneous group of patients for the volumetric measurements, we excluded those with multiple surgeries that could influence ventricular volume or CSF hydrodynamics. Therefore, we designated all patients who underwent repeat cranial surgery after the initial ETV into the failed ETV group. Patients who did not undergo subsequent surgery after the initial ETV were included in the successful ETV group.

Volumetry, Evans index, frontal and occipital horn ratio

The volumetric analysis was performed on the available radiological source image with the thinnest slice thickness, which was on average 1.78 ± 1.14 mm for assessing lateral ventricle volume, EI, and FOHR, and 1.17 ± 0.72 mm for the third ventricle. For CT imaging, the soft tissue sequences were consistently used for volumetry. In MRI imaging, thin-slice T1-weighted magnetization prepared rapid acquisition with gradient echoes (MPRAGE) or T2-weighted constructive interference in steady state (CISS) sequences were used for volumetry in most cases. If thin slice MRI sequences were only conducted in the sagittal plane, encompassing the third and fourth ventricles but not the lateral ventricles,

different radiological source images were used for volumetric assessments of the different parts of the ventricles to ensure the highest image quality and maximum precision. The volumetric analysis was performed using a semi-automated segmentation tool (Sectra Workstation IDS7, Sectra, Linköping, Sweden), which automatically captures large parts of the ventricle based on a selected region. However, the narrow portions of each ventricle, especially the temporal horns, often require manual correction with the same tool to capture the entire ventricle (Fig. 1).

The EI was calculated from axial CT or MRI images at the level of the anterior and posterior commissure by dividing the maximum width of the frontal horns anterior to the foramina of Monro by the maximum inner width of the skull at the same slice. The Evans Index was measured 1 cm above the bi-commissural plane [8]. The FOHR was measured following the method previously described by O'Hayon et al. [17] The source images for the EI and FOHR calculations had the same slice thickness as those used for the volumetry of the lateral ventricles.

Statistical analysis

Baseline characteristics, functional outcomes, and the rate of revision surgery for the entire cohort were presented descriptively. The primary endpoint was the longitudinal relative changes in the LTV volume within the successful ETV group.

To evaluate whether different groups of longitudinal courses of ventricular volume after successful ETV in AS exist, we performed a cluster analysis. For cluster formation, we first calculated standard z-values using linear regression based on LTV volume measurements

