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Shape Analysis of the Corpus Callosum in Pediatric Hydrocephalus: A Comparison Between Cases with and without Shunt Revision Surgery

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ABSTRACT

AIM: To investigate corpus callosum shape differences in pediatric hydrocephalus patients with and without shunt revisions.

MATERIAL and METHODS: Midsagittal magnetic resonance imaging studies from 45 cases (25 with and 20 without shunt revision surgeries) that underwent ventriculoperitoneal shunt surgery between 2016 and 2025 were retrospectively analyzed. Corpus callosum shape deformations were evaluated using thin plate spline (TPS) analysis. Landmark-based geometric morphometric methods were applied, and growth curve modeling was used to assess the relationship between centroid size and the number of shunt revisions.

RESULTS: TPS analysis revealed that patients with multiple shunt revisions exhibited the most prominent corpus callosum deformations in the posterior region. Atrophy was detected mainly in the splenium region.

CONCLUSION: This study identified changes in the corpus callosum of pediatric hydrocephalus patients with multiple shunt revisions compared to those without shunt revisions. These findings may help characterize the clinical features of cases with multiple shunt revisions.

KEYWORDS: Hydrocephalus, Corpus callosum, Shunt revision, Shape analysis

ABBREVIATIONS: CC: Corpus callosum, **CSF:** Cerebrospinal fluid, **MRI:** Magnetic resonance imaging, **NY:** New York, **TPS:** Thin plate spline

INTRODUCTION

Hydrocephalus is a neurological condition characterized by the abnormal accumulation of cerebrospinal fluid (CSF) within the brain, resulting in ventricular enlargement. The standard treatment involves surgical placement of a ventriculoperitoneal shunt to divert CSF into the peritoneal cavity, thereby reducing intracranial pressure. In hydrocephalus, damage to the corpus callosum (CC), resulting from mechanical pressure against the falx cerebri and deterioration of myelin, is associated with motor and cognitive deficits. Disruption of normal myelination adversely affects the microstructural architecture of the posterior CC (1).

The CC comprises five subdivisions, each with distinct functional connections. The posterior part (splenium) connects the visual cortices of the occipital lobes. Anterior to this, the middle posterior part (isthmus) connects motor, somatosensory, and primary auditory regions. Central (body) fibers project through the cerebral cortex and ascend into the corona radiata, contributing to several key white matter tracts. The middle frontal part (genu) connects the middle and lateral surfaces

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of the frontal lobe, while the anterior part (rostrum) serves as a critical conduit between the orbital surfaces of the frontal lobe (1).

Magnetic resonance imaging (MRI) studies in patients with hydrocephalus have frequently revealed thinning of the CC and scalloping of its margins, both before and after shunt surgery. In rare cases, however, thickening of the CC has been observed in patients who have undergone successful shunt placement (4).

Shape analyses of the CC have been conducted across a variety of neurological conditions, revealing disease-specific morphological differences. In patients with multiple sclerosis, structural deformities have been identified in the CC and cerebellum (19). In cases of scaphocephaly, longitudinal shape analyses have shown that the expansion of the cranial vault over time is associated with an enlargement of the splenium region of the CC (3). In individuals with restless legs syndrome, callosal deformations have been mainly localized to the posterior middle region and, to a lesser extent, the anterior region. Furthermore, increased disease duration and severity have been correlated with significant reductions in the size of the CC (20).

Studies investigating the effect of a disease, surgery, or pathological conditions on brain structures have primarily relied on single morphometric measures such as volume or density. In contrast, landmark-based shape analysis focuses on the intrinsic geometric properties of anatomical structures. Shape is defined as the geometric information that remains invariant under translation, rotation, and scaling, thus enabling a more detailed assessment beyond scalar measurements (7,11,12). With advances in image-processing software and the availability of high-resolution digital imaging from various modalities, landmark-based shape analysis has been increasingly applied in neuroanatomical research (18-22). When combined with thin plate spline (TPS) analysis, this approach enables the precise localization of shape differences across cortical and subcortical brain regions, revealing even subtle morphological deformations (14,15,17).

This study aimed to compare shape differences in the CC of pediatric patients with hydrocephalus who underwent shunt revision surgery with those who did not. Using landmark-based shape analysis, we evaluated regional deformations across CC subregions to identify potential morphological alterations. Furthermore, we investigated whether the number of shunt revisions predicts CC abnormalities in this patient population.

