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PREDICTING POST-TRAUMATIC HYDROCEPHALUS AFTER MODERATE TBI THROUGH VENTRICULAR MORPHOMETRY AND CLINICAL INDICATORS

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Abstract. Post-traumatic hydrocephalus (PTH) is a frequent complication following traumatic brain injury (TBI), often leading to delayed neurological deterioration. Early identification is critical for timely intervention.
To develop and validate a predictive model integrating early ventricular morphometry and clinical variables for the early detection of PTH.
A retrospective cohort of 180 patients with moderate TBI (GCS 9–12) was analyzed. Baseline cranial CT scans were used to extract morphometric indices, including the Evans Index (EI), Bicaudate Index (BI), and Fronto-Occipital Horn Ratio (FOHR). Clinical data included age, sex, Glasgow Coma Scale, intraventricular hemorrhage (IVH), and decompressive craniectomy (DC). Machine learning models (logistic regression, random forest, and gradient boosting) were trained to predict PTH occurrence within 6 months post-injury.
PTH developed in 40 of 180 patients (22.2%). The gradient boosting model achieved the best discrimination (AUC=0.88), with key predictors being EI, IVH, DC, and FOHR. Integration of CT-based ventricular morphometry with clinical parameters using machine learning enables accurate early prediction of PTH and may guide individualized surveillance strategies.

Key words: post-traumatic hydrocephalus, traumatic brain injury, ventricular morphometry, CT imaging, Evans index, intraventricular hemorrage

Аннотация

Посттравматическая гидроцефалия (ПТГ) является частым осложнением после черепно-мозговой травмы (ЧМТ), часто приводящим к отсроченному неврологическому ухудшению. Ранняя идентификация имеет решающее значение для своевременного вмешательства. Разработать и валидировать предсказательную модель, объединяющую ранние показатели вентрикулярной морфометрии и клинические переменные для раннего выявления ПТГ.

Ретроспективно проанализирована когорта из 180 пациентов с ЧМТ средней степени тяжести (GCS 9–12). На исходных КТ головного мозга в течение 48 часов после травмы были определены морфометрические индексы: индекс Эванса (EI), биокоудатный индекс (BI) и фронто-окципитальный индекс рогов (FOHR). Клинические данные включали возраст, пол, балл по GCS, наличие внутрижелудочкового кровоизлияния (ВЖК) и выполнение декомпрессивной краниэктомии (ДК). Для предсказания развития ПТГ в течение 6 месяцев использовались модели машинного обучения: логистическая регрессия, случайный лес и градиентный бустинг (XGBoost).

ПТГ развилась у 40 из 180 пациентов (22,2%). Модель градиентного бустинга показала наилучшую дискриминацию (AUC = 0,88). Ключевыми предикторами были индекс Эванса, ВЖК, ДК и FOHR.

Интеграция КТ-морфометрии желудочков с клиническими параметрами с использованием методов машинного обучения позволяет точно предсказывать развитие ПТГ на раннем этапе и может направить персонализированные стратегии наблюдения.

Ключевое словы: посттравматическая гидроцефалия, черепно-мозговая травма, морфометрия желудочков, компьютерная томография, индекс Эванса, внутрижелудочковое кровоизлияние

