Shunt-Dependent Post-Traumatic Hydrocephalus: Predictors and Long-Term Functional Outcomes

Hao Xu · Yongfei Dong · Dejun Bao · Xiangpin Wei · Chaoshi Niu · Xinfeng Liu

ABSTRACT

Introduction: As a disorder of the brain in adults and children, traumatic brain injury (TBI) is considered the major cause of mortality and morbidity. As a serious complication of TBI, post-traumatic hydrocephalus (PTH) is commonly identified and significantly associated with neurocognitive impairment, motor dysfunction, and growth impairment. The long-term functional outcomes after shunt dependence are totally not clear.

Methods: This study included 6279 patients between 2012 and 2022. To identify the unfavorable functional outcomes and the PTH-re-

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lated factors, we carried out univariable logistic regression analyses. To identify the occurrence time of PTH, we conducted the log-rank test and Kaplan–Meier analysis.

Results: Mean patient age was 51.03 ± 22.09 years. Of the 6279 patients with TBI, 327 developed PTH (5.2%). Several PTH development-associated factors, such as intracerebral hematoma, diabetes, longer initial hospital stay, craniotomy, low GCS (Glasgow Coma Scale), EVD (external ventricular drain), and DC (decompressive craniectomy) ($p < 0.01$), were identified. We also analyzed the factors of unfavorable outcomes after TBI including > 80 years, repeated operations, hypertension, EVD, tracheotomy, and epilepsy ($p < 0.01$). Ventriculoperitoneal shunt (VPS) itself is not an independent factor of the unfavorable outcome but shunt complication is a strong independent factor of unfavorable outcome ($p < 0.05$).

Conclusion: We should emphasize the practices that can minimize the risks of shunt complications. Additionally, the rigorous radiographic and clinical surveillance will benefit those patients at high risk of developing PTH.

Trial registration: ClinicalTrials.gov identifier, ChiCTR2300070016.

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Key Summary Points

Why carry out this study?

As an acute brain damage, in adults and children, traumatic brain injury (TBI) is considered the major cause of mortality and morbidity. Globally, the annual incidence of TBI is estimated at 27–69 million.

This study identified the PTH predictors after TBI and clarified the functional outcomes after PTH shunt dependence.

What was learned from the study?

Although ventriculoperitoneal shunt itself is not an independent factor of the unfavorable outcome, reducing shunt complications is still an important way to improve the prognosis of patients.

Therefore, we believe that practices for minimizing the risks of shunt complications should be emphasized. Patients with an elevated risk for developing PTH may also benefit from more rigorous clinical and radiographic surveillance.

INTRODUCTION

As the major cause of mortality and morbidity amongst the general population, traumatic brain injury (TBI) is considered as an medico-social issue of importance and usually results in heavy financial burden [1]. As one kind of sequela of TBI, post-traumatic hydrocephalus (PTH) is frequently identified in patients with severe brain trauma. Therefore, to prevent the occurrence of neurological compromise, early treatment and diagnosis of PTH are necessary for patients with recurrent TBI [2].

PTH incidence ranges from 0.7% to 29% [3]. Several factors, such as poor neurological condition, intraventricular hemorrhage (IVH), and acute hydrocephalus, were reported as independent risk factors of the occurrence of hydrocephalus [4]. For example, the chronic hydrocephalus of PTH can be predicted by the decompressive craniectomy [5, 6]. However, the long-term functional outcomes after shunt dependence are totally unclear. This study aimed to (1) define the predictors of shunt-dependent hydrocephalus after TBI and (2) determine the effect of shunt dependence on functional outcomes of patients with TBI.

METHODS

Study Design

A comprehensive institutional database was employed to evaluate data of all patients with TBI. The study was registered at clinicaltrials.gov (ChiCTR2300070016). All the enrolled patients were administrated from 2012 to 2022 at a single center. Through direct chart review, we obtained the data. All the information of the enrolled patients was de-identified. The approval of this study was obtained from the institutional review board.

The patients (1) hospitalized for TBI, (2) with sufficient treatment characteristics and baseline clinical information, and (3) having the outcome data about the necessity of a shunt or lack thereof were enrolled in this study. PTH was defined as persistent symptomatic hydrocephalus after TBI that required permanent cerebrospinal fluid (CSF) diversion. Ventricular enlargement (defined as Evans' index [EI] > 0.3) was required on imaging. Patients with symptoms attributable to ventricular enlargement (new-onset neurological deficits, raised intracranial pressure, and fullness of the scalp defect) were defined to have PTH.

