(Original Article)

Correlation Between Medial Margin-to-Midline Distance in Decompressive Craniectomy and Postoperative Hydrocephalus

Sittinon Sangkharo, M.D., Plt.Off. Tanabat Somboonsub, M.D., Wg.Cdr. Anupharp Pankhongsap, M.D.
Neurosurgery Unit, Department of Surgery, Bhumibol Adulyadej Hospital, Directorate of Medical Services, RTAF.
Correspondence to: sittinon2550@gmail.com

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Abstract

Purpose: To evaluate whether decompressive craniectomy with a distance to the midline (DTM) of 2.5 cm. is associated with post-craniectomy hydrocephalus in patients with traumatic brain injury and stroke, and to determine the optimal DTM cut-off value with the highest specificity for predicting post-craniectomy hydrocephalus.

Method: A retrospective analysis study was conducted on patients who were diagnosed with traumatic brain injury, ischemic infarction and hemorrhagic stroke who underwent decompressive craniectomy. A 3D reconstruction CT scan was used to determine the DTM and follow up post-operative hydrocephalus.

Results: In 109 patients, the mean DTM was significantly shorter in the post-craniectomy hydrocephalus group (2.07±0.89 cm) compared to the non-hydrocephalus group (2.48±1.12 mm; P=0.033). Univariate analysis showed that DTM ≤2.5 cm was associated with hydrocephalus (crude OR=2.39; 95% CI: 1.10–5.28; P=0.029). However, after adjusting for potential confounders (age, post-operative GCS, ICH, infection, evacuation, and IVH) using multiple logistic regression, DTM was not an independent predictor of hydrocephalus (adjusted OR=2.17; 95% CI: 0.85–5.68; P=0.107). Significant independent risk factors identified were age (P=0.013) and intraventricular hemorrhage (P=0.044). We found the maximum specificity cut-point found that interval more or less than 1.64 centimeters, so that more incidence of hydrocephalus. However, adjusted for this by multiple logistic regression, found no significant difference between the interval of midline and margin of craniectomy and the occurrence of hydrocephalus.

Conclusion: While a medial margin-to-midline distance (DTM) of ≤2.5 cm showed an initial association with hydrocephalus in univariate analysis, it was not identified as an independent risk factor in the multivariable model. Advanced age and intraventricular hemorrhage (IVH) are the primary independent predictors of post-craniectomy hydrocephalus. Clinical risk assessment should prioritize these patient-related factors alongside surgical considerations.

Keywords: decompressive craniectomy, distance to the midline, post-craniectomy hydrocephalus
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(นิพนธ์ต้นฉบับ)

ความสัมพันธ์ระหว่างระยะห่างของขอบกะโหลกและแนวกึ่งกลางในการผ่าตัดเปิดกะโหลกศีรษะ เพื่อลดความดันและภาวะน้ำคั่งในโพรงสมองหลังผ่าตัด

นพ.สิทธินนท์ สังฆะโร, พ.บ., ร.ต.ธนบัตร สมบูรณ์ทรัพย์, พ.บ., น.ท.อานุภาพ พันธุ์คงทรัพย์, พ.บ.

หน่วยประสาทศัลยศาสตร์ กองศัลยกรรม โรงพยาบาลภูมิพลอดุลยเดช กรมแพทย์ทหารอากาศ

บทคัดย่อ

วัตถุประสงค์: เพื่อศึกษาและพิสูจน์ระยะห่างของขอบกะโหลกและแนวกึ่งกลาง (distance to midline, DTM) ในการผ่าตัดเปิดกะโหลกศีรษะ (decompressive craniectomy) ที่ระยะห่าง 2.5 เซนติเมตร ส่งผลต่อการเกิดภาวะน้ำคั่งในโพรงสมอง (post-craniectomy hydrocephalus) ในผู้ป่วยสมองบาดเจ็บ ผู้ป่วยโรคหลอดเลือดสมองตีบและโรคหลอดเลือดสมองแตก และนิยามระยะห่างใหม่ของขอบกะโหลกและแนวกึ่งกลางที่จำเพาะต่อการเกิดภาวะน้ำคั่งในโพรงสมอง

วิธีดำเนินการวิจัย: การศึกษาแบบย้อนหลัง (retrospective analysis study) เก็บข้อมูลในผู้ป่วยสมองบาดเจ็บ ผู้ป่วยโรคหลอดเลือดสมองตีบและโรคหลอดเลือดสมองแตกที่ได้รับการผ่าตัดเปิดกะโหลกศีรษะ ข้อมูลระยะห่างของขอบกะโหลก และแนวกึ่งกลางเก็บจากภาพสแกนเอกซเรย์คอมพิวเตอร์แบบสามมิติและติดตามภาวะน้ำคั่งในโพรงสมองหลังการผ่าตัด