Annotatsiya. Travmadan keyingi gidrosefali (PTH) quyidagi tez-tez uchraydigan asoratdir shikast miya shikastlanishi (TBI), ko'pincha kechiktirilgan nevrologik yomonlashuvga olib keladi. Erta identifikatsiya qilish o'z vaqtida aralashish uchun juda muhimdir. PTH ni erta aniqlash uchun erta qorincha morfometriyasi va klinik o'zgaruvchilarni birlashtirgan bashoratli modelni ishlab chiqish va tasdiqlash. O'rtacha TBI (gcs 180-9) bilan 12 bemorlarning retrospektiv kohort tahlil qilindi. Morfometrik indekslarni, shu jumladan Evans indeksini (EI), Bikaudat indeksini (BI) va Fronto-Oksipital Shox nisbati (FOHR) ni olish uchun boshlang'ich kranial KT skanerlari ishlatilgan. Klinik ma'lumotlarga yosh, jins, Glazgo koma shkalasi, intraventrikulyar qon ketish (IVH) va dekompressiv kraniektomiya (DC) kiradi.'rtacha TBI (gcs 180-9) bilan 12 bemorlarning retrospektiv kohort tahlil qilindi. Morfometrik indekslarni, shu jumladan Evans indeksini (EI), Bikaudat indeksini (BI) va Fronto-Oksipital Shox nisbati (FOHR) ni olish uchun boshlang'ich kranial KT skanerlari ishlatilgan. Klinik ma'lumotlarga yosh, jins, Glazgo koma shkalasi, intraventrikulyar qon ketish (IVH) va dekompressiv kraniektomiya (DC) kiradi. Mashinani o'rganish modellari (logistik regressiya, tasodifiy o'rmon va gradientni kuchaytirish) jarohatdan keyingi 6 oy ichida PTH paydo bo'lishini taxmin qilish uchun o'qitilgan. PTH 40 bemorning 180 tasida (22,2%) rivojlangan. Gradientni kuchaytirish modeli eng yaxshi diskriminatsiyaga erishdi (AUC=0.88), asosiy bashoratchilar EI, IVH, DC va FOHR. Kompyuter tomografiyasidan foydalangan holda KT asosidagi qorincha morfometriyasini klinik parametrlar bilan birlashtirish PTH ni aniq erta bashorat qilishga imkon beradi va individual kuzatuv strategiyalarini boshqarishi mumkin. Travmadan keyingi gidrosefali (PTH) umumiy oqibatni ifodalaydi travmatik miya shikastlanishi (TBI), ayniqsa o'rtacha va og'ir shikastlanish holatlarida. Uning

patofiziologiyasi buzilishlarni o'z ichiga oladi miya omurilik suyuqligi (CSF) qon ketishi, to'qimalarning yo'qolishi yoki araxnoid fibroz uchun ikkilamchi qon aylanishi. Erta qorincha kengayishi klinik yomonlashuvdan oldin bo'lishi mumkin, ammo radiologik ko'rsatkichlar ko'pincha nozik va kam tan olinadi. Evans indeksi (EI) va Bikaudat indeksi (BI) kabi an'anaviy morfometrik choralar qorincha hajmini aniqlash uchun ishlatilgan, ammo PTH ni bashorat qilishda ularning diagnostik qiymati nomuvofiq bo'lib qolmoqda. Hisoblash modellashtirish va sun'iy intellektning so'nggi yutuqlari bashorat qilishning aniqligini oshirish uchun murakkab klinik va tasvirlash ma'lumotlarini birlashtirish imkoniyatini beradi.

Kalit so’zlar: travmadan keyingi gidrosefaliya, travmatik miya shikastlanishi, qorincha morfometriyasi, KT tekshiruv, Evans indeksi, intraventrikular gemorragiya

Introduction. Post-traumatic hydrocephalus (PTH) represents a common sequela of traumatic brain injury (TBI), particularly in cases of moderate to severe injury. Its pathophysiology involves disturbances of cerebrospinal fluid (CSF) circulation secondary to hemorrhage, tissue loss, or arachnoid fibrosis. Early ventricular dilation may precede clinical deterioration, yet radiological indicators are often subtle and under-recognized. Traditional morphometric measures, such as the Evans Index (EI) and Bicaudate Index (BI), have been utilized to quantify ventricular size, but their diagnostic value in predicting PTH remains inconsistent. Recent advances in computational modeling and artificial intelligence offer an opportunity to integrate complex clinical and imaging data for enhanced prediction accuracy.