MATERIAL and METHODS

The study was approved by the local Ethics Committee (Decision Number/Date: 2024-TBEK 2025/03-07/26.03.2025). Written informed consent was obtained from all participants or their legal guardians. No financial support was received for this study.

Midsagittal MRI studies from 45 patients who had previously undergone ventriculoperitoneal shunt surgery for hydrocephalus between 2016 and 2025 were retrospectively analyzed. Of these patients, 25 patients had undergone shunt revision surgery, while 20 had no history of revision. Patients were excluded if they were aged >17 years, had CC abnormalities that precluded the placement of all required landmarks, or exhibited extreme thinning or deformation of the CC on MRI that would compromise accurate shape analysis.

Demographic and clinical data—including patients' age, sex, hydrocephalus etiology, reasons for shunt revision, and midsagittal MRI images—were retrospectively collected from hospital records. MRI examinations were performed using a 1.5-T scanner (GE Optima MR360, Milwaukee, Wisconsin, USA) equipped with a 16-channel sensitivity-encoding head coil. Sagittal T2-weighted spin-echo sequences were obtained using the following parameters: field of view, 230 × 250 mm; slice thickness, 5 mm; repetition time/echo time, 5800–6700/95–115 ms; flip angle, 90°. These parameters provided optimal contrast between gray and white matter for anatomical evaluation.

Landmark Acquisition

For each patient, the midsagittal section that most clearly displayed the cerebral aqueduct, CC, and superior colliculus was manually selected from the sagittal image set. Sixteen homologous anatomical landmarks were identified on the midsagittal image as described by Sigirli et al (19). Landmark placement was performed using TPSDIG version 2.04 software (Figure 1) (16). To assess intra-rater reliability, a two-facet crossed design was used (5,8). A total of 20 images were randomly selected and reannotated by the same researcher 1 month later. The generalizability coefficient (G) for landmark placement was 0.9925, indicating excellent intra-rater reliability.

Geometric Morphometric Analysis

Shape deformations of the CC were evaluated using TPS analysis. TPS assesses shape differences by deforming one landmark configuration into another, with expansion factors representing the magnitude of deformation. The resulting TPS deformation grids visually show regions exhibiting the greatest degrees of atrophy or expansion, with color-coded representations indicating the magnitude and direction of these deformations (2,9). Overall shape variability was quantified using the root mean square of Kendall's Riemannian distance (ρ) from the mean shape. Centroid size—defined as the square root of the summed squared distances of each landmark from the centroid—was calculated as a size metric derived from Procrustes-aligned landmark configurations. Nonlinear growth curve models were applied to examine the relationship between the number of shunt revisions and the centroid size of the CC. The R v. 4.4.3 software, the Shapes package, and MedCalc 19.1.3 were used for statistical analyses (6,9,13).

Other Statistical Analysis

Continuous variables were summarized as median (range) owing to their non-normal distributions. Comparisons between two independent groups were performed using the Mann–Whitney U test. Categorical variables were reported as frequencies and percentages (n, %), and group comparisons were conducted using Pearson's chi-square test or Fisher's exact chi-square test, as appropriate.

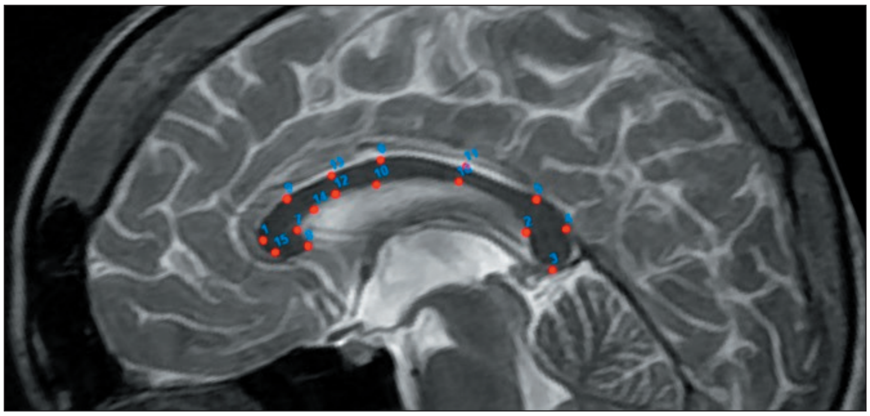

Figure 1: Corpus callosum landmarks used in the study.