Data and Variables

Imaging, clinical, and demographic data collected at follow-up, during the hospital stay, and at admission were employed in this study. General condition and background disease data include patient age (years), GCS (Glasgow Coma

Scale) (3–15), GOS (Glasgow Outcome Scale) (1–5), hypertension, diabetes, coronary heart disease (CHD), and trauma mechanism (motor vehicle accidents, falls, strikes, other); imaging characteristics include whether there was epidural hematoma (epidural hematoma without subdural and intracerebral hematoma), intracranial hemorrhage, subtentorial hemorrhage, intraventricular hemorrhage, subarachnoid hemorrhage (SAH), and open craniocerebral injury occurs; treatment includes whether craniotomy, repeated operations (more than one surgery during the initial hospitalization), DC (decompressive craniotomy), EVD (external ventricular drain), and tracheotomy were performed; hospitalization complications include whether postoperative meningitis, cerebral ischemia, deep venous thrombosis (VET), and epilepsy occurred and initial hospital stay (days).

For patients with DC, we collected the operation-related data including surgical method (bifrontal, unilateral, or bilateral fronto-temporo-parietal craniectomy [FTP]), surgical type (DC with or without evacuation of hematoma), and surgical time (< 24 h or > 24 h). For patients with ventriculoperitoneal shunt (VPS), we collected the time of hydrocephalus development, shunt complications, shunt revision, whether the shunt was placed in initial hospitalization, and 1-year functional outcome since VPS surgery.

Follow-up

For the follow-up, we excluded patients who died during the initial hospitalization. Patients with intact follow-up information were evaluated in this study. The functional outcomes were obtained from clinical notes and hospital records from the local primary care physicians, referring institutions, and study center. At the end of the follow-up, GOS was employed to evaluate the functional outcomes of each patient. At the 1-year follow-up, GOS grade of 4–5 was set as a favorable functional outcome and a GOS grade of 1–3 (such as dead or functionally dependent) was set as an unfavorable

functional outcome. For patients with VPS, GOS was followed up for 1 year after VPS surgery.

Ethics Approval and Consent to Participate

During this study, the relevant regulations and guidelines were strictly applied. A named licensing and institutional committee of USTC approved all of our experimental protocols before the initiation of this study. All patients signed a protocol upon admission informing them that clinical data may be included in the study. The data for this study were obtained from the clinical records system at the time of this study. According to the Helsinki Declaration, the informed consent forms were signed by all the enrolled participants before the initiation of this study. The ethical approval number is 2021RE146.

Statistical Analysis

Categorical variables were expressed as frequency whereas continuous variables were expressed as mean $\pm$ SD. For the comparison of the continuous variables, Student's t test was employed. For the comparison of the categorical variables, Fisher's exact test and Pearson's χ^2 test were conducted. To identify the unfavorable functional outcomes and the PTH-associated factors, we performed univariable logistic regression. Factors with a p value less than 0.20 were further analyzed by multivariable logistic regression. To identify the occurrence time of PTH, we performed Kaplan–Meier analysis and the log-rank test. A p value less than 0.05 was set as the statistical significance threshold. SPSS 26 was applied for the analysis of the collected data.

RESULTS

Study Participants

As shown in Fig. 1, we included 6487 patients with spontaneous TBI in this study from 2012 to 2022 (Fig. 1). Of these patients, 208 were
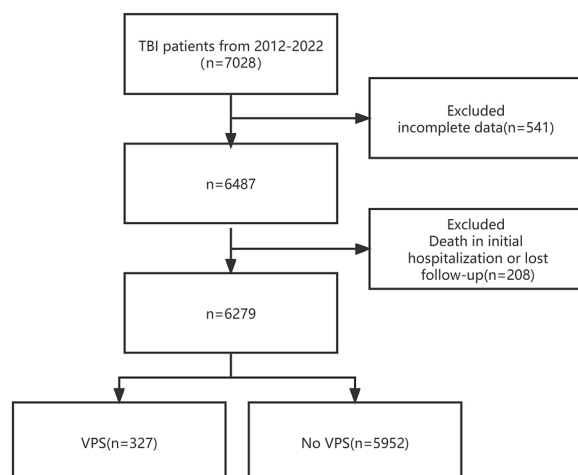
Fig. 1 Flow diagram depicting the study cohort composition

excluded because of incomplete follow-up data or death during initial hospitalization, and 6279 patients were employed to evaluate the long-term functional outcomes. The mean age was 51.03 ± 22.09 years and 4412 were male (70.27%).

Incidence and Prediction Factors of PTH

The etiological details of patients with TBI are summarized in Table 1. The main cause of trauma in our study was motor vehicle accidents (31.31%) and falls (56.27%). Of the 6279 patients with TBI, 327 developed PTH (5.2%) (Table 1).

