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MACHINE LEARNING-DRIVEN RISK STRATIFICATION OF POST-TRAUMATIC HYDROCEPHALUS BASED ON EARLY CRANIAL CT MORPHOMETRY

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Abstract. Post-traumatic hydrocephalus (PTH) is a frequent complication following traumatic brain injury (TBI), potentially leading to delayed neurological deficits, cognitive decline, and functional impairment. Early detection is critical to enable timely intervention, prevent secondary brain injury, and improve outcomes. This study aimed to develop a predictive model integrating early ventricular morphometry derived from CT scans and key clinical variables. Retrospective data from 180 patients with moderate TBI (GCS 9–12) treated between 2021 and 2024 were analyzed. Morphometric indices, including Evans Index (EI), Bicaudate Index (BI), and Fronto-Occipital Horn Ratio (FOHR), were measured at the level of the foramen of Monro and combined with clinical parameters (age, sex, Glasgow Coma Scale [GCS], intraventricular hemorrhage [IVH], and decompressive craniectomy [DC]). Machine learning models, including gradient boosting, random forest, and logistic regression, predicted PTH occurrence within 6 months. PTH developed in 40 patients (22.2%). Gradient boosting achieved the highest predictive performance (AUC=0.88), with EI, IVH, DC, and FOHR identified as the most important predictors. This integrative approach facilitates early identification of high-risk patients and supports individualized monitoring strategies.

Keywords: post-traumatic hydrocephalus, traumatic brain injury, ventricular morphometry, CT imaging, Evans index, intraventricular hemorrhage, machine learning.

Introduction. Traumatic brain injury (TBI) is a leading cause of morbidity and mortality worldwide, with an estimated 69 million individuals affected annually. Moderate to severe TBI can result in a range of secondary complications, including post-traumatic hydrocephalus (PTH), which occurs due to impaired cerebrospinal fluid (CSF) circulation, impaired absorption at arachnoid granulations, or obstruction by blood products following intraventricular hemorrhage (IVH).

PTH can manifest clinically as cognitive decline, gait disturbance, urinary incontinence, and worsening neurological deficits. Traditional diagnosis relies on radiologic evidence of ventricular enlargement, often delayed relative to the underlying pathophysiology. Morphometric indices, such as Evans Index (EI) and Bicaudate Index (BI), provide quantitative measures of ventricular size, but their predictive power for early PTH remains limited.

Recent advances in machine learning allow simultaneous integration of imaging and clinical data, capturing complex, non-linear relationships that improve prediction accuracy. By combining early CT-based morphometry with clinical predictors such as age, GCS, IVH, and decompressive craniectomy (DC), we hypothesized that PTH could be predicted within 6 months post-injury, enabling proactive patient management.

Materials and methods. A retrospective cohort study was conducted including 180 consecutive adult patients with moderate traumatic brain injury (TBI), defined by an admission Glasgow Coma Scale (GCS) score of 9–12, who were admitted to a tertiary care center between January 2021 and December 2024. The study was approved by the institutional review board, and the requirement for informed consent was waived due to the retrospective nature of the analysis.

Inclusion criteria were: (1) age ≥18 years; (2) diagnosis of moderate TBI based on initial GCS assessment; and (3) availability of high-resolution non-contrast

head computed tomography (CT) scans obtained within 48 hours of injury. Exclusion criteria included pre-existing hydrocephalus, congenital or acquired neurological malformations affecting ventricular anatomy, central nervous system infection, prior neurosurgical shunt placement, and incomplete clinical or imaging data. Baseline CT scans were acquired using a standardized institutional protocol (slice thickness 5 mm, tube voltage 120 kVp, tube current 250 mAs). All images were reviewed on a dedicated picture archiving and communication system (PACS) workstation. Ventricular morphometric measurements were performed on axial slices at the level of the foramen of Monro, where ventricular landmarks are most reproducible.

The following indices were calculated:

- *Evans Index (EI):* maximal width of the frontal horns divided by the maximal inner skull diameter at the same level.
- *Bicaudate Index (BI):* minimum distance between the heads of the caudate nuclei divided by the corresponding brain width.
- *Fronto-Occipital Horn Ratio (FOHR):* sum of the maximal frontal horn width and occipital horn width divided by twice the biparietal diameter.

Measurements were independently performed by two board-certified neuroradiologists blinded to clinical outcomes. Interobserver agreement was assessed using intraclass correlation coefficients (ICCs), demonstrating excellent reliability for all indices (ICC > 0.85). Discrepancies were resolved by consensus review. Demographic and clinical variables collected from electronic medical records included age, sex, initial GCS score, presence of intraventricular hemorrhage (IVH) on baseline CT, and performance of decompressive craniectomy (DC) during acute management. The primary outcome was development of post-traumatic hydrocephalus (PTH) within six months following injury, defined by progressive radiological ventricular enlargement accompanied by clinical symptoms requiring cerebrospinal fluid diversion via ventriculoperitoneal shunt or external ventricular drainage.