ผลการวิจัย: จากการศึกษาผู้ป่วย 109 คน พบว่าค่าเฉลี่ยระยะ DTM ในกลุ่มที่มีภาวะน้ำคั่งในโพรงสมอง (2.07$\pm$0.89 ซม.) สั้นกว่ากลุ่มที่ไม่มีภาวะน้ำคั่ง (2.48$\pm$1.12 มม.; P=0.033) จากการวิเคราะห์ปัจจัยเดี่ยว พบว่าระยะ DTM $\leq$2.5 ซม. มีความสัมพันธ์เบื้องต้นกับการเกิดภาวะน้ำคั่ง (crude OR=2.39; 95% CI: 1.10–5.28; P=0.029) อย่างไรก็ตาม เมื่อวิเคราะห์ด้วยโมเดลการถดถอยลอจิสติกพหุคูณโดยปรับปัจจัยรบกวน (อายุ, คะแนน GCS หลังผ่าตัด, การมีเลือดออกในเนื้อสมอง, การติดเชื้อ และภาวะเลือดออกในโพรงสมอง) พบว่าระยะ DTM ไม่ใช่ปัจจัยพยากรณ์อิสระที่มีนัยสำคัญทางสถิติ (adjusted OR=2.17; 95% CI: 0.85–5.68; P=0.107) โดยปัจจัยที่มีอิทธิพลหลักอย่างมีนัยสำคัญคือ อายุ (P=0.013) และภาวะเลือดออกในโพรงสมอง (P=0.044) จากการวิเคราะห์ทางสถิติ ทั้งนี้การวิเคราะห์หาจุดตัดใหม่ที่ระยะ 1.65 ซม. เพื่อให้ได้ค่าความจำเพาะสูงสุด (maximized specificity) ถือเป็นการวิเคราะห์เชิงสำรวจ (exploratory analysis) เพื่อหาแนวทางในการศึกษาเพิ่มเติมในอนาคต โดยไม่ได้มีการปรับแก้ค่านัยสำคัญทางสถิติสำหรับการเปรียบเทียบพหุคูณ (multiple comparisons) ผู้อ่านจึงควรแปลผลในส่วนนี้ด้วยความระมัดระวัง

สรุปผลการวิจัย: อย่างไรก็ตาม แม้ระยะห่างของขอบกะโหลกและแนวกึ่งกลางที่ระยะห่างน้อยกว่า 2.5 เซนติเมตร จะมีความสัมพันธ์ในเบื้องต้นจากการวิเคราะห์ปัจจัยเดี่ยว แต่เมื่อปรับปัจจัยกวนอื่น ๆ พบว่าไม่ใช่ปัจจัยอิสระที่มีนัยสำคัญทางสถิติ อย่างไรก็ตามการรักษาระยะห่างดังกล่าวยังคงเป็นข้อควรระวังในเชิงเทคนิคการผ่าตัดที่ควรคำนึงถึงร่วมกับปัจจัยด้านอายุและพยาธิสภาพของผู้ป่วย

คำสำคัญ: การผ่าตัดเปิดกะโหลกศีรษะ, ระยะห่างของขอบกะโหลกและแนวกึ่งกลาง, ภาวะน้ำคั่งในโพรงสมองหลังผ่าตัด

Introduction

Post-craniectomy hydrocephalus is one of the complications after the operation that reduces the patient's level of consciousness, increases mortality, and length of stay (figure 1). The Incidence has been reported to be 0.7 to 51 percent. This complication not only prolongs the length of stay but also increases the mortality rate. Therefore, preventing this risk can improve the quality of life in these patients. Many risk factors have been reported in literature, such as infection of cerebrospinal fluid (CSF), intraventricular hemorrhage (IVH), and thickness of subarachnoid hemorrhage.

There are few studies[11,22,33] that suggested the distance to midline (DTM) after decompressive craniectomy (DC) is affected dilatation of the ventricle due to disturbance of CSF circulation and venous system injury. There was a region that merged cerebral blood flow and cerebrospinal fluid circulation at the midline. Thus, the length between the bone edge to midline, that 2.5 centimeters influences hydrocephalus, but no consensus to determine this interval specifically.

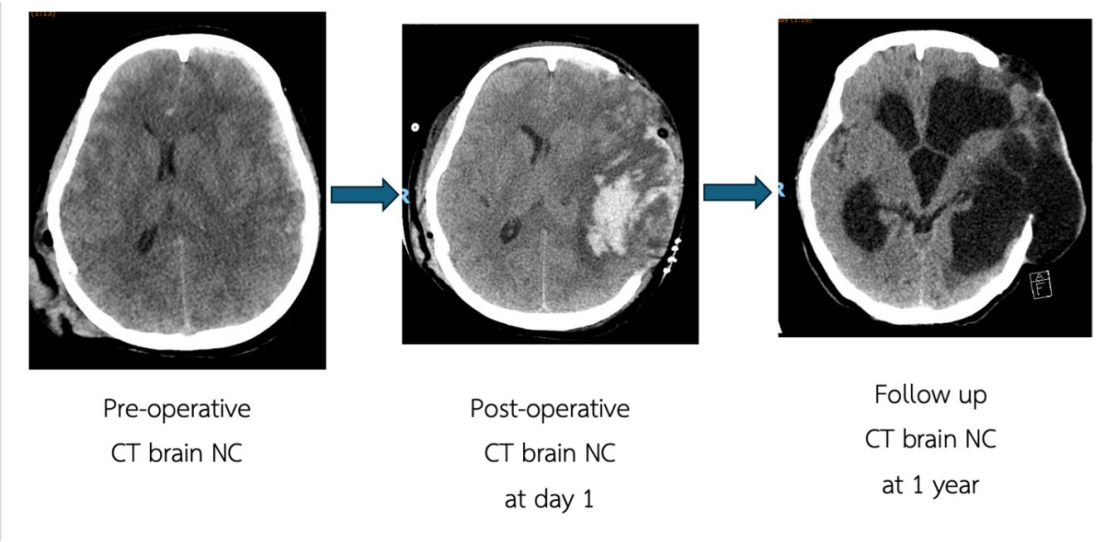


Figure 1: The image showing postoperative follow-up CT imaging after decompressive craniectomy

this study, we aimed to evaluate whether a distance to the midline (DTM) of 2.5 cm is associated with post-craniectomy hydrocephalus in patients with traumatic brain injury and stroke, and to determine the optimal DTM cut-off value with the highest sensitivity and specificity for predicting post-craniectomy hydrocephalus.

