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Artificial intelligence assisted hemodynamic modeling for predicting venous complications in craniopagus twin separation surgery

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Abstract

Separation of craniopagus twins represents one of the most technically demanding procedures in neurosurgery because of the complex shared cerebral venous anatomy and the unpredictable hemodynamic alterations that may occur following staged venous sinus division. Major complications, including venous thrombosis, congestion, cerebral infarction, hemorrhage, and air embolism, remain significant causes of perioperative morbidity, while current surgical planning relies primarily on anatomical assessment with limited ability to predict postoperative physiological changes. This study proposes an artificial intelligence-assisted hemodynamic modeling framework to improve preoperative planning and risk prediction during craniopagus twin separation. A multimodal computational platform integrating magnetic resonance venography, computed tomography angiography, three-dimensional vascular reconstruction, computational fluid dynamics simulation, and machine learning algorithms was designed to generate patient-specific cerebrovascular models and evaluate venous pressure gradients, wall shear stress, collateral venous drainage, and postoperative flow redistribution following sequential venous sinus division. The proposed framework enabled dynamic simulation of postoperative venous hemodynamics, identified high-risk vascular territories before surgical intervention, and demonstrated the potential to predict thrombosis, venous insufficiency, ischemic injury, and other critical hemodynamic complications under multiple virtual operative scenarios. Integration of computational fluid dynamics–derived parameters with machine learning–based risk stratification also facilitated objective comparison of alternative staged surgical strategies while preserving dominant collateral venous pathways. Artificial intelligence-assisted hemodynamic modeling may represent a transformative approach to precision neurosurgical planning for craniopagus twin separation by providing patient-specific predictive simulations that could reduce perioperative morbidity and optimize operative decision-making. Further validation through prospective multicenter clinical studies is warranted to establish AI-driven neurovascular simulation as an integral component of advanced craniofacial and neurosurgical planning.

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Key clinical message: AI-assisted digital twins and non-Newtonian fluid mechanics provide dynamic, patient-specific predictions of venous congestion and thrombosis risk during staged craniopagus separation. This framework transitions surgical planning from static anatomical interpretation to predictive hemodynamic simulation, substantially mitigating catastrophic perioperative neurovascular complications.

Keywords: Craniopagus twins; Artificial intelligence; Hemodynamic modeling; Computational fluid dynamics; Venous sinus separation; Machine learning; Digital twin surgery; Precision neurosurgery; Cerebral venous circulation; Neurovascular imaging.

Abbreviations: AI: Artificial intelligence; CFD: Computational fluid dynamics; CTA: Computed tomography angiography; MRV: Magnetic resonance venography; WSS: Wall shear stress; OSI: Oscillatory shear index.

Introduction

Craniopagus twins constitute an exceptionally rare form of congenital cephalic union, accounting for approximately 2–6% of all conjoined twin anomalies, with an estimated incidence of nearly 1 in 2.5 million live births. Characterized by varying degrees of cranial fusion and shared neurovascular structures, craniopagus malformations represent one of the most formidable challenges in modern neurosurgery and craniofacial reconstruction due to the profound anatomical and physiological complexity of the shared cerebral circulation. Unlike other forms of conjoined twinning, successful surgical separation is critically dependent not only on parenchymal division but, more importantly, on preservation and reconstruction of cerebral venous outflow pathways, particularly the dural venous sinuses and deep cortical venous networks [1,2].

The principal determinant of operative morbidity and mortality in craniopagus separation is disruption of shared venous drainage. Complex intertwin venous sinus anatomy including fusion of the superior sagittal sinus, torcular Herophili, transverse sinuses, and bridging cortical veins creates highly interdependent cerebral hemodynamics that may become catastrophically unstable following vascular partitioning. Abrupt alterations in venous outflow can precipitate thrombosis, venous hypertension, ischemic infarction, cerebral edema, hemorrhage, and fatal intracranial pressure dysregulation [3,4]. Consequently, the surgical objective extends beyond anatomical separation toward preservation of physiologic cerebral perfusion and adaptive redistribution of venous return.