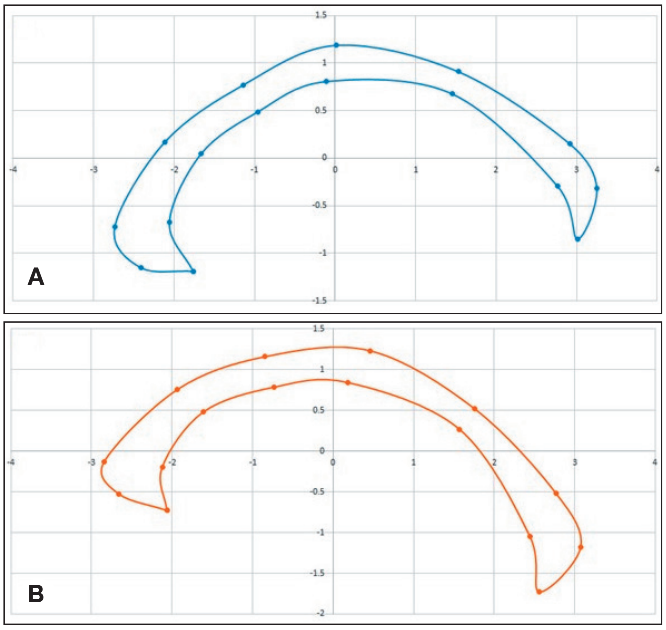

Figure 2: Procrustes mean shapes of the CC in patients **A)** with shunt revision, and **B)** without shunt revision.

Table I: Comparison of Hydrocephalus Etiologies Between the with and without Revision Groups

Etiologies	Without revision	With revision	p-value
Spina bifida	8 (38.1)	10 (38.5)	0.980
Encephalocele	1 (4.8)	1 (3.8)	1.000
Antenatal hydrocephalus	5 (23.8)	5 (19.2)	0.734
Premature germinal matrix hemorrhage	3 (14.3)	4 (15.4)	1.000
Infection	2 (9.5)	0 (0.00)	0.194
Intracranial mass	2 (9.5)	4 (15.4)	0.678
Aquaduct stenosis	0 (0.00)	2 (7.7)	0.496

Data presented as n (%)

RESULTS

The median age was 3.50 years (range: 0.25–16.42 years) in the revision group and 2.42 years (range: 0.17–14.92 years) in the non-revision group, with no significant difference between the groups (p = 0.705). Sex distribution was also comparable between the two groups (boys: 50.0% vs. 42.9%, p = 0.626). No significant differences were observed in the etiologies of hydrocephalus between the revision and non-revision groups (Table I). Among patients who underwent shunt revision, the most common indication was shunt dysfunction (n = 17, 65.4%), followed by shunt infection (n = 11, 42.3%) and shunt malposition (n = 4, 19.2%).

Box's M test indicated a lack of homogeneity in the variance–covariance matrices (p < 0.001); therefore, the James F_J test with resampling was applied. No significant difference in overall CC shape was detected between patients with and without shunt revision (p = 0.386).

The root mean square of Kendall's Riemannian distance (ρ) to the mean shape was 0.154 in the revision group and 0.180 in the non-revision group, indicating greater overall shape variability in patients without shunt revision.

TPS analysis demonstrated that the most prominent shape deformations were observed in the posterior region of the CC. In particular, atrophy was detected between landmarks 2, 3, 4, and 5, corresponding to the splenium. Additionally, minimal atrophy was observed in the rostral region near landmarks 12 and 13 (Figures 2 and 3).

The relationship between CC centroid size and the number of shunt revisions was evaluated using several growth curve models. The three-parameter logistic model provided the best fit (p < 0.001, R^2 = 0.029), indicating that centroid size decreased with the increase in the number of shunt revisions (Figure 4).

DISCUSSION

The CC is the largest commissural fiber tract in the human brain, comprising approximately 200–300 million axons with varying degrees of myelination, diameter, and density. Ana-