The characteristics of patients with TBI without or with PTH are compared in Table 2. The mean age of patients was 51.03 ± 22.09. Patients younger than 14 years were more likely

Table 1 Mechanism of injury in patients with TBI

Trauma mechanism	No.	Percentage (%)
Motor vehicle accidents	1966	31.31
Falls	3433	56.27
Strikes	466	7.42
Other	314	5.00
Total	6279	100.0

to have PTH ($p < 0.05$). Patients with PTH were more likely to have low GCS (9.19 ± 3.78 vs 11.10 ± 3.54, $p < 0.01$), diabetes (6.42% vs 3.36%, $p < 0.05$), intracerebral hematoma (64.83% vs 55.91%, $p < 0.01$), subtentorial hemorrhage (6.42% vs 2.71%, $p < 0.01$), intraventricular hemorrhage (3.36% vs 1.13%, $p < 0.01$), undergo craniotomy (57.19% vs 29.02%, $p < 0.01$), repeated operations (13.15% vs 5.80%, $p < 0.01$), EVD placement (22.63% vs 1.55%, $p < 0.01$), DC (36.70%, 12.03, $p < 0.01$), postoperative meningitis (0.66% vs 2.75%, $p < 0.01$), cerebral ischemia (8.24% vs 4.59%, $p < 0.05$), and longer initial hospital stay (24.31 ± 19.94 vs 16.54 ± 20.41, $p < 0.01$) (Table 2).

Details of the PTH predictors after TBI are summarized in Table 3. According to multivariable analysis, significant low GCS ($p < 0.01$), diabetes ($p < 0.01$), intracerebral hematoma, DC ($p < 0.01$), EVD ($p < 0.01$) placement, and longer initial hospital stay ($p < 0.01$) were observed. After DC (odds ratio [OR] 2.578), EVD presence (OR 13.392) can be used as the strongest independent predictor for shunt dependence. Furthermore, only epidural hematoma tends to be a significant protective factor (OR 2.046) (Table 3).

Table 4 compares the characteristics of patients with PTH without or with EVD placement. Of 327 patients with PTH, 74 (22.62%) of them underwent EVD during the initial hospitalization.

During the initial hospitalization, the patients with shunt-dependence and subjected to EVD placement were more likely to have a lower GCS score at presentation (mean 7.27 ± 2.78 vs 9.75 ± 3.85; $p < 0.01$), subtentorial hemorrhage (14.86% vs 3.95%; $p < 0.01$), intraventricular hemorrhage (9.46% vs 1.58%, $p < 0.01$), SAH (45.45% vs 27.03%, $p < 0.01$), postoperative meningitis (8.11% vs 1.19%, $p < 0.01$), longer initial hospital stay (35.81 ± 25.76 vs 20.95 ± 16.50, $p < 0.01$), and to undergo repeated operations (25.68% vs 9.49%, $p < 0.01$) and tracheotomy (36.49% vs 16.21%, $p < 0.01$).

Table 5 compares the characteristics of patients with PTH without or with DC. During the initial hospitalization, a DC was performed

Table 2 Comparison of characteristics between patients with TBI with and without shunt-dependent hydrocephalus

Factor	No shunt (5952)	Shunt (327)	*p*
General condition			
Age	50.99 ± 22.20	51.93 ± 19.82	0.408
< 14	560 (9.41)	18 (5.50)	0.017*
> 80	454 (7.22)	302 (7.34)	0.929
Gender (male)	4178 (74.12)	230 (70.34)	0.975
GCS	11.10 ± 3.54	9.19 ± 3.78	0.000**
Background disease			
Hypertension	820 (13.79)	48 (14.68)	0.650
Diabetes	382 (6.42)	11 (3.36)	0.026*
CHD	34 (0.57)	1 (0.31)	0.805
Imaging characters			
Epidural hematoma	758 (12.75)	48 (14.68)	0.309
Subtentorial hemorrhage	161 (2.71)	21 (6.42)	0.000**
Intracerebral hematoma	3325 (55.91)	212 (64.83)	0.002**
SAH	2454 (41.26)	135 (41.28)	0.994
Intraventricular hemorrhage	67 (1.13)	11 (3.36)	0.001**
Open craniocerebral injury	848 (14.26)	53 (16.21)	0.328
Treatment			
Craniotomy	1726 (29.02)	187 (57.19)	0.000**
Repeated operations	345 (5.80)	43 (13.15)	0.000**
DC	716 (12.03)	120 (36.70)	0.000**
EVD	92 (1.55)	74 (22.63)	0.000**
Tracheotomy	584 (9.82)	68 (20.80)	0.000**
Hospitalization complications			
Postoperative meningitis	39 (0.66)	9 (2.75)	0.000**
Cerebral ischemia	490 (8.24)	15 (4.59)	0.018*
VET	108 (1.82)	3 (0.92)	0.230
Epilepsy	280 (4.71)	21 (6.42)	0.158
Initial hospital stay	16.54 ± 20.41	24.31 ± 19.94	0.000**

*$p < 0.05$, **$p < 0.01$

in 836 patients with TBI and 74 (44.58%) of them eventually underwent shunt placement. Of 327 patients with PTH, 120 (36.69%) of them underwent EVD.