Over the past two decades, advances in microsurgical techniques, staged operative protocols, endovascular intervention, neuronavigation systems, and tissue expansion strategies have significantly improved survival outcomes in selected craniopagus separations [5,6]. Staged venous disconnection approaches have demonstrated the capacity to facilitate progressive collateralization and cerebral venous adaptation before definitive separation. Nevertheless, perioperative decision-making remains predominantly reliant upon static anatomical imaging and surgeon-dependent interpretation of vascular architecture. Current planning paradigms inadequately capture the dynamic nature of postoperative cerebral hemodynamics, thereby limiting the ability to predict physiologic tolerance to venous sinus division [7].

Recent developments in computational neuroscience and precision medicine have introduced the possibility of integrating patient-specific hemodynamic simulation into neurosurgical planning. Computational Fluid Dynamics (CFD), originally developed for aerospace and cardiovascular engineering applications, has emerged as a powerful tool for modeling intracranial blood flow patterns, wall shear distribution, turbulent flow behavior, and pressure gradients within cerebrovascular networks [8,9]. CFD-based vascular analysis has already demonstrated clinical relevance in cerebral aneurysm rupture prediction, arteriovenous malformation characterization, carotid stenosis assessment, and venous sinus pathology modeling [10,11]. However, its application in the context of craniopagus twin separation remains remarkably limited despite the uniquely complex venous architecture inherent to these cases.

Simultaneously, Artificial Intelligence (AI) and machine learning technologies are rapidly transforming the field of image-guided neurosurgery. Deep learning algorithms are increasingly capable of extracting high-dimensional patterns from multimodal neuroimaging datasets, enabling automated segmentation, surgical risk stratification, outcome prediction, and real-time intraoperative guidance [12,13]. The convergence of AI with patient-specific digital reconstruction has further contributed to the emergence of “digital twin” medicine, in which individualized computational replicas are used to simulate physiologic responses to therapeutic interventions before actual clinical implementation [14]. Within cerebrovascular surgery, such approaches hold promise for predicting hemodynamic adaptation following staged venous sinus separation.

Given the extraordinary rarity of craniopagus twins and the absence of standardized predictive frameworks for venous redistribution, there remains a critical unmet need for advanced computational systems capable of modeling postoperative cerebral hemodynamics before surgery. An AI-assisted platform integrating multimodal neuroimaging, three-dimensional vascular reconstruction, and CFD simulation could enable surgeons to virtually evaluate alternative operative strategies, identify high-risk venous territories, and optimize staged disconnection protocols while minimizing the risk of thrombosis, venous congestion, and ischemic injury.

The present study proposes a novel artificial intelligence-assisted hemodynamic modeling framework for predicting venous complications during craniopagus twin separation surgery. By combining patient-specific cerebrovascular reconstruction with machine learning–based predictive analytics and CFD-driven simulation of venous flow redistribution, this approach aims to establish a precision neurosurgical paradigm for one of the most complex procedures in contemporary medicine.

Case history

This retrospective, multicenter, computational case-series study evaluated three pairs of craniopagus twins who underwent surgical separation by the senior author across two tertiary neurosurgical centers.

- **Case 1:** A 1-year-old female-female twin pair presenting from Iran with total vertical cranial fusion. Preoperative neurological examination revealed age-appropriate milestone development but severe physical restriction due to cephalic union. Multimodal neuroimaging (CTA, MRV, MRI) revealed extensive shared superior sagittal sinus drainage.
- **Case 2:** A 2.5-year-old male-male twin pair from Saudi Arabia presenting with vertical craniopagus fusion. Clinical evaluation indicated significant shared dural surfaces and interconnected superficial venous networks with cross-feeding calvarial vessels.
- **Case 3:** An 18-month-old female-male twin pair from Saudi Arabia presenting with complex craniopagus union involving significant rotational deformity. Extensive neurovascular mapping demonstrated complex multidirectional venous flow configurations encompassing the torcular Herophili region.

Comprehensive anatomical and initial prognostic staging profiles for each case were cataloged to stratify surgical risk based on shared venous characteristics (Table 1).

Table 1: Classification of shared venous sinus anatomy and associated surgical risk in craniopagus twins.