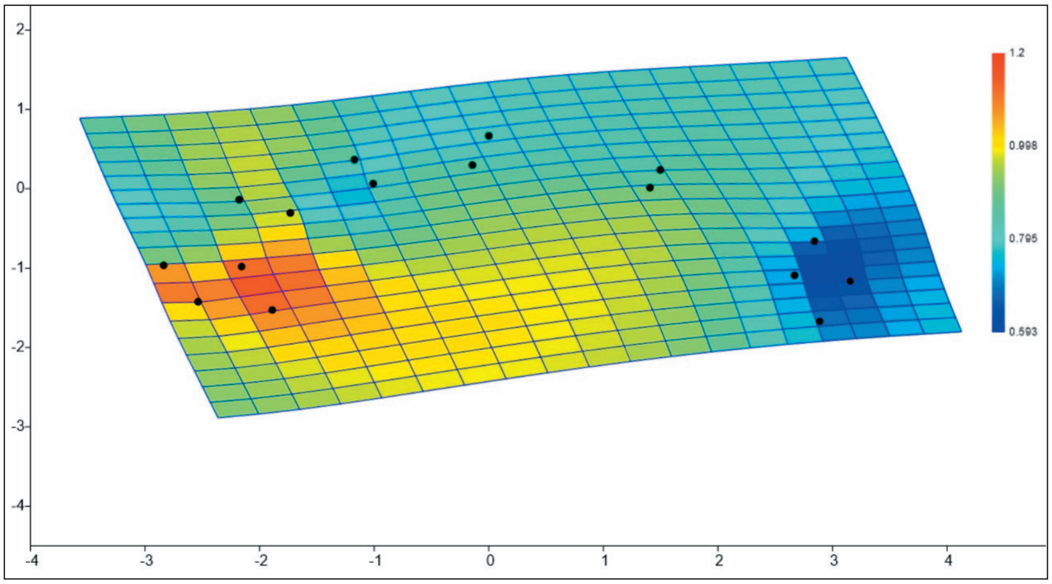

Figure 3: Thin plate spline (TPS) deformation map illustrating shape differences between patients without shunt revision and those with shunt revision.

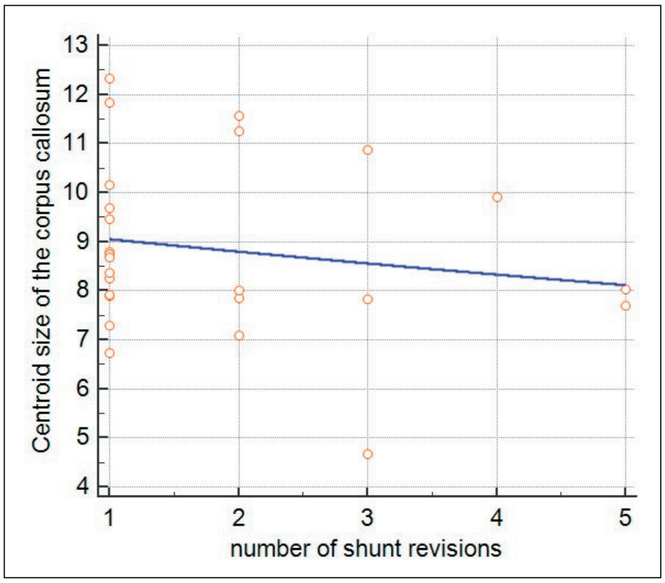

Figure 4: Growth curve model illustrating the relationship between the centroid size of the splenium and the number of shunt revisions. Model: Centroid size = 0.035/[1 + (–0.9963 × e^(0.0001 × number of revisions))]

tomically, it consists of five parts: the rostrum, genu, body, isthmus, and splenium. The CC is supplied by a rich vascular network, primarily derived from branches of the anterior cerebral artery, with additional contributions from the middle cerebral artery and the posterior communicating artery (10).

In cases of hydrocephalus, structural and vascular changes can occur within the CC. Experimental studies have suggested that ischemic injury in the CC results from mechanical compression accompanied by a reduction in capillary density. In addition, stretching of the pericallosal arteries due to ventricular enlargement may lead to edema (4).

Ischemia of the CC in acute noncommunicating hydrocephalus has been observed in the splenium, a posterior subregion of the CC, as well as in the cerebellum. These findings suggest that specific anatomical regions are particularly vulnerable to infarction under conditions of acute ventricular dilation. In case of severe expansion of the lateral ventricle and increased intraventricular pressure, infarction of the splenium may occur due to compression of the posterior pericallosal artery and pericallosal pial plexus (10). In this study, the atrophy observed in the splenium may be attributed to ischemic changes resulting from repeated episodes of acute hydrocephalus in patients who underwent multiple shunt revisions.

In a previous study analyzing CC shape in patients with multiple sclerosis, significant differences were observed compared with healthy controls, with the greatest deformation reported in the anterior region, including the genu and rostrum (19). Disease-related shape alterations in the CC may therefore manifest in various regions depending on the underlying pathology. Although no significant differences in CC shape were observed between patients with and without shunt revisions, TPS analysis revealed atrophy in the splenium. We hypothesize that the absence of a statistical difference may be due to the exclusion of cases with the most severe CC deformation—particularly patients with multiple shunt revisions in whom landmark placement was not feasible because of extreme thinning and distortion. Nevertheless, visual inspection showed that the CC in patients with multiple revisions was more deformed than in those without shunt revisions (Figure 5).