Methods

Ethical approval was granted by the Human Research Ethics Committee of Bhumibol Adulyadej Hospital, ensuring that all clinical data and patient information were collected with informed consent.

The data was collected from medical records that diagnosed ICD10 I60-I69 Cerebrovascular diseases, S00-S09 Injuries to the head, with ICD9 0124 Other craniotomy, 0125 Other craniectomy, 0131 Incise cerebral meninges, 0159 Other brain excision patient from January 2020 to August 2023. The inclusion criteria comprised patients who underwent unilateral craniectomy. The exclusion criteria included patients with associated injuries to other organs, those who underwent craniotomy, and those who had bilateral craniectomy. The computerized tomography (CT) showed ventriculomegaly from another cause, and patients who lost follow-up were excluded. The characteristic data included age, sex, pre-operative and post-operative Glasgow Coma Scale (GCS). The appearance of hematoma from the CT scan was categorized into epidural hematoma (EDH), subdural hematoma (SDH), and intracerebral hematoma (ICH), intraventricular hemorrhage (IVH), and the side of the lesion was collected.

Figure 2-3. The 3D reconstruction CT scan was used to determine the DTM. This distance was measured from the sagittal suture to the point nearest the edge of the craniectomy defect. If a craniectomy was carried across the midline, the distance from midline was recorded as zero. In addition, the width and length of the craniectomy were measured and calculated as an area in square centimeters. In this study, post-craniectomy hydrocephalus was defined as radiographically shown dilation of the ventricle and clinical deterioration. The measurement of Evan's index, that more than 30 % with decreased consciousness defined by decreased GSC score was diagnosed. The duration of onset of post-traumatic hydrocephalus was observed. In the operation, evacuation of the hematoma in operation was observed. Postoperative infection and the appearance of a hygroma on CT scan were recorded.