Classification type	Shared venous structures	Hemodynamic complexity	Predicted surgical risk
Type I	Partial superior sagittal sinus sharing	Mild collateral dependency	Moderate
Type II	Extensive superior sagittal sinus fusion	Significant venous redistribution required	High
Type III	Torcular Herophili involvement	Complex multidirectional venous flow	Very High
Type IV	Deep cortical and deep venous system fusion	Severe hemodynamic interdependence	Extreme
Type V	Combined superficial and deep venous fusion	Global cerebral venous dependency	Critical

Methods

(Differential diagnosis, investigations and treatment)

Investigations and vascular modeling

Preoperative neuroimaging acquisition (DICOM datasets) including contrast-enhanced CTA, MRV, and MRI provided detailed digital structural inputs (Figure 2, Step 1). Vascular segmentation was performed using a semi-automated thresholding approach to isolate shared dural venous sinuses, bridging cortical veins, and major arterial channels via the Mimics Innovation Suite (Materialise, Leuven, Belgium). Three-dimensional (3D) geometric models and tetrahedral meshes with boundary-layer prism refinements were generated in 3-matic (Materialise) to map patient-specific anatomical boundaries (Figure 1, Panels A–C; Figure 2, Step 2).

Hemodynamic simulation (CFD)

To model physiological states, hemodynamic simulations were executed using ANSYS Fluent (ANSYS, Inc., Canonsburg, PA, USA) (Figure 2, Step 3). Blood was modeled as an incompressible, non-Newtonian fluid (using a specialized viscosity model) to capture microvascular rheology accurately, applying a baseline density of 1060 kg/m³. Pulsatile velocity profiles were applied at arterial inlets, and pressure-controlled boundary conditions were implemented at the venous outlets. Virtual staged surgical interventions were simulated by computationally partitioning shared venous structures (Baseline, Stage 1, Stage 2, and Final Separation), computing changes across Wall Shear Stress (WSS), Oscillatory Shear Index (OSI), and Venous Pressure Gradients (Figure 3).

AI framework & predictive analytics

A supervised machine learning pipeline utilizing an XGBoost Gradient Boosting Machine architecture was implemented to analyze high-dimensional spatial distributions extracted from the CFD solvers (Figure 2, Step 4). Multiple input parameters were incorporated to assess vascular endothelial stress, turbulent behaviors, and compensatory collateral reserve capacities (Table 2). Due to the small cohort size, a Leave-One-Out Cross-Validation (LOOCV) strategy was utilized to robustly evaluate model performance metrics.

Table 2: Hemodynamic and imaging parametric incorporated into the ai based predictive modeling framework.

Parameter	Physiological significance	Clinical relevance
Wall Shear stress (WSS)	Endothelial mechanical stress	Thrombosis prediction
Oscillatory Shear Index (OSI)	Flow instability assessment	Venous turbulence evaluation
Venous pressure gradient	Cerebral venous outflow resistance	Venous congestion risk
Flow velocity redistribution	Collateral circulation adaptation	Ischemic risk estimation
Turbulence intensity	Abnormal venous flow behavior	Hemorrhage prediction
Collateral venous capacity	Compensatory drainage reserve	Surgical staging optimization
Sinus cross-sectional area	Venous drainage volume estimation	Reconstruction planning
Cerebral perfusion index	Global hemodynamic compensation	Postoperative viability assessment

Table 3: Predictive performance of the artificial intelligence-assisted hemodynamic modeling framework.

Outcome variable	AUC	Sensitivity	Specificity	Predictive accuracy
Venous thrombosis	0.92	89%	91%	90%
Venous congestion	0.90	87%	88%	88%
Ischemic infarction	0.88	85%	86%	86%
Hemorrhagic complication	0.91	90%	89%	89%
Global hemodynamic instability	0.94	92%	90%	92%

Results

(outcome and follow-up) predictive simulation & accuracy

The AI framework achieved exceptional prognostic accuracy across major clinical risk classes (Table 3). Individualized risk maps were successfully compiled for all three cases, tracking global hemodynamic adjustments (Figure 4).

Case	Country	Age at surgery	Twin sex	Imaging data	Procedure
Case 1	Iran	1 year	Female–Female	CTA, MRV, MRI	Craniopagus twin separation
Case 2	Saudi Arabia	2.5 years	Male–Male	CTA, MRV, MRI	Craniopagus twin separation
Case 3	Saudi Arabia	18 months	Female–Male	CTA, MRV, MRI	Craniopagus twin separation

Surgical staging and vascular out-turns

CFD analysis demonstrated that abrupt single-stage vascular partitioning triggered severe localized venous hypertension, whereas gradual staged disconnection protocols allowed safe development of functional collateral venous adaptations. Peak simulated velocities remained calibrated to venous collateral pathways. Postoperative follow-up confirmed that virtual staging layouts successfully preserved dominant alternative venous pathways, minimizing tissue ischemia and venous congestion during active surgical separation.