Table 3 Univariable and multivariable logistic regression analyses for factors associated with shunt-dependent hydro-cephalus after TBI

Factor	Univariable			Multivariable		
	p	OR	95% CI	*p*	OR	95% CI
General condition						
Age	0.159	0.994	0.987–1.002	0.127	0.995	0.988–1.002
< 14	0.004	0.397	0.212–0.743	0.004	0.405	0.220–0.744
> 80	0.918	1.028	0.604–1.751			
Gender (male)	0.665	0.943	0.722–1.231			
GCS	0.001	0.939	0.903–0.976	0.000	0.934	0.901–0.969
Background disease						
Hypertension	0.062	1.391	0.983–1.968	0.145	1.289	0.916–1.814
Diabetes	0.017	0.444	0.228–0.866	0.010	0.418	0.216–0.809
CHD	0.840	0.805	0.098–6.625			
Injury condition						
Epidural hematoma	0.002	1.938	1.268–2.963	0.000	2.046	1.379–3.035
Subtentorial hemorrhage	0.957	1.017	0.559–1.850			
Intracerebral hematoma	0.001	0.572	0.411–0.796	0.000	0.547	0.396–0.756
SAH	0.451	1.102	0.856–1.417			
Intraventricular hemorrhage	0.578	1.259	0.558–2.839			
Open craniocerebral injury	0.319	1.181	0.852–1.638			
Treatment						
Craniotomy	0.009	1.619	1.127–2.325	0.003	1.708	1.204–2.422
Repeated operations	0.112	0.708	0.463–1.083	0.135	0.729	0.481–1.103
DC without hematoma	0.521	1.333	0.554–3.205			
DC	0.000	4.239	3.341–5.379	0.000	2.578	1.870–3.553
EVD	0.000	14.654	9.753–22.017	0.000	13.392	9.235–19.419
Tracheotomy	0.993	0.998	0.698–1.427			
Hospitalization complications						
Postoperative meningitis	0.550	1.331	0.521–3.399	0.550	1.331	0.521–3.399
Cerebral ischemia	0.002	0.398	0.221–0.717	0.526	1.348	0.536–3.394
VET	0.039	0.240	0.062–0.928	0.040	0.245	0.064–0.937
Epilepsy	0.882	1.040	0.617–1.753			

Table 3 continued

Factor	Univariable			Multivariable		
	p	OR	95% CI	p	OR	95% CI
Initial hospital stay	0.012	1.004	1.001–1.008	0.012	1.004	1.001–1.008

Only factors with $p < 0.20$ in the univariable analysis are listed
*$p < 0.05$, **$p < 0.01$

Table 4 Comparison of characteristics between shunt-dependent patients with TBI with and without EVD placement during initial hospitalization

Factor	No EVD (253)	EVD (74)	p
Age	52.32 ± 18.85	50.58 ± 22.90	0.552
< 14	11 (4.35)	7 (9.46)	0.090
> 80	16 (6.35)	8 (10.81)	0.196
Gender (male)	181 (71.54)	49 (66.22)	0.378
GCS	9.75 ± 3.85	7.27 ± 2.78	0.000**
Hypertension	39 (15.42)	9 (12.16)	0.487
Diabetes	7 (2.77)	4 (5.41)	0.268
CHD	1 (0.40)	0 (0.00)	0.588
Subtentorial hemorrhage	10 (3.95)	11 (14.86)	0.001**
Intracerebral hematoma	157 (62.06)	55 (74.32)	0.052
SAH	20 (27.03)	115 (45.45)	0.005**
Intraventricular hemorrhage	4 (1.58)	7 (9.46)	0.001**
Open craniocerebral injury	45 (17.79)	8 (10.81)	0.152
Tracheotomy	41 (16.21)	27 (36.49)	0.000**
Repeated operations	24 (9.49)	19 (25.68)	0.000**
Postoperative meningitis	3 (1.19)	6 (8.11)	0.001**
Cerebral ischemia	10 (3.95)	5 (6.76)	0.310
VET	3 (1.19)	0 (0.00)	0.347
Epilepsy	14 (5.53)	7 (9.46)	0.226
Initial hospital stay	20.95 ± 16.50	35.81 ± 25.76	0.000**

*$p < 0.05$, **$p < 0.01$

The patients with shunt-dependence and who underwent DC were more likely to be older (12.50% vs 4.37%, $p < 0.05$), were more likely to have a lower GCS score at presentation (mean 6.53 ± 2.45 vs 10.72 ± 3.56; $p < 0.01$), were less likely to have intracerebral hematoma (1.67% vs 4.35%, $p < 0.01$), were more likely to undergo repeated operations (30.00% vs 3.38%,

Table 5 Comparison of characteristics between shunt-dependent patients with TBI with and without DC