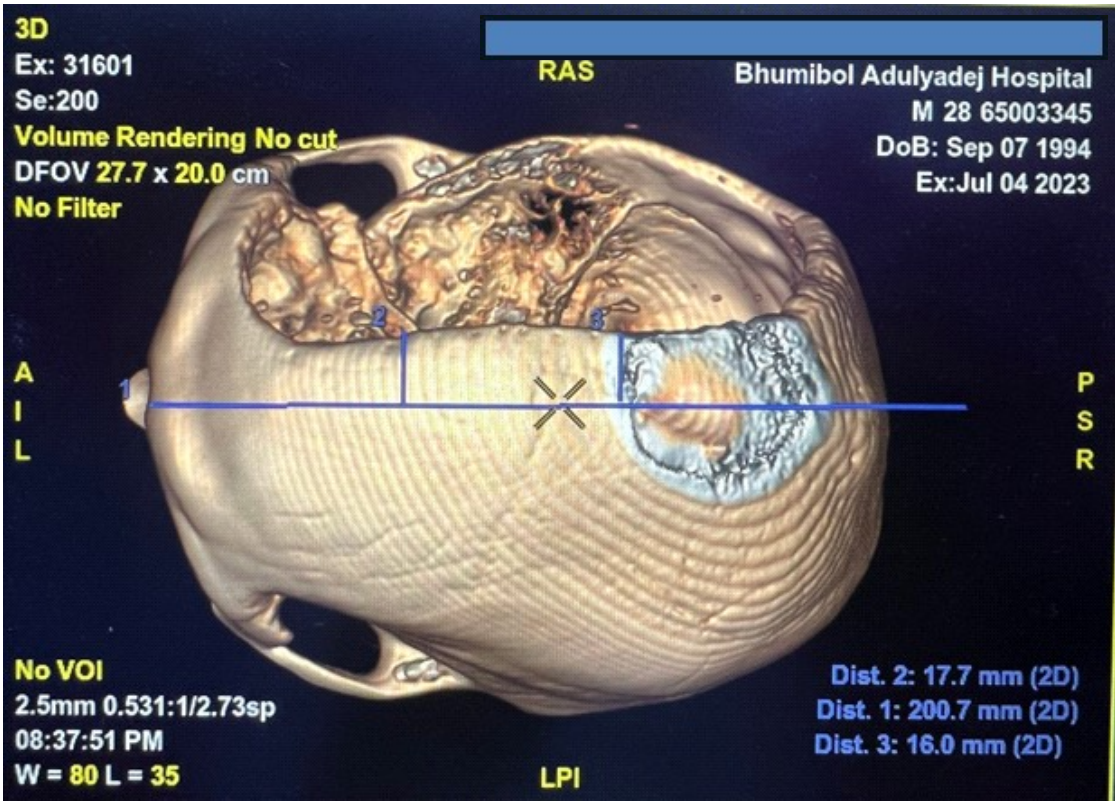


Figure 2.1

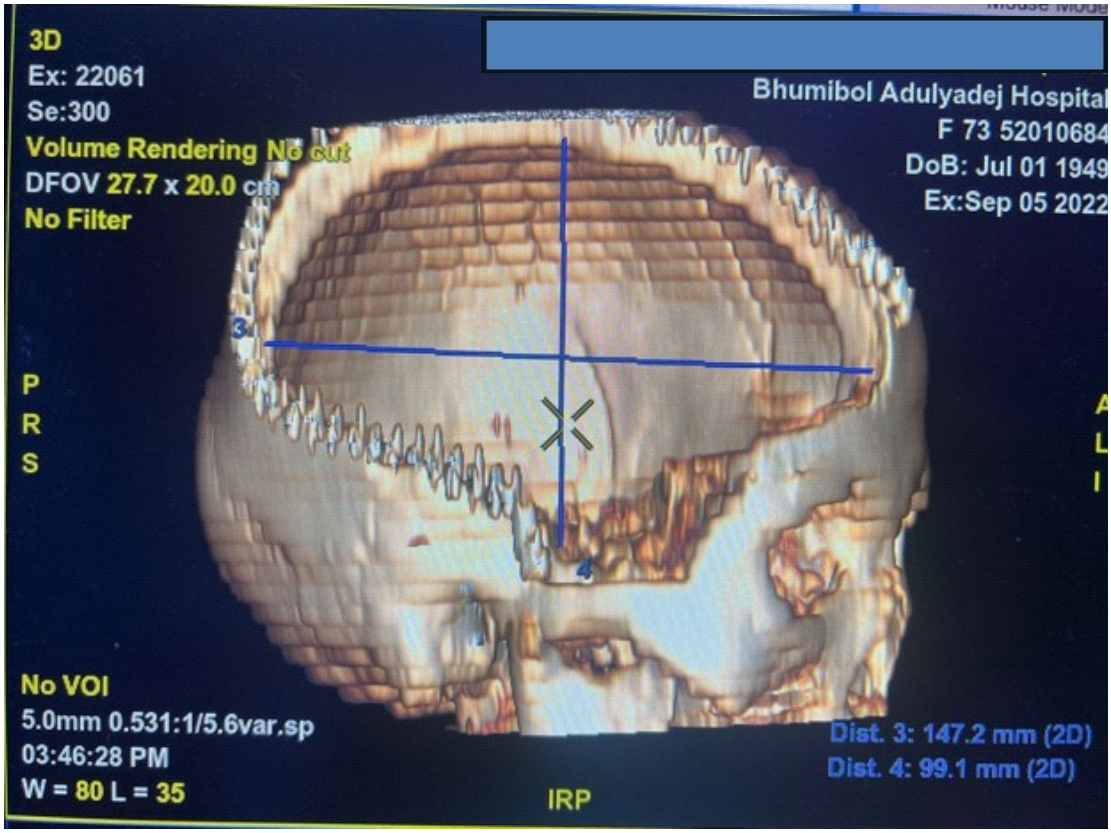


Figure 2.1, 2.2: The 3D reconstruction image showing the measurement of the distance to the midline and width and length of craniectomy.

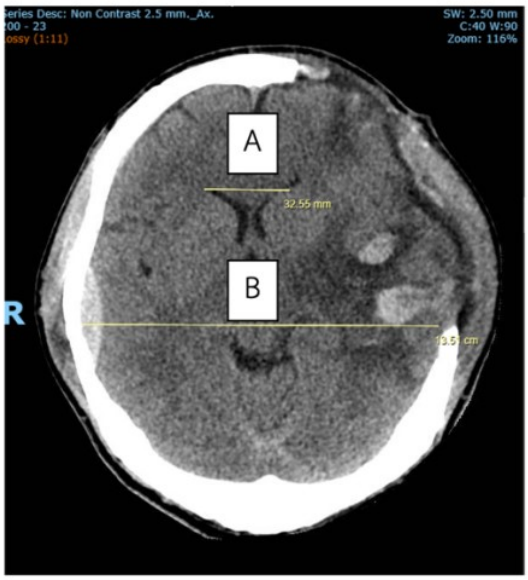


Figure 3: The CT scan image showing the ratio of the maximal width of the frontal horns of the lateral ventricles to the internal skull diameter.

Statistical analysis

Statistical analysis evaluated demographic, clinical, and radiologic factors associated with post-craniectomy hydrocephalus after decompressive craniectomy. Continuous variables were expressed as mean±SD or median (IQR); categorical variables as n (%). Comparisons between patients with and without post-craniectomy hydrocephalus used Student's t-test or Mann–Whitney U test for continuous variables, and Chi-square or Fisher's exact test for categorical variables (Chi-square also used for multiple categories such as hematoma type). Comparisons among the three etiologic groups (TBI, infarction, hemorrhage) used ANOVA or Kruskal–Wallis tests for continuous variables, and Chi-square or Fisher's exact test for categorical variables. A P-value <0.05 was considered statistically significant. Logistic regression assessed the association between DTM and post-craniectomy hydrocephalus, analyzing DTM as a continuous variable and at cut-off points determined by Youden's Index. Multiple logistic regression adjusted for confounders (age, postoperative GCS, infection, hematoma evacuation, hygroma, IVH), with significance tested using Wald and Likelihood Ratio tests. Model discrimination and predictive performance were evaluated via ROC analysis, using AUC and sensitivity specificity plots to illustrate diagnostic accuracy. All analyses were performed using R software version 4.4.1 (R Core Team, 2024). Multivariable analysis was performed using multiple logistic regression to identify independent predictors. The identification of a secondary cut-point at 1.65 cm to maximize specificity was performed as an exploratory analysis. No formal correction for multiple comparisons was applied to the P-values of these sub-group analyses.