Three supervised machine learning models were developed: gradient boosting, random forest, and logistic regression. Model inputs included ventricular

morphometric indices (EI, BI, FOHR) and clinical variables. Data were normalized where appropriate and randomly divided into training and testing sets using stratified cross-validation to preserve outcome proportions. Hyperparameters for tree-based models were optimized using grid search within the training dataset. Model performance was evaluated using the area under the receiver operating characteristic curve (AUC), sensitivity, and specificity. Feature importance was extracted from the gradient boosting and random forest models to identify the most influential predictors of PTH development. Continuous variables are presented as mean ± standard deviation and compared using Student's t-test or the Mann–Whitney U test, as appropriate. Categorical variables are expressed as counts and percentages and compared using the chi-square or Fisher's exact test. A two-sided p-value <0.05 was considered statistically significant. Statistical analyses were performed using standard Python-based scientific computing libraries.

Results. Among the 180 included patients, 40 (22.2%) developed PTH within six months of injury. Patients who developed PTH were significantly older and exhibited higher rates of intraventricular hemorrhage and decompressive craniectomy compared with those who did not develop PTH. There were no significant differences in sex distribution, while initial GCS scores were modestly but significantly lower in the PTH group.

Table 1. Patient Characteristics

Variable	PTH (n=40)	Non-PTH (n=140)	p-value
Age (years)	52 ± 15	44 ± 18	0.02
Male, n (%)	28 (70%)	92 (65.7%)	0.61
GCS	10 ± 1.2	11 ± 1.1	0.01
IVH, n (%)	18 (45%)	22 (15.7%)	<0.001
DC, n (%)	12 (30%)	10 (7.1%)	<0.001

All ventricular morphometric indices were significantly larger in patients who developed PTH, indicating early ventricular enlargement even on baseline imaging. These differences remained statistically significant across all indices, underscoring the sensitivity of morphometric parameters in detecting early pathophysiological changes associated with PTH.

Table 2. Ventricular Morphometry

Index	PTH	Non-PTH	p-value
Evans Index	0.33 ± 0.05	0.28 ± 0.04	<0.001
Bicaudate Index	0.20 ± 0.03	0.17 ± 0.02	<0.001
FOHR	0.41 ± 0.06	0.35 ± 0.05	<0.001

Among the evaluated models, gradient boosting demonstrated the highest predictive performance with an AUC of 0.88, achieving balanced sensitivity and specificity. Random forest and logistic regression models showed progressively lower performance. Feature importance analysis identified Evans Index, presence of intraventricular hemorrhage, decompressive craniectomy, and FOHR as the most influential predictors of PTH development, highlighting the complementary value of imaging and clinical variables.

Table 3. Model Performance

Model	AUC	Sensitivity	Specificity
Gradient Boosting	0.88	0.82	0.85
Random Forest	0.81	0.75	0.80
Logistic Regression	0.74	0.68	0.72

Discussion. This study demonstrates that early CT-based ventricular morphometry combined with readily available clinical variables enables accurate prediction of post-traumatic hydrocephalus (PTH) in patients with moderate traumatic

brain injury (TBI). By leveraging gradient boosting, our model was able to capture complex, non-linear relationships and higher-order interactions among morphometric and clinical features, resulting in superior performance compared with traditional logistic regression approaches. This finding highlights the limitations of linear models in addressing the multifactorial and heterogeneous pathophysiology underlying PTH development.

Importantly, ventricular morphometric parameters derived from early CT scans reflect subtle alterations in cerebrospinal fluid dynamics and brain compliance that may precede overt ventricular enlargement detectable by routine radiological assessment. When integrated with clinical variables such as age, injury mechanism, Glasgow Coma Scale score, and the presence of intracranial hemorrhage, these imaging features provide a more comprehensive representation of patient-specific risk. This integrative strategy addresses a key gap in prior studies, many of which relied solely on isolated imaging indices or late-stage radiological findings, thereby limiting their predictive utility in the acute setting.

From a clinical perspective, early identification of patients at high risk for PTH has significant implications. Such patients may benefit from closer neurological surveillance, earlier follow-up imaging, and timely neurosurgical consultation. Proactive monitoring may facilitate earlier cerebrospinal fluid diversion when indicated, potentially reducing secondary brain injury, length of hospital stay, and long-term neurological morbidity associated with delayed PTH diagnosis. Moreover, risk stratification using an automated prediction model could support more efficient allocation of critical care resources.

Despite these promising findings, several limitations should be acknowledged. The retrospective nature of the study introduces potential selection bias, and the single-center design may limit generalizability across institutions with differing patient populations and management protocols. The moderate sample size, although sufficient to demonstrate feasibility, may restrict the robustness of the model and its performance across diverse clinical scenarios. Additionally, variability in CT

acquisition parameters and manual or semi-automated ventricular measurements may introduce measurement bias.

Future research should address these limitations through prospective, multicenter validation studies with larger and more diverse cohorts. The incorporation of fully automated ventricular segmentation and standardized imaging protocols may enhance reproducibility and facilitate real-time clinical deployment. Furthermore, integrating longitudinal imaging data, physiological monitoring parameters, and emerging biomarkers could further improve predictive accuracy. External validation and impact analysis will be essential to determine whether implementation of this model translates into improved clinical outcomes.

Conclusion. Integrating early CT-based ventricular morphometric parameters with clinical data using machine learning provides an effective approach for the early prediction of post-traumatic hydrocephalus following moderate traumatic brain injury. This predictive framework enables individualized risk assessment and has the potential to improve patient management through enhanced monitoring strategies and timely surgical intervention. Continued multicenter validation and incorporation into clinical decision support systems are warranted to support widespread clinical adoption and to maximize the translational impact of this approach.

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