In a study involving CC shape analysis in patients operated on for scaphocephaly, no statistically significant postoperative shape differences were detected; however, enlargement of the splenium was observed on imaging (3). Similarly, in con-

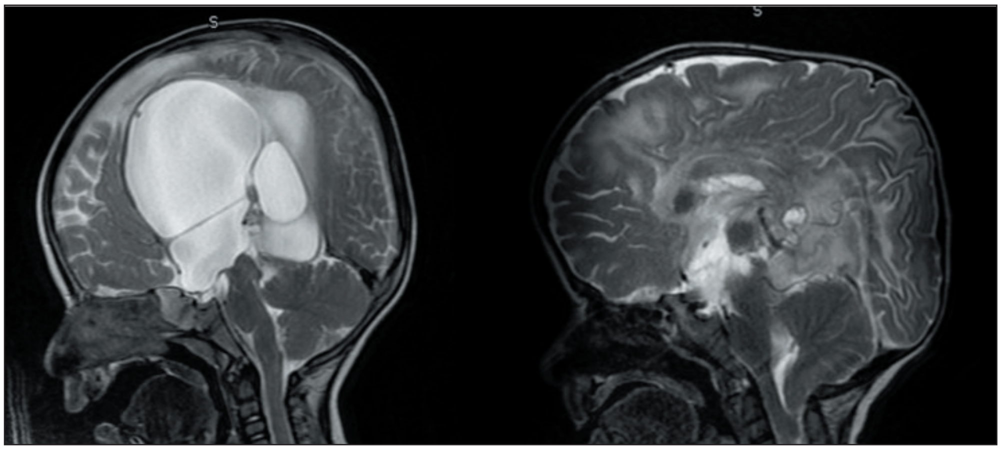

Figure 5: Two representative cases with multiple shunt revisions where shape analysis could not be performed due to severe thinning and deformation of the corpus callosum.

ditions associated with increased intracranial pressure, such as scaphocephaly and hydrocephalus, shape alterations are frequently observed in the splenium region (3,19,20). These findings suggest that the splenium is the most susceptible subregion of the CC to intracranial pressure–related structural changes.

Elevated intracranial pressure in hydrocephalus imposes mechanical stress on white matter tracts, potentially altering axonal orientation and contributing to myelin degradation. Myelinated fibers are located in the posterior regions of the CC, whereas thinner, unmyelinated fibers are located in the anterior regions. During childhood and adolescence, increased area measurements in the isthmus and splenium indicate an increase in axon diameter and myelin deposition. Oligodendrocytes, the cells responsible for myelin production, may be particularly vulnerable during periods of rapid myelination. Consequently, disruption of the myelination process may have significant implications on the microstructural architecture of the posterior CC. This observation suggests a dynamic interaction between hydrocephalus-related pathophysiological processes and brain development, particularly during the phase of active myelination (1). In patients requiring one or more shunt revisions, repeated and sustained elevations in intracranial pressure are likely to exert greater mechanical stress on the CC compared with patients without revisions. The atrophy observed in the posterior regions can be explained by the increased exposure of myelinated fibers in this region to intracranial pressure. Supporting this interpretation, our growth model demonstrated a decrease in the centroid size of the CC with an increasing number of shunt revisions.

CONCLUSION

In pediatric patients with hydrocephalus who underwent multiple shunt revisions, the most prominent CC deformations were localized to the posterior region, particularly the splenium, as demonstrated by TPS analysis. Minimal atrophy was also observed in the rostral region. Our growth curve model further revealed a negative association between the number of shunt revisions and the centroid size of the CC. We believe that these findings will help characterize the clinical features of cases with multiple shunt revisions.

Declarations

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Availability of data and materials: The datasets generated and/or analyzed during the current study are available from the corresponding author by reasonable request.

Disclosure: The authors declare no competing interests.

AUTHORSHIP CONTRIBUTION

Study conception and design: EBG, DS

Data collection: EBG, DS

Analysis and interpretation of results: EBG, DS

Draft manuscript preparation: EBG

Critical revision of the article: EBG, DS

Other (study supervision, fundings, materials, etc...): EBG, DS

All authors (EBG, DS) reviewed the results and approved the final version of the manuscript.

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