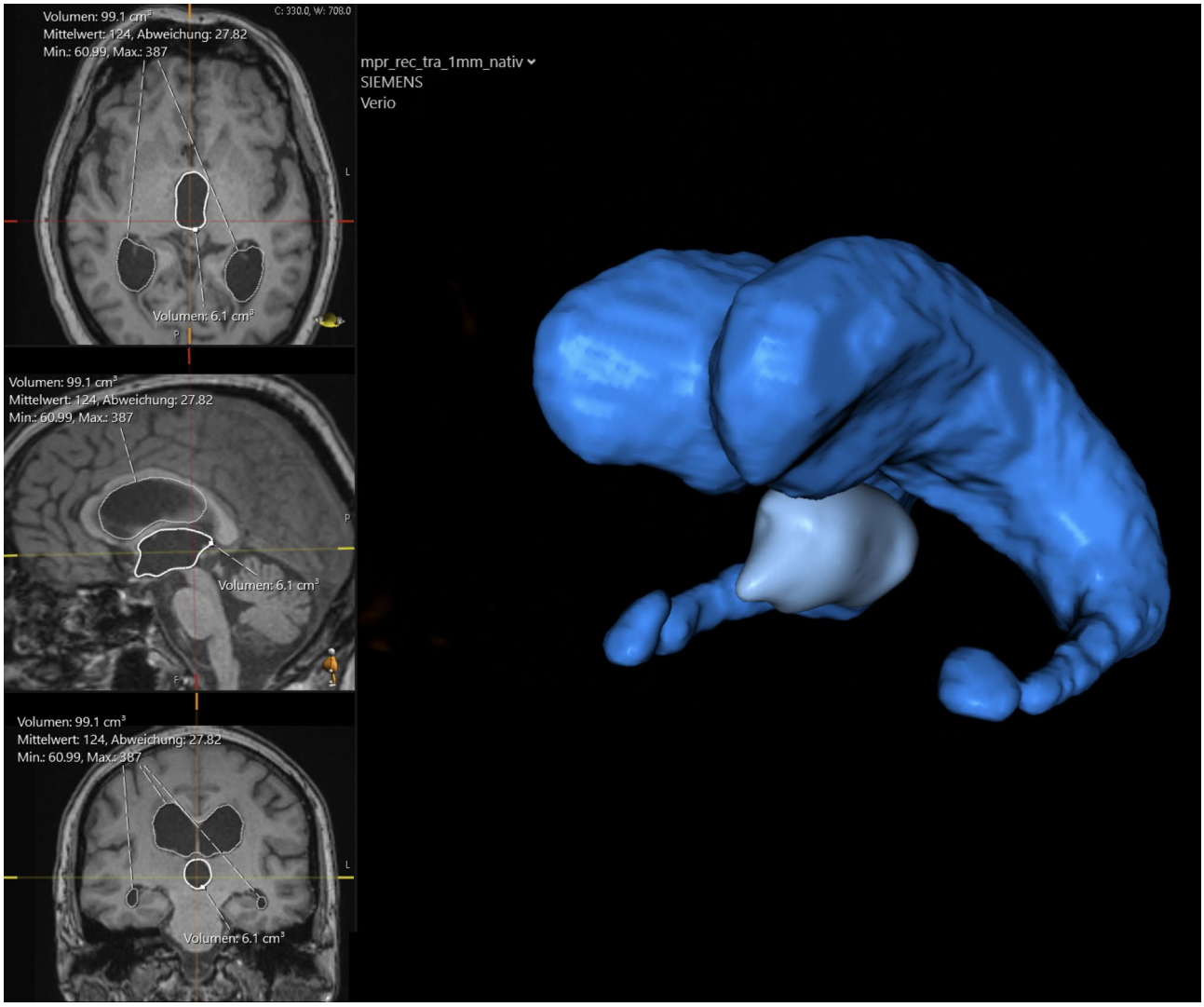

Fig. 1 Illustration of the volumetric analysis of the third and lateral ventricles in the radiology program (Sectra Workstation IDS7, Sectra, Linköping, Sweden)

and time points. These z-values were used to perform an exploratory hierarchical cluster analysis using the Ward method, followed by creating three clusters using k-means cluster analysis [24]. Logistic regression analyses were further used to identify predictive factors for the respective cluster affiliations.

Secondary endpoints were the comparison between the longitudinal relative changes in EI and FOHR and the LTV volumes using a Pearson correlation analysis. Furthermore, logistic regression analysis was used to assess the influence of the relative LTV volume change postoperatively and at the last follow-up on improving clinical symptoms and the mRS improvement. Finally, we analyzed the relative LTV volume changes in patients who underwent revision surgery before and after the revision and during the last follow-up.

All statistical analyses were performed using SPSS, version 28.0 (IBM Corp., Armonk, New York, USA). Univariate analysis was performed using the Fisher exact or chi-square test for categorical data and the Mann-Whitney U or the Kruskal-Wallis test for continuous data. Values are reported as mean ± standard deviation or median with interquartile range (IQR). A p-value < 0.05 was considered significant.

The local ethics committee (EKNZ, Basel, Switzerland) approved this study and waived the need for informed patient consent due to its retrospective nature.

Results

Out of 138 patients screened who underwent neuroendoscopic surgery, 85 (64.4%) were adults, and of these, 46 patients (33.3%) underwent ETV due to AS. A total of 238 cranial radiological images from 46 patients were analyzed. The analysis included 197 (82.8%) MRI and 41 (17.2%) CT scans, with a median of 5 images per patient. The mean patient age was 50.4 ± 20.7 years, and 28 (60.9%) were female. AS was mostly due to an aqueductal web (n = 24, 52.2%) followed by a tumor in the pineal or tectal region (n = 16, 34.8%). In 35 (76.1%) patients, ETV alone was performed, while in 8 (17.4%) and 3 (6.5%) patients, an ETV was combined with an endoscopic biopsy or cyst fenestration, respectively. Preoperatively, 27 (58.7%) patients had a favorable mRS.

Of the 46 patients, 39 (84.8%) did not require revision surgery (successful ETV group). Seven patients (15.2%) underwent 8 revision surgeries (failed ETV group). There were no significant differences in baseline characteristics between the successful and failed ETV groups (Table 1). The average time to the first and second revision surgery was 1.1 ± 1.1 and 0.86 years, respectively. Re-ETV was performed in 57.1% of the failed cases (n = 4), while insertion of a ventriculoperitoneal shunt (VPS) was done in 42.9% (n = 3). Re-ETVs were undertaken due to closure of the stoma or lack of significant reduction in ventricular volume. Two VPS insertions were due to the absence of clinical improvement, and one after a CSF

Table 1 Baseline characteristics of the cohort and between the two groups

Variables	Total	Successful-ETV	Failed-ETV	*P* value
Number of patients	46	39 (84.8)	7 (15.2)	
Mean age ± SD, years	50.4 ± 20.7	52.2 ± 21.6	40.4 ± 11.7	0.278
Females	28 (60.9)	23 (59)	5 (71.4)	0.534
mRS at baseline				0.928
≤ 2	27 (58.7)	23 (59)	4 (57.1)	
> 2	19 (41.3)	16 (41)	3 (42.9)	
Etiology for Aqueduct stenosis				0.436
Membrane	24 (52.2)	20 (51.3)	4 (57.1)	
Lesion/Tumor pineal or tectal region	16 (34.8)	14 (35.9)	2 (28.6)	
Pineal cyst	4 (8.7)	4 (10.3)	-	
Occlusion/Stenosis without membrane	2 (4.3)	1 (2.6)	1 (14.3)	
Procedure type				0.71
ETV	35 (76.1)	29 (74.4)	6 (85.7)	
ETV + Endoscopic biopsy	8 (17.4)	7 (17.9)	1 (14.3)	
ETV + Endoscopic cyst fenestration	3 (6.5)	3 (7.7)	-	
Radiology preoperatively				
Evans Index ± SD	0.36 ± 0.06	0.37 ± 0.06	0.36 ± 0.04	0.929
FOHR ± SD	0.48 ± 0.06	0.48 ± 0.06	0.48 ± 0.06	1
Volume lateral ventricles, cm^3	171 ± 182.1	172.3 ± 192.1	163.9 ± 123	0.905
Volume 3rd ventricle, cm^3	5.8 ± 3.4	5.9 ± 3.6	5.4 ± 2	0.891
Volume 4th ventricle, cm^3	1.3 ± 1	1.3 ± 1.1	1.2 ± 0.7	0.902
Volume lateral and 3rd ventricles, cm^3	176.8 ± 184.9	178.2 ± 195.1	169.2 ± 123.7	0.891