Multicollinearity among independent variables was screened using the Variance Inflation Factor (VIF). In cases where significant shifts in odds ratios were observed, such as with ICH and IVH, clinical redundancy and model parsimony were considered during final model selection.

Results

Table 1 demonstrated demographic, clinical, and radiologic characteristics of 109 patients who underwent decompressive craniectomy following traumatic brain injury, cerebral infarction and hemorrhagic stroke, stratified by development of post-craniectomy hydrocephalus. In this cohort of 109 patients who underwent decompressive craniectomy, 62 patients (56.9 %) developed post-craniectomy hydrocephalus. Table 1, 2 summarizes demographic, clinical, and radiologic characteristics of patients with and without hydrocephalus. Several variables demonstrated statistically significant associations with the development of hydrocephalus ($P < 0.05$). Patients in the hydrocephalus group were significantly older (mean age 55.9±21.0 years) compared to those without hydrocephalus (46.0±20.2 years; P=0.015). Post-operative Glasgow Coma Scale scores were lower in the hydrocephalus group (mean 8.5±3.8) than in the non-hydrocephalus group (10.9±3.9; P=0.002). Among the hemorrhagic patterns, only intracerebral hemorrhage demonstrated a statistically significant difference between patients with and without hydrocephalus. ICH was markedly more frequent in the hydrocephalus group, occurring in 50.0 % of patients, compared with 19.1 % in the non-hydrocephalus group (P=0.002). In contrast, epidural hematoma, infarction, and subdural hematoma did not differ

significantly between the two groups. The mean distance to midline was significantly shorter in the hydrocephalus group (2.07±0.89 cm) compared to the non-hydrocephalus group (2.48±1.12 cm; P=0.033).

Additionally, hydrocephalus patients had higher rates of infection (30.6 % vs. 10.6 %; P=0.024) and required evacuation procedures more frequently (43.5 % vs. 14.9 %; P=0.003). Intraventricular hemorrhage was markedly associated with hydrocephalus, present in 51.6 % of hydrocephalus patients and only 12.8 % of non-hydrocephalus patients (P<0.001). There were no significant differences between the hydrocephalus and non-hydrocephalus groups regarding sex, pre-operative GCS, laterality of craniectomy (Side: left or right), craniectomy area (width x length), individual width (W) or length (L) measurements, presence of hygroma, and diseases (traumatic, infarction, and hemorrhagic stroke). Table 3 summarizes the duration of hydrocephalus according to etiology, expressed as median and interquartile range (IQR). The overall median duration was 29 days (IQR 14–80 days). Patients with traumatic brain injury had the shortest median duration of hydrocephalus (20.5 days; IQR 13–43.5), followed by those with infarction stroke (29 days; IQR 15.2–82.5). The longest duration was observed in patients with hemorrhagic stroke, with a median of 35 days (IQR 20.5–115.5). However, the differences in duration among the three etiological groups were not statistically significant (P=0.162)

Table 1 Demographic, clinical and radiologic characteristics of 109 patients who underwent decompressive craniectomy

Number of patients	Post-craniectomy hydrocephalus			P-value
	Total (n=109)	Yes (n=62)	No (n=47)	
Sex[c]				0.553
Female	37 (33.9)	23 (37.1)	14 (29.8)	
Male	72 (66.1)	39 (62.9)	33 (70.2)	
Age (year)[a]				0.015*
Mean±SD	51.6±21.2	55.9±21	46±20.2	
GCS Pre[b]				0.102
Median (IQR)	7 (5,10)	6 (5,9)	7 (5,11)	
GCS Post[a]				0.002*
Mean±SD	9.5±4.0	8.5±3.8	10.9±3.9	
EDH[c]				0.163
No	104 (95.4)	61 (98.4)	43 (91.5)	
Yes	5 (4.6)	1 (1.6)	4 (8.5)	
ICH[d]				0.002*
No	69 (63.3)	31 (50)	38 (80.9)	
Yes	40 (36.7)	31 (50)	9 (19.1)	
Infarction[d]				0.332
No	87 (79.8)	52 (83.9)	35 (74.5)	
Yes	22 (20.2)	10 (16.1)	12 (25.5)	

Table 1 (Cont.)

Number of patients	Post-craniectomy hydrocephalus			P-value
	Total (n=109)	Yes (n=62)	No (n=47)	
SDH[d]				0.178
No	67 (61.5)	42 (67.7)	25 (53.2)	
Yes	42 (38.5)	20 (32.3)	22 (46.8)	
Side[c]				1.000
Lt	56 (51.4)	32 (51.6)	24 (51.1)	
Rt	53 (48.6)	30 (48.4)	23 (48.9)	
Distance to midline (cm)[b]				0.033*
Mean±SD	2.2±1.0	2.1±0.9	2.5±1.1	
Craniectomy area (WxL)[b]				0.734
Median (IQR)	11880 (11094.5, 13069.8)	11873.4 (11225.9, 12964.4)	11883.3 (10990.7, 13083.8)	
W[b]				0.838
Median (IQR)	135.2 (127.3, 141.2)	135.4 (125, 141.3)	134.7 (129.7, 140.6)	
L[b]				0.624
Median (IQR)	89.4 (82.8, 96)	87.8 (81.8, 96.2)	89.6 (85.3, 94.4)	
Infection[c]				0.024*
No	85 (78)	43 (69.4)	42 (89.4)	
Yes	24 (22)	19 (30.6)	5 (10.6)	
Evacuation[c]				0.003*
No	75 (68.8)	35 (56.5)	40 (85.1)	
Yes	34 (31.2)	27 (43.5)	7 (14.9)	
Hygroma[c]				0.827
No	93 (85.3)	52 (83.9)	41 (87.2)	
Yes	16 (14.7)	10 (16.1)	6 (12.8)	
IVH[c]				<0.001*
No	71 (65.1)	30 (48.4)	41 (87.2)	
Yes	38 (34.9)	32 (51.6)	6 (12.8)	

