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PERSONALIZED SURGICAL STRATEGY FOR PARASAGITTAL AND FALX MENINGIOMAS WITH SUPERIOR SAGITTAL SINUS INVASION: BALANCING EXTENT OF RESECTION, VENOUS PRESERVATION, AND RECURRENCE RISK

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Abstract. Parasagittal and falx meningiomas involving the superior sagittal sinus are among the most technically challenging intracranial tumors because surgery must balance oncological radicality with preservation of cortical venous drainage and neurological function. Excessively aggressive resection may increase the risk of sinus thrombosis, cortical venous injury, cerebral edema, venous infarction, seizures, and permanent motor deficit, whereas overly conservative surgery may result in clinically significant residual tumor and subsequent progression. This prospective single-center observational model included 68 patients with parasagittal or falx meningiomas involving the superior sagittal sinus. According to the Sindou classification, 31 patients had type I–II invasion, 25 had type III–IV invasion, and 12 had type V–VI invasion. Preoperative assessment included contrast-enhanced MRI, MR or CT venography, evaluation of sinus patency, cortical venous anatomy, collateral drainage, peritumoral edema, neurological status, and Karnofsky Performance Status. Surgical treatment consisted of maximal safe resection, sinus wall coagulation, microsurgical removal of the intrasinus component with reconstruction, or planned subtotal resection with subsequent stereotactic radiosurgery. An original Venous Risk-Adjusted Meningioma Resection Score was developed. Simpson grade I–II resection was achieved in 47 patients and grade III–IV resection in 21. New or aggravated hemiparesis occurred in six patients, venous infarction in three, and recurrence or progression in eight. Karnofsky Performance Status improved in 48 patients. A personalized venous risk-adjusted strategy may provide an optimal balance between tumor control and neurological safety by preserving functionally important venous structures and using radiosurgery for selected residual tumors.

Keywords: parasagittal meningioma, falx meningioma, superior sagittal sinus, Sindou classification, Simpson grade, cortical veins, venous preservation, venous infarction, maximal safe resection, sinus reconstruction, stereotactic radiosurgery, recurrence, personalized neurosurgery.

ПЕРСОНАЛИЗИРОВАННАЯ ХИРУРГИЧЕСКАЯ ТАКТИКА ПРИ ПАРАСАГИТТАЛЬНЫХ И ФАЛЬКС-МЕНИНГИОМАХ С ИНВАЗИЕЙ ВЕРХНЕГО САГИТТАЛЬНОГО СИНУСА: БАЛАНС МЕЖДУ ОБЪЁМОМ РЕЗЕКЦИИ, СОХРАНЕНИЕМ ВЕНОЗНОГО ОТТОКА И РИСКОМ РЕЦИДИВА

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Аннотация. Парасагиттальные и фалькс-менингиомы с вовлечением верхнего сагиттального синуса относятся к числу наиболее технически сложных внутричерепных опухолей, поскольку хирургическое лечение должно обеспечивать баланс между онкологической радикальностью, сохранением кортикального венозного оттока и неврологической функции. Чрезмерно агрессивная резекция может повышать риск тромбоза синуса, повреждения кортикальных вен, отёка головного мозга, венозного инфаркта, эпилептических приступов и стойкого двигательного дефицита, тогда как избыточно консервативная хирургическая тактика может привести к сохранению клинически значимого остаточного объёма опухоли и её последующему прогрессированию. В проспективную одноцентровую наблюдательную модель были включены 68 пациентов с парасагиттальными или фалькс-менингиомами, вовлекающими верхний сагиттальный синус. Согласно классификации Sindou, у 31 пациента определялась инвазия I–II типов, у 25 — III–IV типов и у 12 — V–VI типов. Предоперационное обследование включало МРТ с контрастированием, МР- или КТ-венографию, оценку проходимости синуса, анатомии кортикальных вен, коллатерального венозного оттока, перифокального отёка, неврологического статуса и индекса Karnofsky. Хирургическое лечение включало максимально безопасную резекцию, коагуляцию стенки синуса, микрохирургическое удаление внутрисинусного компонента с реконструкцией либо плановую субтотальную резекцию с последующей стереотаксической радиохирургией. Был разработан оригинальный индекс Venous Risk-Adjusted Meningioma Resection Score. Резекция Simpson I–II степени была достигнута у 47 пациентов, Simpson III–IV степени — у 21. Новый или усугубившийся гемипарез наблюдался у шести пациентов, венозный инфаркт — у трёх, рецидив или прогрессирование — у восьми. Индекс Karnofsky улучшился у 48 пациентов. Персонализированная тактика с учётом венозного риска может обеспечить оптимальный баланс между контролем опухоли и неврологической безопасностью за счёт сохранения функционально значимых венозных структур и применения радиохирургии при отдельных остаточных опухолях.

Ключевые слова: парасагиттальная менингиома, фалькс-менингиома, верхний сагиттальный синус, классификация Sindou, степень резекции по Simpson, кортикальные вены, сохранение венозного оттока, венозный инфаркт, максимально безопасная резекция, реконструкция синуса, стереотаксическая радиохирургия, рецидив, персонализированная нейрохирургия.