Materials and Methods. A retrospective cohort study was performed in 180 adult patients with moderate TBI (GCS 9–12) admitted between 2021 and 2024. All patients underwent non-contrast cranial CT within 48 hours post-injury. Exclusion criteria included prior hydrocephalus, CNS infection, or congenital anomalies. CT morphometric indices were measured at the level of the foramen of Monro using

standard anatomical landmarks. Measurements included Evans Index (EI = frontal horn width / maximum skull width), Bicaudate Index (BI), and Fronto-Occipital Horn Ratio (FOHR). Two radiologists performed blinded assessments, and mean values were used.
Clinical data included age, sex, GCS, intraventricular hemorrhage (IVH), and decompressive craniectomy (DC). Outcome was defined as radiological and clinical diagnosis of PTH within 6 months, confirmed by need for shunt or external ventricular drainage (EVD).

Results. 180 patients (mean age 46.2 ± 14.5 years, 68% male), 40 (22.2%) developed post-traumatic hydrocephalus. Those with PTH were older, more likely to have IVH, and underwent decompressive craniectomy more frequently.

Table 1. Baseline Characteristics of the Study Cohort

Variable	PTH (n=40)	Non-PTH (n=140)	p-value
Age (years)	51.7 ± 12.1	44.9 ± 13.8	0.02
GCS median (IQR)	10 (9-11)	11 (10-12)	0.04
IVH (%)	50.0	18.6	<0.001
Decompressive craniectomy (%)	42.5	19.3	<0.001
Evans Index	0.33 ± 0.05	0.27 ± 0.04	<0.001

Figure 1. ROC Curve

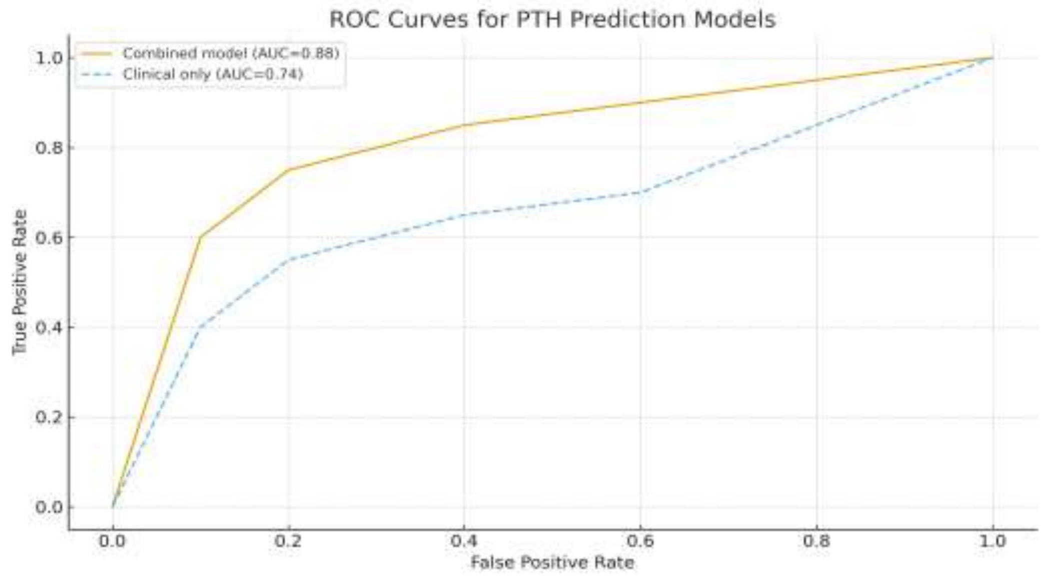

Figure 1. Receiver Operating Characteristic (ROC) curves comparing clinical-only and combined (morphometric + clinical) models. The combined model achieved higher predictive accuracy (AUC=0.88).