Factor	No DC	DC	p
General condition			
Age	51.65 ± 18.35	52.41 ± 22.18	0.738
< 14	8 (3.86)	10 (8.33)	0.088
> 80	9 (4.37)	15 (12.50)	0.007*
Gender (male)	139 (67.15)	91 (75.83)	0.975
GCS	10.72 ± 3.56	6.53 ± 2.45	0.000**
Hypertension	32 (15.46)	16 (13.33)	0.601
Diabetes	6 (2.90)	5 (4.17)	0.540
CHD	1 (0.48)	0 (0.00)	0.446
Subtentorial hemorrhage	11 (5.31)	10 (8.33)	0.283
Intracerebral hematoma	9 (4.35)	2 (1.67)	0.000*
SAH	81 (39.13)	54 (45.00)	0.299
Intraventricular hemorrhage	66 (1.19)	12 (1.69)	0.195
Open craniocerebral injury	38 (18.36)	15 (12.50)	0.166
Repeated operations	7 (3.38)	36 (30.00)	0.000**
Tracheotomy	21 (10.14)	47 (39.17)	0.000**
Postoperative meningitis	4 (1.93)	5 (4.17)	0.234
Cerebral ischemia	9 (4.35)	6 (5.00)	0.786
VET	2 (0.97)	1 (0.83)	0.903
Epilepsy	7 (3.38)	14 (11.67)	0.003**
Initial hospital stay	21.24 ± 17.84	29.62 ± 22.22	0.001**

$^*p < 0.05$, $^{**}p < 0.01$

$p < 0.01$) and tracheotomy (39.17% vs 10.14%, $p < 0.01$), and were more likely to have postoperative epilepsy (11.67% vs 3.38%, $p < 0.01$) and longer initial hospital stay (29.62 ± 22.22 vs 21.24 ± 17.84, $p < 0.01$).

Table 6 compares the characteristics of the patients without or with VPS who underwent DC during the initial hospitalization. Shunt-dependent patients were more likely have an unfavorable GOS (1–3) on admission (27.81% vs 12.5%, $p < 0.01$). Surgical method (bifrontal, unilateral FTP, or bilateral FTP), surgical type

(DC with or without evacuation of hematoma), and surgical time (< 24 h or > 24 h) showed no significant differences.

Time Survival Analysis of PTH

According to the above research results, the patients were subdivided into different subgroups including GOS 1–3 vs GOS 4–5, diabetes vs no diabetes, intracerebral hematoma vs no intracerebral hematoma, EVD vs no EVD, DC vs no DC, and craniotomy vs no craniotomy. The

Table 6 Comparison of characteristics of patients with and without VPS who underwent EVD placement during the initial hospitalization

Factor	No VPS	VPS	*P*
Surgical type			
DC only	56 (8.51)	10 (8.33)	0.949
DC + evacuation of hematoma	602 (91.49)	110 (91.67)	
Surgical time			
Primary (< 24 h)	568 (86.32)	109 (90.83)	0.176
Secondary (> 24 h)	90 (13.68)	11 (9.17)	
GOS on admission			
0–3	475 (72.19)	105 (87.50)	0.000*
4–5	183 (27.81)	15 (12.50)	
Surgical method			
Bifrontal	39 (5.93)	7 (5.83)	0.445
Unilateral FTP	503 (76.44)	86 (71.67)	
Bilateral FTP	116 (17.63)	27 (22.50)	

*$p < 0.05$, **$p < 0.01$
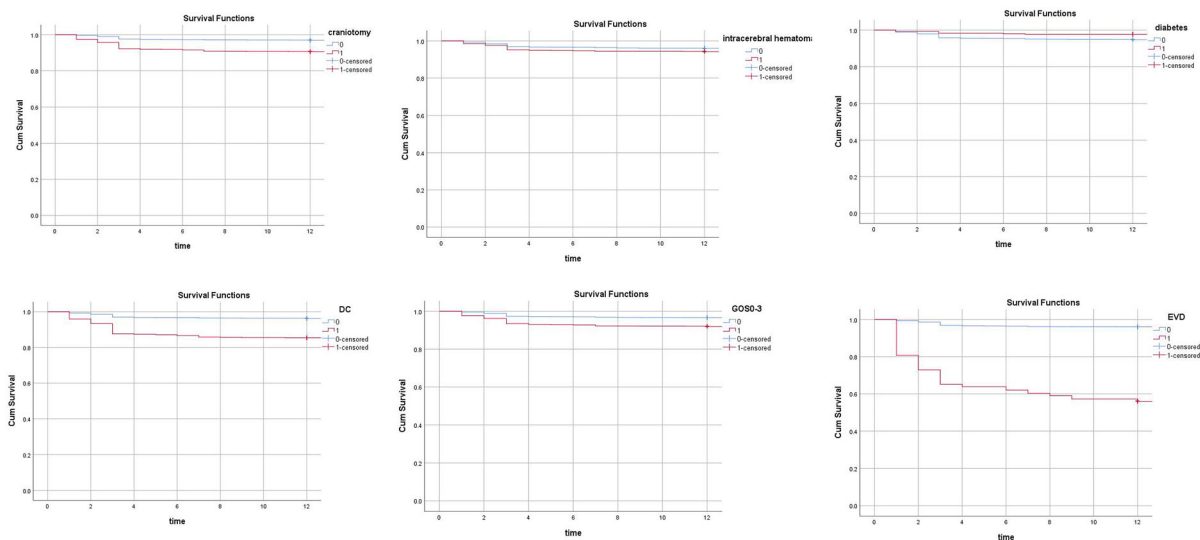
Fig. 2 Kaplan–Meier curves for subgroup analyses. Log-rank tests showed a significant difference in all subgroups ($p < 0.01$)