Note: Continuous variables are presented as mean±SD or median (IQR), and categorical variables as n (%). P-values were derived using appropriate statistical tests: a=Student's t-test, b=Mann-Whitney U test, c=Chi-square or Fisher's exact test, d=Chi-square test for multiple categories. * Indicates statistical significance at $P<0.05$.

Table 2 Etiology of 109 patients who underwent decompressive craniectomy

Etiology	Total (n=109)	Post-craniectomy hydrocephalus		P-value
		Yes (n=62)	No (n=47)	
Traumatic brain	45 (41.3)	22 (35.5)	23 (48.9)	0.064
Infarction	25 (22.9)	12 (19.4)	13 (27.7)	
Hemorrhagic	39 (35.8)	28 (45.2)	11 (23.4)	

Table 3 Duration of hydrocephalus in patients with etiology

Duration (day)[f]	Total	Traumatic brain (n=45)	Infarction stroke (n=25)	Hemorrhagic stroke (n=39)	P-value
Median (IQR)	29 (14, 80)	20.5 (13, 43.5)	29 (15.2, 82.5)	35 (20.5, 115.5)	0.162

Association between Distance to Midline (DTM) and post craniectomy hydrocephalus

Logistic regression analysis was performed to evaluate the association between the distance to midline and the development of post-craniectomy hydrocephalus when treated as a continuous variable, each 1 cm increase in DTM was significantly associated with decreased odds of developing hydrocephalus (odds ratio [OR] = 0.65; 95% confidence interval [CI]: 0.43–0.96; P=0.037) Figures 5-6 and Table 4. Reference cut-off of DTM ≤2.5 cm also showed a significant crude association with hydrocephalus (OR=2.39; 95% CI: 1.10–5.28; P=0.029) shown in Table 4-5 and Figures 7. In addition, a lower cut-off point derived from maximal specificity (DTM ≤1.64 cm) also demonstrated a significant crude association with hydrocephalus. Patients with DTM ≤1.64 cm had 2.49 times higher odds of developing hydrocephalus (95% CI: 1.05–6.32; P=0.045). This threshold yielded high specificity (80.9 %) but lower sensitivity (37.1 %), indicating that while it is effective at ruling out patients unlikely to develop hydrocephalus, it may miss a considerable proportion of true cases.

A multiple logistic regression model adjusting for potential confounders including age, post-operative GCS, ICH, infection, evacuation and IVH, the association between DTM cut-off points and hydrocephalus was no longer statistically significant (Table 6). The adjusted odds ratios (Adj.OR) were 2.17 (95% CI: 0.85–5.68; P=0.107) for the reference cut-off of ≤2.5 cm. Likewise, the maximal-specificity cut-off (DTM ≤1.65 cm) yielded an Adj.OR of 2.22 (95% CI: 0.79–6.56; P=0.145), indicating loss of statistical significance after multivariable adjustment (Tables 7).

These findings suggest that although lower DTM values are associated with higher odds of hydrocephalus in crude analyses, DTM alone does not function as an independent predictor once important clinical factors are considered. In contrast, variables such as age, post-operative GCS, and particularly IVH which remained significant or borderline significant across models substantially contribute to the predictive performance of the multivariable models. This highlights that hydrocephalus risk stratification is strengthened when DTM is interpreted alongside strong clinical determinants rather than used in isolation.

Table 4 Association between distance to midline and post-craniectomy hydrocephalus: Odds Ratios (OR) from logistic regression, including continuous DTM and cut-off points

Distance to midline (cm)	OR (95%CI)	P-value	AUC	Sensitivity (95%CI)	Specificity (95%CI)
DTM increases by 1 cm	0.65 (0.43,0.96)	0.037*	0.639	-	-
DTM Cut-off point		0.029*	0.605	0.677	0.532
Reference)				(0.547, 0.791)	(0.381, 0.679)
<=2.5	2.39 (1.1, 5.28)				
>2.5 (ref.)	1				
DTM Cut-off point		0.045*	0.590	0.371	0.809
(Max Specificity)				(0.252, 0.503)	(0.667, 0.909)
<=1.65	2.49 (1.05,6.32)				
>1.65 (ref.)	1				

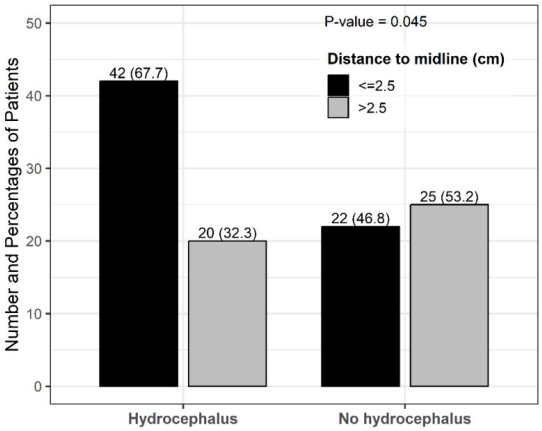


Figure 5 Number and percentage of patients with post-craniectomy hydrocephalus stratified by Distance to Midline (≤2.5 cm vs. >2.5 cm).