SD = standard deviation, mRS = modified Rankin Score, ETV = Endoscopic third ventriculostomy, FOHR = Frontal occipital horn ratio

All values presented as number (%) of patients or mean ± SD, if not otherwise specified

infection leading to additional communicating hydrocephalus. One patient, showing no clinical improvement after a repeat ETV, required, in addition, a VPS insertion (Table 2). Among the 46 patients included in the study, 76.1% ($n=35$) demonstrated a favorable mRS at discharge, with 67.4% of patients ($n=31$) showing clinical symptom improvement. During the last follow-up, 88.2% of patients ($n=30$) maintained a favorable mRS, and 78.8% ($n=26$) continued to exhibit clinical improvement. Functional outcomes at discharge and last follow-up were comparable between the successful and failed ETV groups (Table 2).

Longitudinal ventricular volume changes and cluster analysis within successful ETV group

In the 39 patients of the successful ETV group, 180 cranial radiological images were analyzed, consisting of 157 (87.2%) MRI and 23 (12.8%) CT scans, with a median of 4 images per patient. Postoperatively and during the last follow-up, a flow void was detected based on MRI scans in 94.4% and 93.3% of patients, respectively. The mean slice thickness was 1.71 ± 1.13 mm for assessing lateral and 1.1 ± 0.6 mm for the third ventricle volume. The LTV volume decreased on average by 15% ± 15.5% on MRI ($n=37$) and on CT ($n=2$) after surgery (mean 4.5 ± 7.6 days postoperatively). The LTV volume decreased by 19.6% ± 28.5% during the first 3 months, followed by cumulative decreases of 31% ± 26.3% and 47.5% ± 25.7% after 3–6 months and 6–12 months, respectively. One year after surgery, the LTV volume appears to stabilize with a cumulative volume reduction of 38.7% ± 25.5% (Fig. 2, Supplementary Table 1).

We identified 3 clusters that grouped patients with similar longitudinal ventricular volume trajectories. This clustering approach allowed us to identify potential patterns and subgroups in the postoperative volume changes, providing insights into different responses to ETV treatment. Most patients were allocated to clusters 1 and 3, with 10 (25.6%) and 27 (69.2%) patients, respectively. Only 2 (5.1%) patients were allocated to cluster 2.

In clusters 1 and 3, there was a trend towards different levels of LTV volume reductions. In cluster 1, the LTV volume decreased by a mean of 56% ± 16.1% one year postoperatively, whereas in cluster 3, it decreased by a mean of 18.9% ± 20.8% one year postoperatively. In cluster 2, there was a tendency towards an increase in LTV volume postoperatively (Fig. 2).

The etiology of AS was associated with cluster allocation and, consequently, with the postoperative course of LTV volume. The presence of a membrane as the cause of AS predisposed patients to cluster 3 (OR 5.1, [95% CI 1.1–23.37]; $p=0.036$). In contrast, a pineal or tectal lesion showed a negative correlation with cluster 3 allocation (OR 0.14, [95% CI 0.03–0.64]; $p=0.011$) but tended to

Table 2 Clinical outcome and revision surgery between both groups

Variables	Total	Successful-ETV	Failed-ETV	*P* value
Number of patients	46	39 (84.8)	7 (15.2)	
mRS at discharge				0.107
≤ 2	35 (76.1)	28 (71.8)	7 (100)	
> 2	11 (23.9)	11 (28.2)	-	
Clinical improvement at discharge				0.499
Improved	31 (67.4)	25 (64.1)	6 (85.7)	
Same	12 (26.1)	11 (28.2)	1 (14.3)	
Worse	3 (6.5)	3 (7.7)	-	
mRS last follow-up				0.278
≤ 2	30 (88.2)	23 (85.2)	7 (100)	
> 2	4 (11.8)	4 (14.8)	-	
Clinical improvement last follow-up				0.82
Improved	26 (78.8)	20 (76.9)	6 (85.7)	
Same	6 (18.2)	5 (19.2)	1 (14.3)	
Worse	1 (3)	1 (3.8)	-	
Last Follow-up (years)	2.6 ± 2.5	2.5 ± 2.6	3.3 ± 1.9	0.144
Type of 1st revision surgery				
Re-ETV	4 (8.7)	-	4 (57.1)	-
VPS	3 (6.5)	-	3 (42.9)	-
Time to 1st revision surgery (years)	1.1 ± 1.1	-	1.1 ± 1.1	-
Type of 2nd revision surgery				
VPS	1 (2.2)	-	1 (14.3)	-
Time to 2nd revision surgery (years)	0.86	-	0.86	-

SD = standard deviation, mRS = modified Rankin Score, ETV = Endoscopic third ventriculostomy, FOHR = Frontal occipital horn ratio

All values presented as number (%) of patients or mean ± SD, if not otherwise specified