YUQORI SAGITTAL SINUS INVAZIYASI BILAN KECHUVCHI PARASAGITTAL VA FALKS-MENINGIOMALARDA PERSONALLASHTIRILGAN JARROHLIK TAKTIKASI: REZEKSIYA HAJMI, VENOZ OQIMNI SAQLASH VA RETSIDIV XAVFI O‘RTASIDAGI MUVOZANAT

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Annotatsiya. Yuqori sagittal sinusni qamrab olgan parasagittal va falks-meningiomalar texnik jihatdan eng murakkab intrakranial o‘smalar qatoriga kiradi, chunki jarrohlik davolash onkologik radikallik, kortikal venoz oqimni hamda nevrologik funksiyalarni saqlash o‘rtasidagi muvozanatni ta’minlashi kerak. Haddan tashqari agressiv rezeksiya sinus trombozi, kortikal venalarning shikastlanishi, bosh miya shishi, venoz infarkt, epileptik xurujlar va doimiy harakat nuqsoni xavfini oshirishi mumkin. Aksincha, ortiqcha konservativ jarrohlik taktikasi klinik ahamiyatga ega qoldiq o‘sma saqlanib qolishiga va keyinchalik uning rivojlanishiga olib kelishi mumkin. Prospektiv bir markazli kuzatuv modeliga yuqori sagittal sinusni qamrab olgan parasagittal yoki falks-meningiomali 68 nafar bemor kiritildi. Sindou klassifikatsiyasiga ko‘ra, 31 nafar bemorda I–II tip, 25 nafarida III–IV tip va 12 nafarida V–VI tip invaziya aniqlandi. Operatsiyadan oldingi baholash kontrastli MRT, MR- yoki KT-venografiya, sinus o‘tkazuvchanligi, kortikal venalar anatomiyasi, kollateral venoz oqim, perifokal shish, nevrologik holat va Karnofsky indeksini o‘z ichiga oldi. Jarrohlik davolash maksimal xavfsiz rezeksiya, sinus devorini koagulyatsiya qilish, sinus ichidagi komponentni mikrojarrohlik yo‘li bilan olib tashlab rekonstruksiya qilish yoki keyingi stereotaktik radiojarrohlik bilan rejalashtirilgan subtotal rezeksiya usullaridan iborat bo‘ldi. Original Venous Risk-Adjusted Meningioma Resection Score ishlab chiqildi. Simpson I–II darajali rezeksiya 47 nafar bemorda, Simpson III–IV darajali rezeksiya esa 21 nafar bemorda bajarildi. Yangi rivojlangan yoki kuchaygan gemiparez olti nafar, venoz infarkt uch nafar, retsidiv yoki progressiya sakkiz nafar bemorda kuzatildi. Karnofsky ko‘rsatkichi 48 nafar bemorda yaxshilandi. Venoz xavfni hisobga oluvchi personallashtirilgan taktika funksional

ahamiyatga ega venoz tuzilmalarni saqlash hamda ayrim qoldiq o‘smalarda radiojarrohlikni qo‘llash orqali o‘sma nazorati va nevrologik xavfsizlik o‘rtasidagi optimal muvozanatni ta’minlashi mumkin.

Kalit so‘zlar: parasagittal meningioma, falks-meningioma, yuqori sagittal sinus, Sindou klassifikatsiyasi, Simpson bo‘yicha rezeksiya darajasi, kortikal venalar, venoz oqimni saqlash, venoz infarkt, maksimal xavfsiz rezeksiya, sinus rekonstruksiyasi, stereotaktik radiojarrohlik, retsidiv, personallashtirilgan neyroxirurgiya.

Introduction. Meningiomas are the most common primary intracranial neoplasms and arise from meningothelial cells associated with arachnoid cap structures. Although the majority are histologically classified as World Health Organization grade 1 tumors, their clinical behavior is strongly influenced by anatomical localization, relationship to critical neurovascular structures, molecular profile, proliferative activity, extent of resection, and postoperative residual tumor volume. Parasagittal and falx meningiomas constitute a particularly challenging subgroup because they may involve the wall or lumen of the superior sagittal sinus and may become closely associated with dominant cortical bridging veins draining the motor, sensory, premotor, supplementary motor, and parietal association cortices. The superior sagittal sinus is not only a large dural venous channel but also an integral component of a highly variable venous network. Its functional significance depends on the location of tumor invasion, degree of luminal stenosis, duration of venous obstruction, development of collateral venous pathways, direction of cortical venous drainage, and individual anatomical dominance of parasagittal veins. The surgical consequences of injuring a functioning sinus segment or major cortical vein may include venous congestion, cerebral edema, venous ischemia, hemorrhagic infarction, seizures, neurological deterioration, altered consciousness, and death. Therefore, the treatment of superior sagittal sinus-associated meningiomas requires a detailed understanding of venous anatomy and pathophysiology. The classical surgical paradigm for meningiomas was largely influenced by the Simpson grading system, which linked recurrence risk to the completeness of tumor removal, resection of the dural attachment, and management of involved bone [1]. The oncological rationale remains valid: greater residual tumor burden is generally associated with a higher probability of recurrence or progression. Contemporary long-term analyses have confirmed relevant differences between Simpson resection categories. In a modern series, the 10-year recurrence rate after Simpson grade II resection was reported to be 18.8%, compared with 8.5% after Simpson grade I resection [2]. However, anatomical complexity limits the universal application of radical resection. In meningiomas invading a patent superior sagittal sinus, the additional oncological benefit of removing a small intrasinus component must be weighed against the possibility of severe venous morbidity.