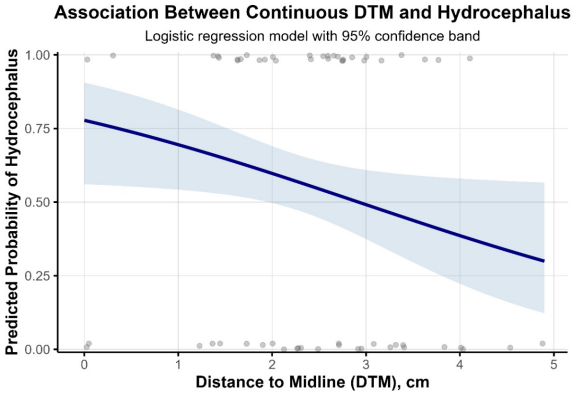


Figure 6 Predicted probability of post-craniectomy hydrocephalus across continuous DTM values based on a logistic regression model (OR per 1-cm increase = 0.65; 95% CI: 0.43–0.96). The solid line represents the fitted probability, and the shaded band indicates the 95% confidence interval.

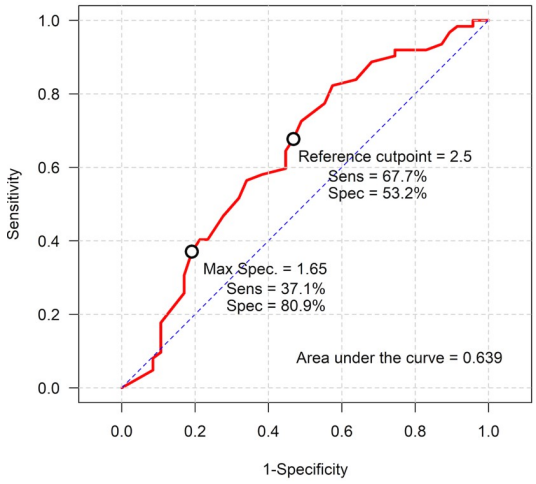


Figure 7 ROC Curve illustrates the model's ability to distinguish between positive and negative cases. Reference and Max Specificity cut points are marked with corresponding sensitivity and specificity values.

Table 5 Association between distance to midline (cm) and post-craniectomy hydrocephalus was estimated using a multiple logistic regression model. Adjusted Odds Ratios (Adj.OR) were calculated adjusted for age, post-operative GCS, ICH, infection, evacuation and IVH.

Distance to midline (cm)	Crude OR (95%CI)	Adj.OR (95%CI)	P-value	AUC
DTM Cut-off point (Reference)			0.107	0.105
<=2.5	2.39 (1.1, 5.28)	2.17 (0.85, 5.68)		
>2.5 (ref.)	1	1		
DTM Cut-off point			0.135	0.129
(Max Specificity)				
<=1.65	2.49 (1.05, 6.32)	2.22 (0.79, 6.56)		
>1.65 (ref.)	1	1		

Table 6 Association between distance to midline cut-off point 2.5 (reference) and post-craniectomy hydrocephalus using multiple logistic regression

Variables	Crude OR (95%CI)	Adj. OR (95%CI)	P (Wald's test)	P (LR-test)
Distance to midline (cm)				0.105
<=2.5	2.39 (1.10,5.28)	2.17 (0.85,5.68)	0.107	
>2.5	1	1		
Age (year)	1.02 (1.00,1.04)	1.03 (1.01,1.05)	0.017*	0.013*
GCS Post	0.85 (0.77,0.95)	0.88 (0.78,0.98)	0.030*	0.026*
ICH				0.946
No	1	1		
Yes	4.22 (1.80,10.65)	1.06 (0.18,6.09)	0.946	
Infection				0.365
No	1	1		
Yes	3.71 (1.35,12.02)	1.83 (0.49,7.31)	0.369	
Evacuation				0.614
No	1	1		
Yes	4.41 (1.79,12.13)	1.55 (0.27,8.50)	0.613	
IVH				0.044*
No	1	1		
Yes	7.29 (2.86,21.36)	3.82 (1.04,15.80)	0.050	

* Significantly statistical p-value <0.05; AUC=0.815

Table 7 Association between distance to midline cut-off point 1.65 (max specificity point) and post-craniectomy hydrocephalus using multiple logistic regression

Variables	Crude OR (95%CI)	Adj. OR (95%CI)	P (Wald's test)	P (LR-test)
Distance to midline (cm)				0.140
<=1.65	2.49 (1.05, 6.32)	2.22 (0.79, 6.56)	0.145	
>1.65	1	1		
Age (year)	1.02 (1.00, 1.04)	1.03 (1.01, 1.05)	0.015*	0.012*
GCS Post	0.85 (0.77, 0.95)	0.87 (0.77, 0.98)	0.022*	0.019*
ICH				0.892
No	1	1		
Yes	4.22 (1.8, 10.65)	0.88 (0.14, 5.32)	0.892	
Infection				0.469
No	1	1		
Yes	3.71 (1.35, 12.02)	1.63 (0.44, 6.44)	0.469	
Evacuation				0.594
No	1	1		
Yes	4.41 (1.79, 12.13)	1.60 (0.28, 9.12)	0.594	
IVH				0.022*
No	1	1		
Yes	7.29 (2.86, 21.36)	4.54 (1.24, 19.11)	0.027*	