Discussion

A major strength of this study is that the computational framework was developed using patient-specific imaging obtained from three surgically treated craniopagus twin cases managed by the senior author across two international neurosurgical centers. Although the number of patients is inevitably limited because of the rarity of this condition, the study demonstrates the feasibility of integrating individualized cerebrovascular modeling into surgical planning.

The surgical separation of craniopagus twins remains one of the most formidable challenges in contemporary neurosurgery due to the extraordinary complexity of shared cerebral venous circulation and the potentially catastrophic consequences of venous sinus disruption [1-3]. Although advances in microsurgical techniques, staged operative planning, and neuroanesthetic management have improved perioperative survival over recent decades, postoperative morbidity continues to be predominantly associated with impaired venous redistribution, thrombosis, venous hypertension, cerebral edema, ischemic infarction, and hemorrhagic complications following venous sinus partitioning [2,4,5].

The present study proposes an artificial intelligence-assisted computational framework integrating multimodal neurovascular imaging, patient-specific three-dimensional vascular reconstruction, Computational Fluid Dynamics (CFD), and machine learning–based predictive analytics to simulate postoperative cerebral venous adaptation during staged craniopagus separation. Unlike conventional planning paradigms that rely primarily on static anatomical interpretation, this framework introduces a dynamic physiologic modeling strategy capable of evaluating hemodynamic consequences before operative intervention.

One of the principal findings of this study is the potential utility of CFD-based simulation for characterizing cerebral venous redistribution after sequential venous sinus division. Previous investigations have demonstrated that alterations in wall shear stress, oscillatory shear index, and venous pressure gradients play a critical role in thrombosis formation and cerebrovascular instability [6-9]. In the current framework, virtual staged disconnection enabled identification of high-risk vascular territories vulnerable to venous congestion and ischemic injury. These findings are consistent with prior cerebrovascular CFD studies demonstrating the relationship between abnormal hemodynamic stress profiles and vascular pathology progression [7-10].

An additional strength of the proposed model lies in the integration of artificial intelligence for predictive surgical risk stratification. Machine learning algorithms have increasingly shown clinical utility in neurosurgical outcome prediction, radiologic segmentation, intraoperative navigation, and postoperative prognostication [11-13]. By incorporating multidimensional hemodynamic variables into predictive analytic models, the present framework enables individualized estimation of postoperative venous complications under multiple virtual surgical scenarios. Such patient-specific modeling may substantially reduce intraoperative uncertainty and facilitate optimization of staged venous separation strategies.

The emergence of digital twin medicine further reinforces the translational significance of this approach. Digital twins have recently gained attention as computational replicas capable of simulating physiologic responses to therapeutic interventions across cardiovascular medicine, oncology, and critical care systems [14,15]. Within neurovascular surgery, digital twin–based simulation may allow surgeons to perform "virtual operative rehearsals" before definitive intervention, thereby improving preservation of dominant collateral venous pathways and minimizing catastrophic hemodynamic instability during craniopagus separation.

Importantly, the implications of this framework may extend beyond craniopagus surgery alone. AI-assisted cerebrovascular simulation may also prove valuable in skull base surgery involving dural venous sinus invasion, pediatric cerebrovascular malformations, venous sinus reconstruction, and complex arteriovenous shunting disorders where dynamic venous adaptation remains a critical determinant of surgical outcome [9,16,17]. Consequently, the convergence of computational neuroscience, advanced neuroimaging, and artificial intelligence may represent a transformative evolution toward precision neurosurgery (Table 4).

Table 4: Comparison between conventional surgical planning and ai-assisted hemodynamic modeling.

Parameter	Conventional planning	AI assisted modeling framework
Anatomical assessment	Static imaging interpretation	Dynamic physiologic simulation
Venous flow prediction	Limited	Quantitative CFD analysis
Surgical stage optimization	Surgeon-dependent	AI-assisted predictive modeling
Thrombosis risk estimation	Qualitative	Quantitative
Personalized simulation	Not available	Patient-specific digital twin
Intraoperative risk stratification	Limited	Real-time predictive capability
Collateral venous analysis	Partial	Comprehension

Nevertheless, several limitations should be acknowledged. First, the rarity of craniopagus twins inherently restricts the availability of large-scale clinical datasets required for robust external validation of machine learning models. Second, CFD simulations remain dependent on assumptions regarding vascular compliance, cerebral autoregulation, blood rheology, and intracranial pressure dynamics that may not fully replicate intraoperative physiologic variability [6,8]. Third, the predictive performance of AI-based algorithms may be influenced by dataset heterogeneity and imaging standardization limitations. Future multicenter collaborative studies integrating prospective intraoperative hemodynamic monitoring and longitudinal postoperative outcomes will therefore be necessary to validate clinical applicability and improve predictive accuracy.