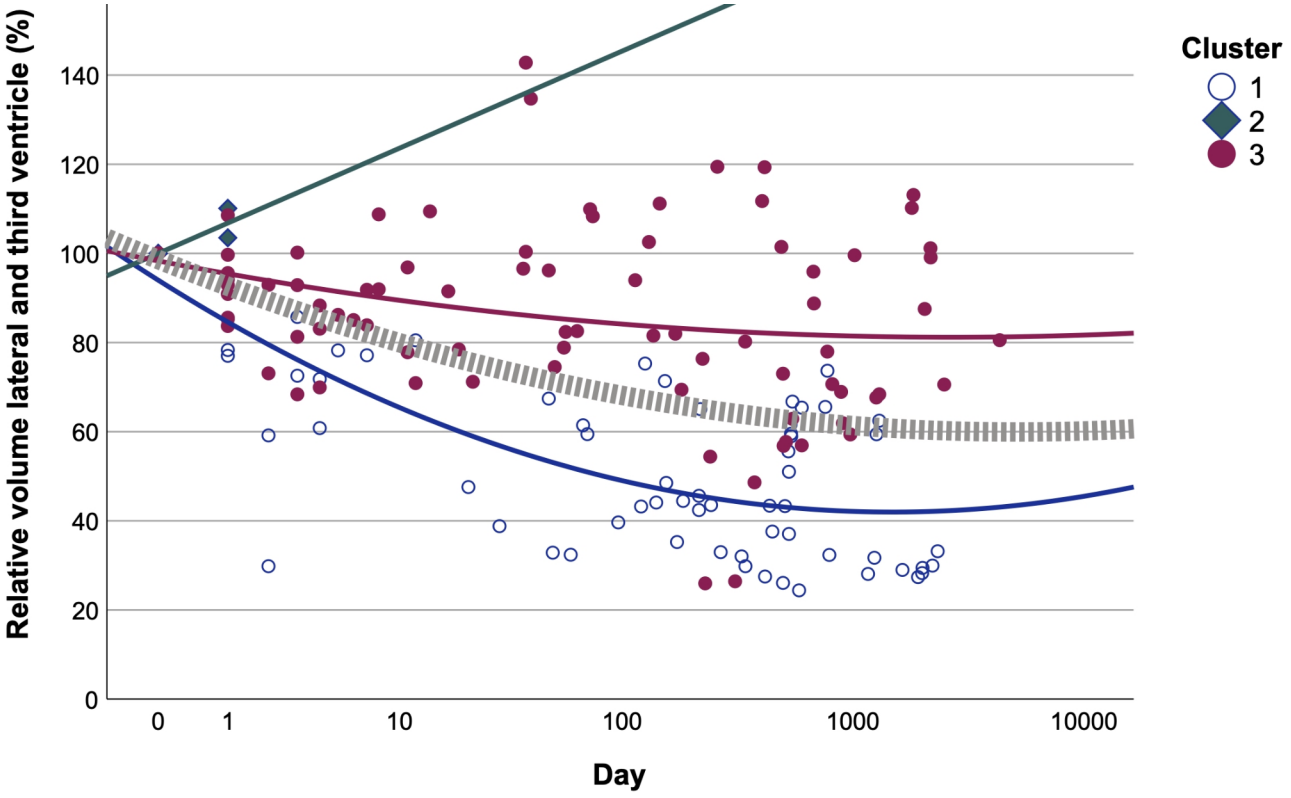

Fig. 2 Illustration of the longitudinal relative changes of the lateral and the third ventricle volume with a quadratic interpolation line (gray dashed) of the successful-group and the three clusters, each with their corresponding quadratic interpolation lines

predispose patients to cluster 1 (OR 3.94, [95% CI 0.88–17.73]; $p = 0.074$) (Supplementary Table 2).

Volumetric compared to linear ventricular measurements

Postoperatively, volumetry indicated a reduction in LTV volume by an average of 15% ± 15.5%. In contrast, EI and FOHR demonstrated significantly smaller decreases, recording 5.1% ± 6.5% and 2.9% ± 4.2%, respectively ($p < 0.001$, Supplementary Table 1).

At last follow-up, volumetry revealed a more substantial reduction in LTV volume by an average of 28.7% ± 30.6%. This reduction was significantly greater compared to the reductions observed with EI and FOHR, which decreased by 8.8% ± 10.3% and 8.4% ± 9.4%, respectively ($p = 0.002$) (Fig. 3, Supplementary Table 1). Although the LTV volumetry shows higher reduction rates than the linear measurements, the volumetric measurements demonstrated a positive correlation with both EI ($r = 0.72$, $p < 0.001$) and FOHR ($r = 0.77$, $p < 0.001$) (Fig. 4). The slight differences in correlation between EI and FOHR compared to volumetry were not statistically significant ($p = 0.143$).

Volumetry as a predictor for functional outcome and revision surgery

Among the 39 patients in the successful ETV group, postoperative LTV volume changes showed no association with improvement in mRS (OR 1.03, 95% CI 0.98–1.07, $p = 0.253$) or clinical symptoms (OR 1.02, 95% CI 0.98–1.07, $p = 0.348$). Similarly, there was no association between the relative decrease in LTV volume and improvement in mRS (OR 1.02, 95% CI 0.99–1.06, $p = 0.245$) or clinical symptoms (OR 1.03, 95% CI 0.99–1.06, $p = 0.195$) during the last follow-up.