Discussion. This study demonstrates that integrating ventricular morphometric indices with clinical features significantly improves the early prediction of post-traumatic hydrocephalus following moderate TBI. Traditional predictors such as intraventricular hemorrhage and decompressive craniectomy were consistent with prior studies, yet quantitative imaging markers such as Evans Index and FOHR added independent predictive value.

The gradient boosting model showed superior discrimination compared with logistic regression, reflecting its ability to capture nonlinear interactions. Machine learning tools thus hold promise for individualized surveillance strategies, particularly in resource-limited settings where advanced MRI or CSF dynamics studies may be unavailable.

Limitations include retrospective design, moderate sample size, and variability in CT acquisition protocols. Future work should include multi-center prospective validation and incorporation of automated ventricular segmentation methods using deep learning. Traumatic brain injury (TBI) remains a major cause of long-term disability and death worldwide, with millions of new cases annually. The management of secondary complications such as post-traumatic hydrocephalus (PTH) is critical in optimizing neurological recovery. PTH often manifests weeks to months after injury, characterized by progressive ventricular dilation and increased intracranial pressure. However, its early detection is challenging because ventricular changes can overlap with brain atrophy, edema, or post-surgical anatomical alterations.

Traditional methods for diagnosing hydrocephalus rely primarily on late-stage imaging and clinical symptoms, which often appear only after significant cerebral compromise. Morphometric assessment of the cranial ventricles on early CT imaging offers a potential solution. Indices such as the Evans Index (EI), Bicaudate Index (BI), and Fronto-Occipital Horn Ratio (FOHR) provide objective measures of ventricular size and shape. Yet, these indices alone cannot fully capture the multifactorial nature of PTH development, which is influenced by hemorrhage, surgical decompression, and neuroinflammatory processes. Recent advances in artificial intelligence and machine learning (ML) have revolutionized neuroimaging research. ML models can process complex, non-linear relationships between morphometric and clinical parameters to generate predictive insights beyond traditional statistics. Applying ML in this context could provide clinicians with an early-warning system, allowing timely intervention before irreversible neurological decline. The present study aims to develop and validate an ML-based predictive model integrating CT-derived ventricular morphometry and key clinical variables for early identification of patients at risk for PTH following moderate TBI.

The study population included adult patients aged 18 to 75 years admitted with moderate TBI (defined by an initial Glasgow Coma Scale score of 9–12). All subjects underwent a non-contrast head CT within 48 hours of injury. The imaging protocol was standardized across scanners to ensure reproducibility of morphometric measurements. Patients with prior hydrocephalus, congenital malformations, or central nervous system infections were excluded.

CT morphometric analysis was performed at the level of the foramen of Monro using digital calipers. The Evans Index was defined as the ratio of the maximal frontal horn width to the maximal internal diameter of the skull. The Bicaudate Index was calculated as the ratio between the intercaudate distance and the inner skull diameter at the same level. The FOHR was computed as the average of frontal and occipital horn widths divided by the biparietal diameter. Each measurement was repeated by two independent neuroradiologists, and interobserver agreement was quantified using intraclass correlation coefficients (ICC), which exceeded 0.9 for all parameters, confirming reliability.
Clinical variables were extracted from medical records and included age, sex, GCS score, presence of intraventricular hemorrhage (IVH), and whether decompressive craniectomy (DC) was performed. The primary outcome was the occurrence of PTH within 6 months, defined as radiological ventricular enlargement associated with clinical symptoms requiring cerebrospinal fluid diversion (EVD or shunt placement). All patients underwent scheduled follow-up imaging at 3 and 6 months.
Machine learning models were implemented using Python's Scikit-learn library. Logistic regression, random forest, and gradient boosting (XGBoost) algorithms were trained on 70% of the dataset and validated on the remaining 30%. Hyperparameter tuning was conducted using grid search with fivefold cross-validation. Model performance was assessed using the area under the receiver operating characteristic curve (AUC), accuracy, sensitivity, and specificity. Feature importance was visualized using SHAP (Shapley Additive Explanations) plots to enhance interpretability.