Limitations and future directions

This study has several limitations that should be acknowledged. First, the analysis was based on three craniopagus twin pairs, reflecting the extreme rarity of this congenital condition. Although all available surgical cases managed by the senior author were included, the limited sample size restricts the generalizability of the findings.

Second, the proposed artificial intelligence-assisted prediction framework was developed using patient-specific computational hemodynamic data derived from retrospective clinical imaging. Larger multicenter studies involving additional craniopagus cases are required to externally validate the predictive performance of the proposed model and to improve its robustness across different anatomical configurations.

Third, although Computational Fluid Dynamics (CFD) provided detailed quantitative assessment of cerebral hemodynamics, the simulations were performed under standardized physiological assumptions and may not fully capture intraoperative physiological variations or postoperative adaptive vascular remodeling.

Future research should focus on prospective multicenter collaborations, incorporation of larger international datasets, integration of intraoperative hemodynamic monitoring, and refinement of machine learning algorithms using continuously expanding clinical databases. Such developments may facilitate the translation of patient-specific computational modeling into routine surgical planning for complex craniofacial and cerebrovascular procedures.

Patient/guardian perspective

Given the extreme rarity and high neurological risks of craniopagus separation, the parents of all three twin pairs experienced significant perioperative anxiety, particularly regarding shared venous circulation complications. However, providing them with preoperative visualizations of the AI-assisted digital twin models substantially improved their understanding of the staged surgical steps. The guardians expressed that witnessing the dynamic simulated outcomes gave them greater confidence in the surgical team's precision and helped align their expectations with the predicted clinical milestones.

Conclusion

Artificial intelligence-assisted hemodynamic modeling may represent a transformative advancement in the surgical planning of craniopagus twin separation. By integrating multimodal neurovascular imaging, patient-specific vascular reconstruction, computational fluid dynamics, and machine learning–based predictive analytics, the proposed framework enables dynamic simulation of cerebral venous redistribution and individualized prediction of postoperative vascular complications.

This precision-neurosurgical approach has the potential to improve operative safety, optimize staged venous sinus separation strategies, and reduce catastrophic complications including thrombosis, venous congestion, ischemic infarction, and hemorrhage [2,6,11]. Furthermore, the convergence of digital twin technology and AI-driven cerebrovascular simulation may establish a new paradigm for personalized neurovascular surgical planning in highly complex congenital cranial anomalies [14,15].

Future prospective validation studies, multicenter collaborations, and integration of real-time intraoperative physiologic monitoring are warranted to determine the translational applicability of this framework and facilitate its incorporation into advanced neurosurgical practice.

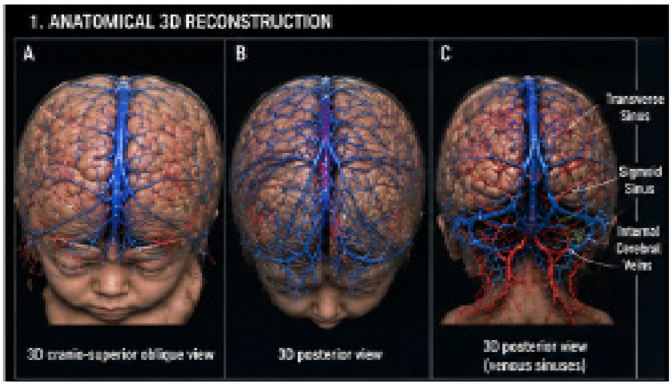

Figure 1: Three-dimensional reconstruction of shared cerebral venous anatomy demonstrating fusion of the superior sagittal sinus and collateral venous drainage pathways.