Seven patients required a total of 8 revision surgeries (failed ETV group). In this group, the LTV volume after the initial surgery significantly decreased by 23.2% ± 20.7% ($p = 0.005$), similar to the successful ETV group. However, there was a subsequent increase in LTV volume by 15.1% ± 25.6% before the first revision surgery, which decreased again by 17.6% ± 13.6% post-revision. At the last follow-up imaging, the relative LTV volume reduction stabilized by a cumulative mean of 36.7% ± 14.3% (Fig. 5).

Discussion

Based on our results, after a successful ETV, the LTV volume showed a continuous decrease of approximately 38.7% after one year, after which it seems to stabilize.

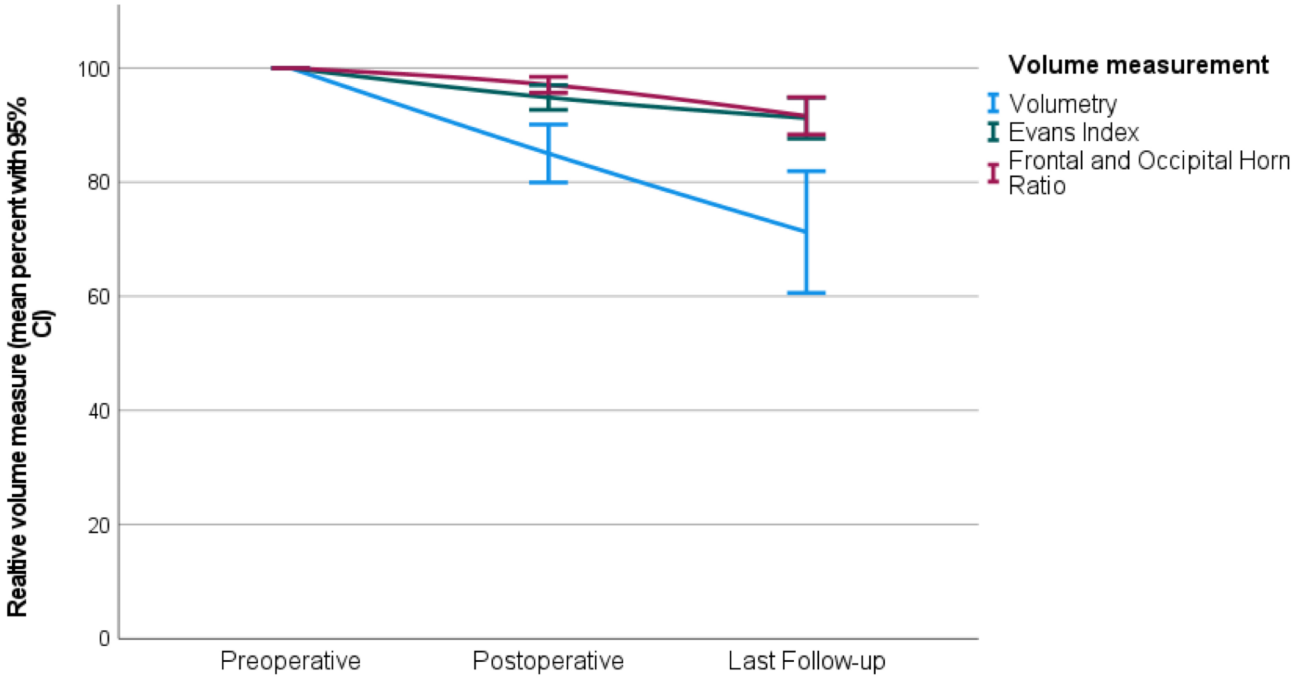

Fig. 3 Comparison of the mean relative volume with the 95% confidence interval of the lateral and the third ventricle volume, Evans index, and frontal and occipital horn ratio during follow-up within the successful-ETV group

Two distinct longitudinal courses were observed: patients with a pronounced LTV volume reduction of 56% after one year, often associated with a pineal or tectal lesion, and those with a less pronounced reduction of 18.9%, typically linked to the presence of an aqueductal membrane. Our findings also revealed that volumetry detects more significant changes in ventricular size than linear measurements such as EI and FOHR. Although these volumetric changes were not predictive of clinical improvement, they were indicative in determining the need for revision surgery where after an initial decrease of LTV, a mean pre-revisional LTV increase of 15.1% was seen on follow-up images.

Longitudinal ventricular size assessment and clustering

The ventricular size is a crucial indicator of hydrocephalus [14]. Different etiologies of hydrocephalus are often associated with characteristic ventricular configurations. AS typically leads to triventricular hydrocephalus with enlargement of the lateral and third ventricles [25]. After surgical treatment, radiological parameters such as ventricular size are often used in clinical practice to monitor the treatment's success. Traditionally, ventricular size has been quantified using linear measurements such as EI and FOHR, which serve as an indirect ventricular size indicator and can be inaccurate due to different measurement techniques [14–17, 20, 26–28]. Volumetric analysis, once considered impractical and time-consuming in everyday clinical practice, has become more accessible with advanced semi- or fully-automated segmentation tools [8, 29–34]. The longitudinal ventricular volume changes after ETV in patients with AS remain unclear, with contradictory reports. Some studies indicate significant decreases in ventricular volume ranging from 33 to 39% over periods of 3 weeks to 45 months post-ETV, while others found no reduction in up to 60.5% of patients [21, 22, 35–39]. The inconsistencies in the literature are partly due to the use of linear measurements, which may not accurately capture ventricular size changes. Additionally, the available studies are limited by the heterogeneity and small size of the cohorts. Often, no distinction is made between children and adults, and multiple etiologies are mixed, even though age and etiology appear to influence the longitudinal course of ventricular volume [35]. Moreover, whether previous CSF diversion procedures were performed, which is known to influence ventricular size development after ETV, was often not considered [13]. Furthermore, the ventricular size is often measured at two different times, preoperatively and during the last follow-up. Therefore, providing a detailed statement about the longitudinal development of ventricular size is impossible.