* Significantly statistical p-value <0.05; AUC = 0.818

Discussion

Postoperative hydrocephalus is a common complication after traumatic brain injury or stroke in patients who need a decompressive craniectomy, which can influence functioning and quality of life. Based on previous studies, some research papers have suggested that lesions close to the midline may influence the incidence of hydrocephalus. In our studies, the incidence of hydrocephalus was increased in post-operative craniectomy, where the margin close to the midline cut-off less than 2.5 cm also showed a significant crude association with hydrocephalus. The overall median duration of onset was 29 days. Furthermore, we identified a new cut-off point of 1.64 cm. Patients with a distance ≤1.64 cm had a higher incidence of hydrocephalus, and this cut-off demonstrated better specificity than the original cut-off point. We found that older age, the presence of intraventricular hemorrhage, and postoperative infection were also risk factors associated with an increased risk of hydrocephalus. However, after adjustment using multiple logistic regression, no significant difference was found between the distance from the midline to the craniectomy margin and the occurrence of hydrocephalus. Moreover, even after applying the new cut-off value that we created, the results remained statistically non-significant.

Interestingly, as the bone edge was closer to the midline, the incidence of hydrocephalus increased. A craniectomy performed closer to the midline may disrupt normal pulsatile intracranial pressure dynamics, impairing cerebrospinal fluid (CSF) absorption through the arachnoid granulations and thereby increasing the risk of hydrocephalus[20]. Studies have suggested that decompressive craniectomy alters intracranial dynamics by flattening the dicrotic cerebrospinal fluid (CSF) pulse waveform[45]. Additionally, some theories suggest that brain tissue herniating through the craniectomy defect may compress or distort the bridging veins draining into the superior sagittal sinus, thereby disrupting cerebrospinal fluid (CSF) circulation[11]. Studies in mice suggest that decompressive craniectomy disrupts global solute distribution, cerebrospinal fluid (CSF) flux along the perivascular spaces, and the glymphatic system within the interstitial space[39]. Interestingly, a shorter distance to the midline was associated with an increased risk of hydrocephalus.

In the current study, although lower DTM values showed a higher incidence of hydrocephalus in crude analysis, this trend did not reach statistical significance after adjusting for confounders. This suggests that DTM alone may not be a robust predictor as previously suggested in other literature when clinical factors such as age and IVH are considered.

Previous studies reported that the average distance from arachnoid granulations to the midline is 13.5 to 14.3 mm.[41]. Consistently, our findings demonstrated that each 1-cm decrease in the distance to the midline was associated with an increased incidence of hydrocephalus. Therefore, the incidence of hydrocephalus was increased even though we found no significant difference after data was analyzed with other risk factors, with the result in both cut-points. Future investigation into the mechanism of cerebrospinal fluid around the midline calvaria would identify these thresholds.

This study has several limitations. Firstly, its retrospective design may introduce inherent selection bias and inconsistencies in clinical data collection. Secondly, a subset of patients was lost to follow-up, which could affect the observed long-term incidence. Thirdly, the measurement of the distance to the midline (DTM) was performed manually on 3D reconstructed CT scans, which may be subject to inter-observer variability. Crucially, the lack of baseline imaging (pre-morbid or pre-operative CT scans) for comparison remains a significant limitation. In elderly patients, pre-existing brain atrophy or involutional changes can lead to ventriculomegaly (hydrocephalus ex-vacuo), which may confound the diagnosis of post-craniectomy hydrocephalus when relying solely on the Evans' index. Furthermore, the definition of hydrocephalus used in this study, which includes 'decreased consciousness' as a criterion, introduces a risk of circular reasoning when analyzing post-operative Glasgow Coma Scale (GCS) as an independent predictor. This overlap creates a built-in collinearity that likely inflates the statistical significance of post-operative GCS and may obscure the independent effects of other variables. Additionally, the inclusion of a heterogeneous population with both traumatic brain injury and various types of stroke may introduce confounding factors due to differing pathophysiology.

Finally, several statistical constraints must be acknowledged. The analysis of multiple DTM cut points was conducted without formal statistical correction for multiple comparisons; thus, these findings should be regarded as exploratory in nature rather

than definitive clinical thresholds. Moreover, we observed a substantial discrepancy between the crude and adjusted odds ratios for intracerebral hemorrhage (ICH). This likely indicates multicollinearity with intraventricular hemorrhage (IVH) or potential overfitting due to the limited number of events relative to the predictors. These findings suggest that the predictive weight of ICH should be interpreted with caution. Future prospective studies utilizing shunt-dependency as a primary outcome, baseline volumetric analysis, and more parsimonious models in larger cohorts are warranted to validate these findings.

In conclusion, this study identified that advanced age and intraventricular hemorrhage (IVH) are significant independent predictors of postcraniectomy hydrocephalus. Although a DTM of ≤2.5cm was associated with increased risk in crude analysis, it did not remain a statistically significant independent predictor after adjusting for clinical confounders. Therefore, while maintaining an adequate distance from the midline during decompressive craniectomy remains a prudent surgical consideration based on anatomical principles, clinical decisions regarding hydrocephalus risk should prioritize the patient's baseline characteristics and primary pathology. Future prospective studies utilizing baseline volumetric comparisons are warranted to further clarify the independent impact of surgical metrics.

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