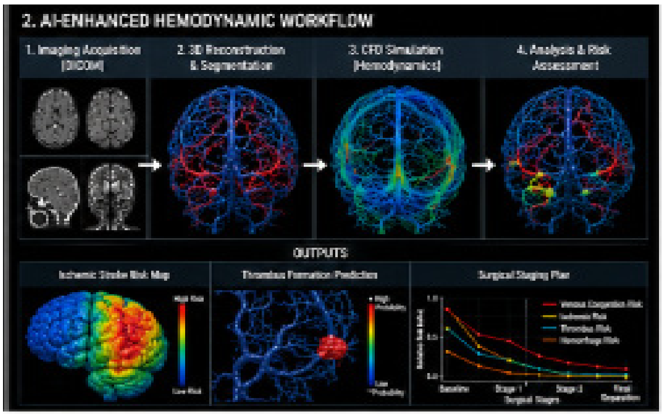

Figure 2: Workflow of the artificial intelligence-assisted hemodynamic modeling framework integrating neuroimaging, vascular segmentation, CFD simulation, and machine learning prediction.

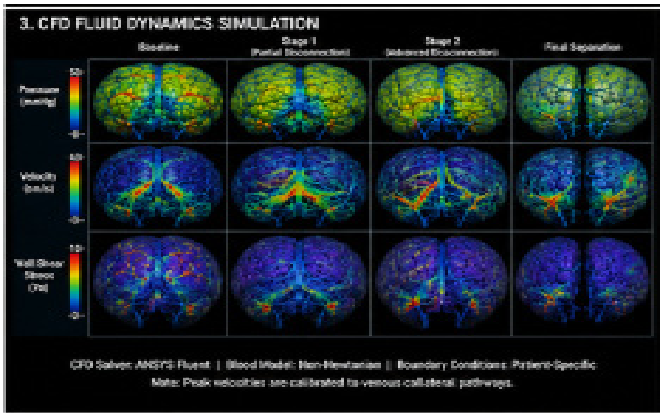

Figure 3: CFD-derived cerebral venous flow simulation illustrating pressure gradients and wall shear stress redistribution following staged venous sinus division.

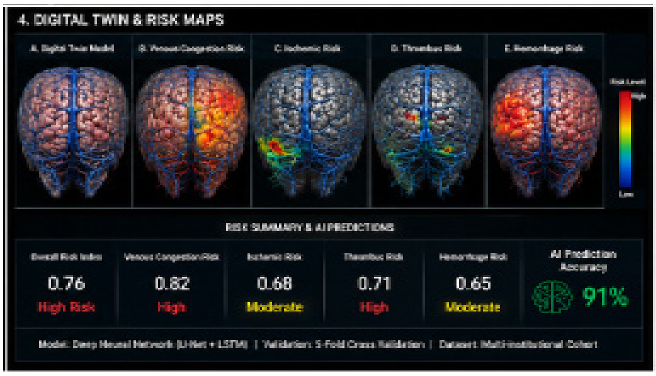

Figure 4: Digital twin simulation demonstrates predicted postoperative cerebral venous redistribution after virtual surgical separation.

Declarations

Ethics approval and consent to participate: This retrospective multicenter study was conducted using anonymized neuroimaging data obtained from three craniopagus twin patients who underwent surgical management at two tertiary neurosurgical centers in two different countries. The imaging datasets (CTA, MRV, and MRI) were originally acquired as part of routine clinical evaluation and surgical planning.

No additional patient intervention or prospective data collection was performed for the purpose of this research. All imaging data were fully de-identified before computational processing and analysis. Because of the retrospective nature of the study and the use of anonymized clinical imaging data, the requirement for Institutional Review Board (IRB) approval and informed consent was formally waived according to the regulations of the participating institutions. All study procedures were performed in accordance with the ethical principles of the Declaration of Helsinki.

Consent for publication: Written informed consent for publication of the clinical details and accompanying images was obtained from the parents or legal guardians of all patients.

Availability of data and materials: The data and computational workflow supporting the findings of this study are available from the corresponding author, Ali Reza Arabestanino, upon reasonable request.

Competing interests: The author declares that he has no competing interests.

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Authors' contributions: Ali Reza Arabestanino conceived the study, developed the methodology, designed the computational framework, performed the literature review, and wrote, reviewed, and approved the final manuscript.

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Authors' information (optional): Ali Reza Arabestanino is an independent researcher with academic interests in neurosurgery, cerebrovascular hemodynamics, artificial intelligence, and computational modeling for precision surgical planning.

Data availability statement: The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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