corresponding Kaplan–Meier curves for these subgroup analyses are shown in Fig. 2. Log-rank tests showed a significant difference in all subgroups ($p < 0.01$).

Functional Outcomes in Patients with TBI

Table 7 compares the characteristics of shunt-dependent patients with TBI according to

Table 7 Comparison of characteristics between patients with TBI according to favorable (GOS 4–5) vs unfavorable (GOS 1–3) outcome

Factor	Favorable	Unfavorable	p
VPS	127 (3.33)	200 (8.11)	0.000**
Age	50.72 ± 21.89	51.51 ± 22.38	0.168
Initial hospital stay	14.83 ± 11.35	20.20 ± 29.12	0.000**
GCS	13.43 ± 1.57	7.26 ± 2.37	0.000**
Age < 14	339 (8.89)	239 (9.69)	0.284
Age > 80	250 (6.56)	204 (8.27)	0.010*
Gender (male)	2639 (69.21)	1773 (71.90)	0.023*
Hypertension	477 (12.51)	392 (15.90)	0.000**
Diabetes	220 (5.77)	173 (7.02)	0.047*
CHD	22 (0.58)	13 (0.53)	0.796
Epidural hematoma only	529 (13.87)	278 (11.27)	0.003**
Subtentorial hemorrhage	102 (2.68)	80 (3.25)	0.188
Intracerebral hematoma	17 (0.45)	61 (2.47)	0.000**
SAH	1443 (37.84)	1148 (46.55)	0.000**
Intraventricular hemorrhage	66 (1.19)	12 (1.69)	0.257
Open craniocerebral injury	3291 (86.31)	2086 (84.59)	0.058
Craniotomy	685 (17.96)	1230 (49.88)	0.000**
DC	134 (3.51)	578 (23.44)	0.000**
EVD	40 (1.05)	126 (5.11)	0.000**
Repeated operations	100 (2.62)	288 (11.68)	0.000**
Tracheotomy	394 (7.08)	258 (36.24)	0.000**
Postoperative meningitis	34 (0.61)	14 (1.97)	0.000**
Cerebral ischemia	447 (8.03)	58 (8.15)	0.914
VET	79 (1.42)	32 (4.49)	0.000**
Epilepsy	239 (4.29)	62 (8.71)	0.000**

*$p < 0.05$, **$p < 0.01$

unfavorable and favorable outcomes. There were 3813 (55.7%) patients with favorable outcomes (GOS 4–5) and 2466 (44.3%) patients with unfavorable (GOS 1–3) outcomes. Those with favorable outcomes had less VPS placement (3.3% vs 8.1%; $p < 0.01$), shorter initial hospital stay (mean 14.83 ± 20 vs 20 ± 29.12 days; $p < 0.01$), were less likely to have low GCS (7.26 ± 2.37 vs 13.43 ± 1.57, $p < 0.01$), were less likely to be over 80 years old (6.56% vs 8.27%; $p < 0.05$), were less likely to have diabetes (5.77% vs 7.02%, $p < 0.05$) and

Table 8 Univariable and multivariable logistic regression analyses for predictors of unfavorable (GOS 1–3) after TBI

Factor	Univariable			Multivariable		
	p	OR	95% CI	p	OR	95% CI
VPS	0.460	1.301	0.647–2.619	0.545	1.178	0.693–2.004
Age	0.204	0.994	0.986–1.003	0.101	0.996	0.990–1.001
Age > 80	0.007	2.080	1.220–3.545	0.020	1.678	1.086–2.594
Initial hospital stay	0.010	1.010	1.002–1.018	0.100	1.007	0.999–1.014
Craniotomy	0.003	1.745	1.209–2.518	0.274	1.171	0.882–1.555
Repeated operations	0.051	1.758	0.997–3.100	0.007	2.199	1.241–3.897
SAH	0.174	1.209	0.919–1.590	0.243	1.138	0.916–1.414
Intraventricular hemorrhage	0.107	2.522	0.820–7.756	0.168	2.234	0.712–7.011
DC	0.082	1.576	0.944–2.630	0.059	1.584	0.982–2.554
EVD	0.046	2.007	1.011–3.983	0.038	1.983	1.038–3.789
GCS	0.000	0.777	0.723–0.835	0.000	0.376	0.359–0.395
Hypertension	0.124	1.322	0.926–1.888	0.002	1.619	1.197–2.190
Cerebral ischemia	0.000	2.599	1.780–3.795	0.084	3.159	0.858–11.627
Tracheotomy	0.000	7.250	4.069–12.917	0.000	7.219	3.914–13.314
Epilepsy	0.000	2.543	1.588–4.073	0.000	2.933	1.808–4.756