Our study uniquely reports on a homogeneous adult cohort suffering from AS treated with ETV without any previous interventions for CSF diversion. We analyzed a median of 5 images per patient, allowing us to chart longitudinal ventricular size evolution rather than merely comparing two time points. Our volumetric data

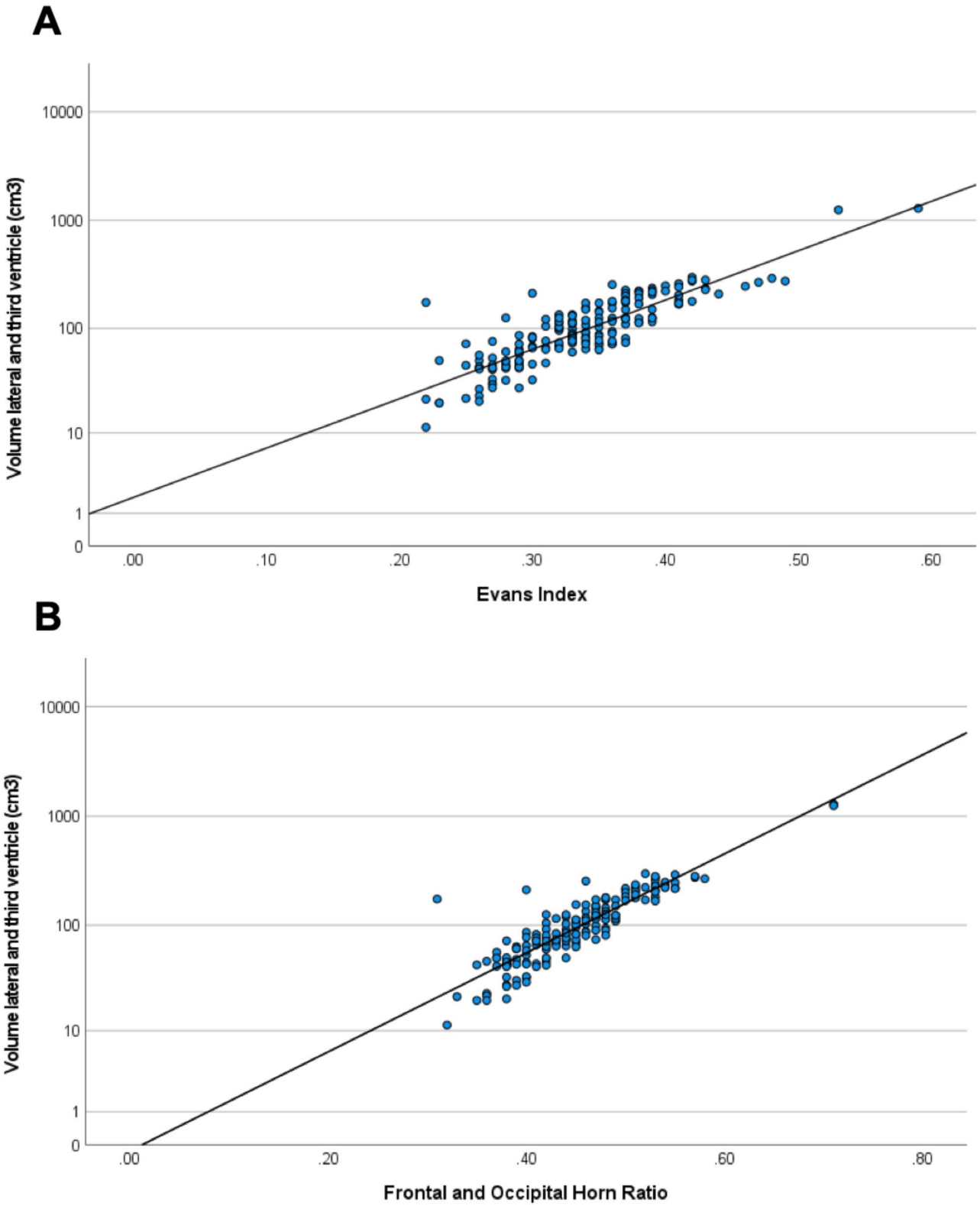

Fig. 4 Scatter plot illustrating the correlation between volumetric measurements of the lateral and the third ventricles and the Evans index ($r = 0.72$, $p < 0.001$) (A), and the frontal and occipital horn ratio ($r = 0.77$, $p < 0.001$) (B)