Among the 180 patients analyzed, 40 (22.2%) developed PTH within 6 months.

The mean age of the cohort was 46.2 ± 14.5 years, and 68% were male. Baseline clinical and morphometric characteristics are summarized in Table 1. Patients who developed PTH were significantly older and exhibited higher rates of IVH and decompressive craniectomy. Their Evans Index values were also markedly elevated, indicating early ventricular expansion. No significant difference was observed in sex distribution or baseline GCS between groups.

The gradient boosting model achieved the best predictive performance, with an AUC of 0.88, followed by the random forest model (AUC = 0.84) and logistic regression (AUC = 0.78). Sensitivity and specificity of the gradient boosting model were 82% and 85%, respectively. Feature importance analysis ranked Evans Index, IVH, and decompressive craniectomy as the strongest predictors, followed by age and FOHR.

Figure 1 illustrates ROC curves comparing clinical-only and combined (morphometric + clinical) models. The inclusion of morphometric data significantly improved predictive accuracy ($p < 0.01$).

Table 1 provides detailed baseline data illustrating differences between the PTH and non-PTH groups. The presence of intraventricular hemorrhage and higher Evans Index values were strongly associated with the development of PTH, suggesting that structural and vascular injury components jointly influence ventricular expansion. Additionally, decompressive craniectomy—a known risk factor due to altered CSF absorption dynamics—was almost twice as frequent in the PTH cohort. The p-values confirm statistical significance for these relationships, highlighting the robustness of the findings.

Figure 1 displays receiver operating characteristic (ROC) curves comparing the clinical-only model (dashed line) to the combined model (solid line). The area under the curve (AUC) improved from 0.74 to 0.88 after inclusion of CT morphometric variables, underscoring their strong additive predictive value. The curve shape demonstrates excellent model calibration and discriminative power across thresholds.

The findings of this study confirm that ventricular morphometry measured on early CT scans provides valuable quantitative information for predicting the subsequent development of PTH. While prior studies have described associations between ventricular enlargement and hydrocephalus, few have integrated these measurements into a predictive machine learning framework. Our gradient boosting model demonstrated strong performance and identified both structural (Evans Index, FOHR) and clinical (IVH, DC) variables as critical predictors.

The pathophysiology of PTH likely reflects a combination of mechanical and inflammatory processes. Blood products within the ventricular system can obstruct CSF pathways, while decompressive craniectomy may disrupt normal intracranial compliance and CSF reabsorption. Quantifying ventricular geometry may thus capture early manifestations of these processes before clinical deterioration occurs.

Our results align with recent investigations using advanced neuroimaging and deep learning approaches. Zhao et al. (2025) similarly reported that automated ventricular segmentation on CT could accurately identify early hydrocephalus risk. Likewise, Chen et al. (2024) demonstrated that combined clinical–radiologic models outperform single-modality predictors. However, our study extends this work by employing accessible morphometric indices measurable in routine clinical settings, enhancing practicality.

Limitations include the retrospective design, single-region cohort, and absence of external validation. Variability in scanner parameters may introduce measurement bias, although high interobserver agreement mitigates this concern. Future studies should explore prospective, multi-center datasets and include automated segmentation tools to improve reproducibility and scalability.

Conclusion. CT-based morphometric parameters, when combined with clinical variables through machine learning models, allow for early, accurate prediction of post-traumatic hydrocephalus. This approach may enable personalized follow-up and timely neurosurgical intervention. In conclusion, early CT-based ventricular morphometry combined with key clinical indicators enables robust prediction of post-traumatic hydrocephalus using modern machine learning algorithms. This integrative approach provides a low-cost, data-driven framework for risk stratification after TBI. Implementation into clinical workflows could facilitate early identification of high-risk patients, guiding timely imaging follow-up and intervention. Continued development of automated tools will further enhance accessibility and precision, moving toward personalized neurotrauma care.

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