Only factors with $p < 0.20$ in the univariable analysis are listed

$^*p < 0.05$, $^{**}p < 0.01$

Table 9 Comparison of characteristics between VPS patients with favorable (GOS 4–5) vs unfavorable (GOS 1–3) outcome

Factor	Favorable	Unfavorable	p
Shunt complications	6 (8.45)	11 (25.00)	0.015*
Shunt revision	0 (0.00)	4 (9.09)	0.010*
Shunt in initial hospitalization	17 (23.94)	13 (29.55)	0.506
Age	53.90 ± 15.32	58.07 ± 13.95	0.145
Gender	55 (77.46)	32 (72.73)	0.565
GCS	11.28 ± 3.46	8.82 ± 4.50	0.003**

$^*p < 0.05$, $^{**}p < 0.01$

hypertension (12.51% vs 15.90%, $p < 0.01$), were less likely to have an intracerebral hematoma (0.45% vs 2.47%, $p < 0.01$) and SAH (37.84% vs 46.55%, $p < 0.01$), were less likely to undergo repeated operations (2.62% vs 11.68%, $p < 0.01$), EVD placement (1.05% vs 5.11%, $p < 0.01$), DC (3.51% vs 23.44%, $p < 0.01$), and tracheotomy (7.08% vs 36.24%, $p < 0.01$), were

Table 10 Univariable and multivariable logistic regression analyses for factors associated with shunt-dependent hydrocephalus after TBI

Factor	Univariable			Multivariable		
	p	OR	95% CI	p	OR	95% CI
Shunt complications	0.021	4.525	1.253–16.339	0.021	4.525	1.253–16.339
Shunt revision	0.788	1.604	0.051–50.451	0.788	1.604	0.051–50.450
GCS	0.002	0.837	0.748–0.937	0.002	0.837	0.748–0.937

Only factors with $p < 0.20$ in the univariable analysis are listed

less likely to have postoperative meningitis (0.61% vs 1.97%, $p < 0.01$), VET (1.42% vs 4.49%, $p < 0.01$), and epilepsy (4.29% vs 8.71%, $p < 0.05$).

The details of the unfavorable outcomes-related factors after TBI are summarized in Table 8. Multivariable analysis revealed a significant trend of low GCS ($p < 0.01$), age over 80 years ($p < 0.01$), DC ($p < 0.01$), EVD placement ($p < 0.01$), tracheotomy ($p < 0.01$), and hypertension ($p < 0.01$) After repeated operations (OR 2.199), tracheotomy (OR 7.219) can be used to predict the unfavorable outcomes strongly and independently. VPS was not an independent predictor of unfavorable outcomes.

Follow-up was available for 115 patients with PTH and VPS was performed at our center at a mean duration of 24.3 months. Shunt complication occurs in 17 of these patients and four underwent revision surgery.

Functional Outcomes in Patients with PTH

Table 9 compares the characteristics shunt-dependent patients with VPS according to unfavorable or favorable outcomes. There were 71 (61.7%) patients with favorable outcomes (GOS 4–5) and 44 (38.3%) patients with unfavorable (GOS 1–3) outcomes. Those with favorable outcomes had fewer VPS complications (8.45% vs 25.00%; $p < 0.05$), less VPS revision (0.00% vs 9.09%; $p < 0.05$), and higher GCS (11.28 ± 3.46 vs 8.82 ± 4.50, $p < 0.01$). The age, gender, and whether the shunt was placed in initial hospitalization were not significantly different between the two groups ($p > 0.05$).

The details of the predictors for unfavorable (GOS 1–3) outcomes in patients with PTH are summarized in Table 10. Multivariable analysis revealed a significant trend of low GCS ($p < 0.05$) and shunt complications ($p < 0.05$).

DISCUSSION

In line with the previous reports [7-9], we observed a 5.2% shunt dependency rate. For the shunt dependency, many independent risk factors, such as DC, EVD, low GCS, craniotomy, longer initial hospital stay, diabetes, and intracerebral hematoma, were identified ($p < 0.01$). Epidural hematoma (without subdural and intracerebral hematoma) tends to be a significant protective factor ($p < 0.01$).