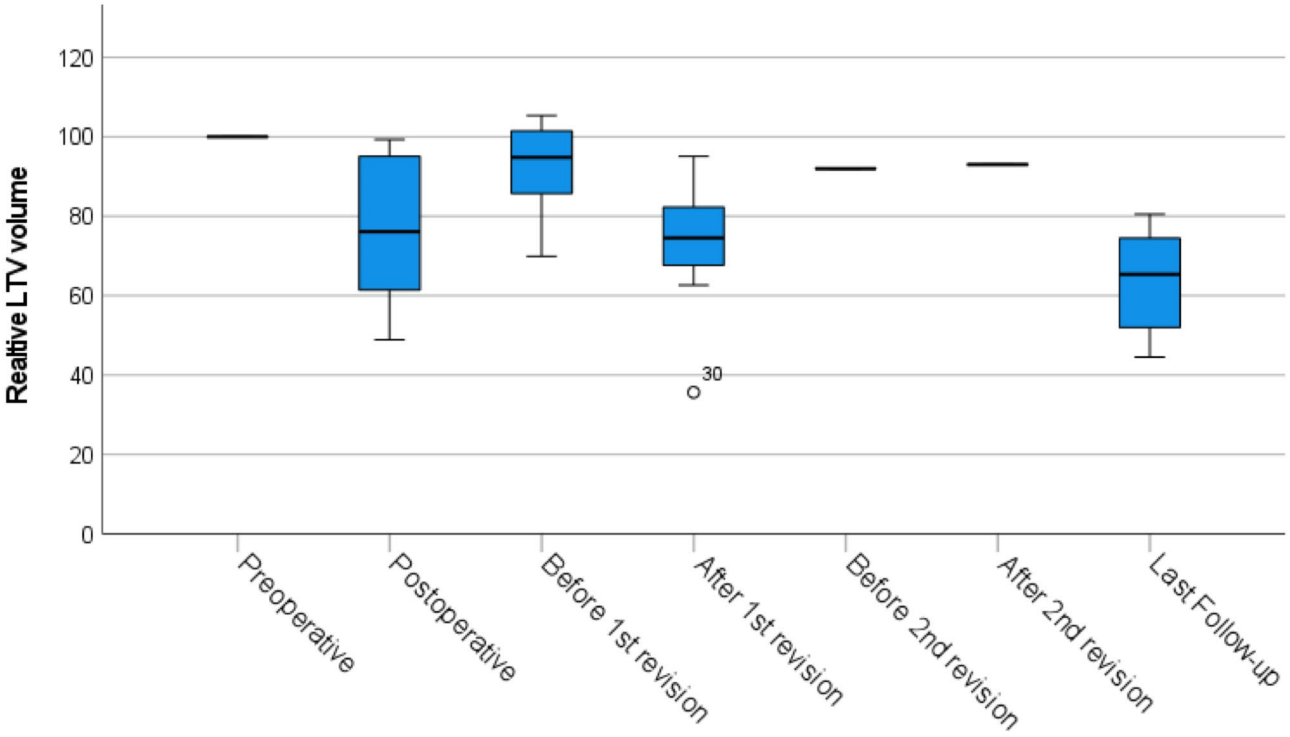

Fig. 5 Illustration of the longitudinal changes of the lateral and the third ventricle (LTV) volume in the failed-ETV group. After the initial ETV, there is a significant reduction in LTV volume, followed by an increase before the first revision surgery, and a subsequent decrease post-revision. The data indicate stabilization at 63.3 ± 14.3% of the initial volume at the last follow-up

of patients from the successful ETV group showed that LTV volume stabilizes after one year with a cumulative mean reduction of 38.7% ± 25.5%. These reduction measures are in a similar range to the sparse and heterogeneous literature [21–23, 35]. Interestingly, we identified two different trajectories of LTV volume after ETV in patients with AS using cluster analysis. In cluster 1, the LTV volume showed a higher reduction rate of 56% after one year, while in cluster 3, the reduction was smaller at 18.9%. Additionally, we found that the etiology of AS is associated with the corresponding postoperative course of LTV volume. Overall, this suggests that LTV volume decreases after ETV in AS, but to different extents. These findings may be important for follow-up, providing an easily measurable variable with corresponding reference values to assess the functionality of the ETV, especially in patients who are difficult to assess clinically.

Similarly, based on our data, EI and FOHR showed continuous reduction as estimates for ventricular volume, with a rather strong correlations ($r = 0.72$, $r = 0.77$) to volumetric data (Fig. 4). This correlation was slightly better than that reported by Saehle et al., who found a correlation of $r = 0.5$ between EI and volumetry [28]. Notably, as shown in Fig. 3, the magnitude of reduction based on volumetric data was significantly higher than that of linear measurements. This aligns with the literature, indicating that treatment effects on ventricular volume are approximately three times higher than those measured by conventional linear metrics like EI [19]. This discrepancy may explain why previous studies using linear measurements reported a wide range of patients showing no reduction in ventricular size after ETV.

Looking ahead, advanced fully automated volumetric techniques, enhanced by artificial intelligence, could streamline follow-up recommendations and treatment decisions based on precise ventricular size data. Although our study offers initial insights, further research is essential to confirm these findings.

Functional outcome and revision surgery related to ventricular volumetry

Whether clinical improvement is related to the development of ventricular volume is debated and has not been conclusively clarified. Several studies have shown a positive correlation between ventricular size and clinical improvement, while others showed no correlation [18, 19, 38–43]. The existing literature is highly heterogeneous, with variations in measurement methods, cohort characteristics, and definitions of clinical improvement contributing to the lack of consensus.

In our study, clinical improvement was observed in 64.1% of patients at discharge and 76.9% at the last follow-up within the successful ETV group without significant association between the extent of LTV volume

reduction and symptom improvement. Our findings suggest that the assessment of ETV success should not rely solely on ventricular volume metrics. A reduction in ventricular size by approximately 40% within the first year post-ETV can be anticipated, but normalization of ventricular size is not a prerequisite for successful outcomes. Stabilization of ventricular size beyond this period should be considered acceptable, indicating that routine long-term MRI monitoring may not be necessary. Consequently, life-long imaging to assess ventricular size might be redundant, and a clinical follow-up schedule, potentially extending to two years post-ETV, could be sufficient for most patients.

In patients who demonstrate absent flow signal through the stoma at one-year follow-up but remain clinically asymptomatic, continued regular clinical monitoring with additional follow-up imaging should be considered. These patients may require closer and more frequent clinical surveillance than standard annual follow-ups. In particular, we emphasize the importance of thorough patient education regarding the possible occurrence of recurrent symptoms. The optimal management strategy in such cases, whether imaging surveillance or purely clinical monitoring, remains to be clarified in future studies.

Seven (15.2%) of the 46 patients received at least one further operation apart from the initial ETV and were classified in the failed ETV group. A failed ETV is defined differently in the literature [44]. Since any neurosurgical intervention involving the CSF space after a successful ETV could potentially impact the CSF circulation, we included all patients who underwent a second operation in the failed ETV group to achieve a homogeneous group in the successful ETV group. In contrast to functional outcomes, the relative changes in LTV volumes were indicative of revision surgery (Fig. 5). However, we did not intend to investigate how ventricular volumetry evolved specifically after re-ETV or VPS following failed ETV, as the number of cases was too small for a robust and meaningful subgroup analysis. Before revision surgery, there was a 15.1% increase in LTV volume, which decreased again during the last follow-up after revision surgery, similar to the successful ETV group, by 36.7%. This suggests that as long as ventricular volume decreases during the first year and then stabilizes, it can be considered reassuring. However, if ventricular size increases alongside symptoms, it may indicate ETV failure. Whether a 15% increase in ventricular volume alone, without symptoms, signifies failure remains unclear and warrants further investigation.

Limitations

This retrospective study is subject to several limitations inherent to its design. First, the nature of retrospective data collection introduces potential biases and limits the data quality. Second, the sample size of the patient cohort is relatively small, which may result in insufficient statistical power for some of the analyses performed, potentially affecting the robustness and generalizability of the findings. Third, the absence of a standardized radiological protocol led to variability in image quality. Volumetric analysis, particularly with thicker image slices, is associated with inaccuracy, which may influence the volumetric data and subsequent results. Fourth, we did not specifically assess clinical or radiological signs of raised intracranial pressure, which could potentially influence ventricular volume dynamics after ETV. Fifth, follow-up duration varied between patients, with some having relatively short follow-up periods, which may impact certain results. Additionally, we assert that detailed neuropsychological testing is essential for accurately assessing functional outcomes in patients undergoing neuroendoscopic surgery. The lack of such assessments in our study limits the interpretation of functional outcomes and their correlation with volumetric changes. These limitations should be considered when interpreting the study's results and their implications for clinical practice.

Conclusion

Our study shows that volumetric analysis more accurately captures postoperative ventricular changes than linear measurements, although linear indices demonstrated a strong correlation with volumetric measures. The cumulative LTV volume reduction reached 38.7% within one year after ETV. Ventricular size stabilized beyond this period, suggesting that lifelong imaging to monitor ventricular size may be unnecessary, and a clinical follow-up schedule could suffice for most patients. The patterns of volume reduction varied, as identified by cluster analysis, indicating different postoperative trajectories correlating with the underlying etiology of aqueduct stenosis. However, volume reduction did not correlate with clinical outcome.

Abbreviations

AS	Aqueduct Stenosis
ETV	Endoscopic Third Ventriculostomy
EI	Evans Index
FOHR	Frontal and Occipital Horn Ratio
LTV	Lateral–Third Ventricle Volume
mRS	Modified Rankin Scale
CSF	Cerebrospinal Fluid
MRI	Magnetic Resonance Imaging
CT	Computed Tomography
CISS	Constructive Interference in Steady State
MPRAGE	Magnetization Prepared Rapid Acquisition with Gradient Echoes
VPS	Ventriculoperitoneal Shunt
EKNZ	Ethics Committee of Northwest and Central Switzerland
IQR	Interquartile Range

Supplementary Information

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Supplementary Material 1

Author contributions

F.E.: Conceptualization, Methodology, Formal analysis, Investigation, Writing – Original Draft, Visualization C.M.: Investigation R.G.: Writing – Review & Editing J.S.: Conceptualization, Methodology, Writing – Review & Editing, Supervision.

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Data availability

The data that support the findings of this study are available on request.

Declarations

Ethics approval

The local ethics committee (EKNZ, Basel, Switzerland) approved this study and waived the need for informed patient consent due to its retrospective nature.

Competing interests

The authors declare no competing interests.

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