EVD represents the development of acute hydrocephalus. The factors leading acute hydrocephalus to become chronic hydrocephalus have been discussed mostly in aneurysmal SAH and less so in TBI [10-13]. In this study, EVD was identified as a strong independent factor for the prediction of shunt dependence after TBI ($p < 0.01$, OR 13.392). Therefore, we identified the difference of the shunt-dependent patients without and with EVD placement. As expected, a high percentage of EVD placement was observed in those patients with worse baseline clinical status, such as lower GCS score, longer initial hospital stay, tracheotomy, and imaging findings (i.e., subtentorial hemorrhage, SAH, intraventricular hemorrhage). Postoperative meningitis, which may be caused by EVD or repeated operations, indicated that the infection is closely related to hydrocephalus. This also suggests that reducing

EVD infection may be an important way to reduce PTH.

The relationship between DC and PTH has been widely discussed [14-17]. It is believed that the impaired venous drainage into the sagittal sinus, loss of pulsatile intracranial CSF dynamics, and the disruption of CSF drainage due to arachnoid adhesions in the basal cisterns are causative factors [18]. In this study, the difference of the shunt-dependent patients without and with DC was identified. We observed that a high percentage of DC happens in those patients with a worse baseline clinical status ($p < 0.01$), while the occurrence of hydrocephalus does not seem to be related to the DC procedures. Currently, the effect of DC on hydrocephalus is also not clear [19, 20]. DC may result in many complications, such as subdural effusion, infection, CSF leakage through the scalp incision, herniation of the cortex through a bone defect, epilepsy, and hematoma expansion or contusion, which may influence the result. However, our research indicates that the main cause of PTH could be primary severe craniocerebral trauma that requires DC rather than DC surgery itself.

Most hydrocephalus were observed 1–3 months after the surgery and the onset time may be related to the patient's prognosis [21]. According to the above research results, we looked at the survival curve of hydrocephalus in the different subgroups. Patients with GOS 4–5, diabetes, intracerebral hematoma, EVD, DC, and craniotomy had a high rate of PTH.

Moreover, the connection between PTH and the functional outcomes was also evaluated here. In patients with aneurysmal SAH, shunt dependency was identified as a unfavorable outcome-associated, independent, and strong variable [22]. In patients with TBI, the role of shunt dependency in the functional status has not been not extensively studied. In our study, VPS is significantly different between favorable and unfavorable outcomes. Nevertheless, the significance was not observed in the multivariable logistic regression. The unfavorable outcome was frequently observed in patients with poorer baseline clinical status, such as > 80 years, repeated operations, hypertension, EVD, tracheotomy, and epilepsy.

However, as a result of death of more seriously ill patients or the appearance of irreversible brain function damage before the onset of hydrocephalus, this connection might be confounded [23].

Of 115 patients who received VPS in our center, shunt complication occurred in 17 patients (14.7%) and 4 patients (3.4%) underwent shunt revision. The occurrence of shunt complications was a strong independent factor of unfavorable outcomes. Therefore we believe the impact of VPS may come from VPS complications. A study of 17,035 patients who underwent VPS surgery reported a 23.8% complication rate during a mean follow-up of 3.9 ($\pm$ 1.8) years [24]. Another multicenter research study showed that 861 of 5092 VPS failed within 90 days and overall about a third of early failures are potentially preventable [25].

For the patient with TBI, the initial cerebral damage is often decisive. After TBI, secondary hydrocephalus can be caused by the deposition of the hemorrhage over the subarachnoid space surface or by the extension of the hemorrhage into the ventricular system. Therapeutic measures such as DC and ETV are often associated with PTH but were also necessary at the time. Some related therapeutic strategies of IVH- and SAH-associated hydrocephalus may be valuable in the treatment of TBI [22]. However, the development and application of the practices to minimize the risk of shunt complications should receive more attention.

To prevent damage to the periventricular temporal brain, it is particularly important to determine ventricular enlargements as early as possible, well before EI becomes positive. Unlike primary hydrocephalus, a very sensitive sign of secondary ventricular enlargement is the dilatation of the temporal horns and posterior horns [26]. Moreover, the width of the third ventricle increases so that it is no longer slit-shaped but rather ballooned or laterally bowed. Callosal angle is also a recent imaging factor that has been suggested to be associated with hydrocephalus [27]. Cella media ratio and frontal horn ratio are also well-used indexes [28]. Joint measures of frontal distances, temporal horn widths, and other relevant indicators should be performed routinely in neuroimaging

analyses to facilitate the rapid diagnosis and treatment of acute or subacute secondary ventricular enlargement.

Limitations

This study has several limitations. The referral, treatment, and selection biases of its physicians and the institution exist because all the patients came from a single center, although we accrued a large cohort of patients with TBI. Additionally, some of the patients (8%) were lost to follow-up. However, of 327 patients with PTH, only 115 (35%) received the VPS placement and were followed up in our center.

CONCLUSION

This study identified several factors for the development of PTH and for unfavorable outcomes after TBI. VPS itself is not an independent factor of the unfavorable outcome but shunt complications are a strong independent factor for the unfavorable outcome. Therefore, we should emphasize the practices to minimize the shunt complications risks. The rigorous radiographic and clinical surveillance will benefit those patients at high risk of developing PTH.

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Data Availability. The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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