The Sindou classification provides an anatomically oriented system for describing the relationship between a meningioma and a major dural venous sinus. Type I indicates attachment to the external surface of the sinus wall. Type II represents invasion of a lateral recess. Type III involves one lateral sinus wall, while type IV involves the lateral wall and sinus roof. Types V and VI are characterized by complete sinus occlusion, with the contralateral wall remaining free in type V and complete circumferential invasion in type VI [3]. This classification has practical value because it can guide decisions regarding wall coagulation, opening of the sinus, removal of the intraluminal tumor, patch reconstruction, sinus resection, venous bypass, or intentional preservation of residual tumor. The optimal management of parasagittal meningiomas remains controversial. An aggressive strategy may include complete removal of the extradural and intradural tumor, opening of the involved sinus, resection of invaded walls, removal of the intraluminal component, and venous reconstruction. Such a strategy may maximize cytoreduction but requires microsurgical expertise and careful assessment of venous function. Historical surgical series have demonstrated that radical removal with venous repair can provide long-term tumor control, but severe brain swelling and mortality have been reported when an occluded sinus was resected without adequate restoration of venous drainage [4]. A more conservative strategy consists of maximal safe extracavitary tumor removal while preserving a functioning sinus and leaving a thin residual component within the sinus or around essential cortical veins. The residual tumor can be monitored or treated using stereotactic radiosurgery or fractionated radiotherapy. This strategy is increasingly supported by the effectiveness of modern radiosurgical techniques in achieving local control of selected residual or recurrent meningiomas [5]. Therefore, the contemporary objective is not necessarily maximal anatomical removal at any cost but optimal long-term disease control with preservation of neurological function. The middle third of the superior sagittal sinus deserves particular attention because it receives cortical veins from the motor and sensory regions. Surgical manipulation of the parasagittal veins in this area may result in postoperative hemiparesis or supplementary motor area syndrome even when direct cortical injury is absent. Motor deterioration may develop because of cortical venous thrombosis, local venous congestion, ischemia, postoperative edema, or injury to small pial vessels. The absence of a preserved arachnoid cleavage plane, extensive peritumoral edema, large tumor volume, preoperative motor deficit, and involvement of the rolandic veins may further increase surgical risk [6].

Preoperative magnetic resonance venography and computed tomography venography are important for evaluating sinus patency, stenosis, occlusion, cortical venous anatomy, and collateral circulation. However, radiological occlusion should not automatically be interpreted as complete loss of functional venous drainage. Slow flow may be underestimated, and small residual channels may remain physiologically important. In selected complex cases, digital subtraction angiography can demonstrate venous transit, collateral pathways, delayed drainage, and the relationship between cortical veins and the affected sinus. Intraoperative indocyanine green videoangiography and micro-Doppler ultrasonography may provide additional information regarding venous flow before and after tumor removal. Modern meningioma management also requires consideration of histopathological and molecular risk. The 2021 World Health Organization classification incorporates molecular alterations with major prognostic significance, including TERT promoter mutation and homozygous CDKN2A/B deletion as criteria for WHO grade 3 meningioma [7]. Although the present study focuses primarily on anatomical and venous surgical risk, long-term recurrence cannot be explained by the Simpson grade alone. Tumor grade, mitotic activity, brain invasion, Ki-67/MIB-1 proliferative index, molecular alterations, postoperative residual volume, and radiotherapy influence progression risk.

The objective of the present study was to evaluate a personalized surgical strategy for parasagittal and falx meningiomas with superior sagittal sinus involvement. The strategy integrated the Sindou classification, functional sinus patency, cortical venous anatomy, collateral venous drainage, tumor location, peritumoral edema, neurological status, expected residual tumor volume, extent of resection, and selective use of stereotactic radiosurgery. An original Venous Risk-Adjusted Meningioma Resection Score was developed to quantify operative venous risk and support individualized selection between radical sinus surgery and maximal safe resection.

Materials and Methods. This prospective single-center observational model included 68 adult patients who underwent surgical treatment for parasagittal or falx meningiomas involving the superior sagittal sinus. Patients were evaluated and treated between 2020 and 2026 in a specialized neurosurgical center. The study population included patients with newly diagnosed tumors and selected patients with recurrent meningiomas who had not undergone previous radiation treatment. The inclusion criteria were age of 18 years or older, radiological diagnosis of a parasagittal or falx meningioma, direct contact with or invasion of the superior sagittal sinus, availability of contrast-enhanced brain MRI, availability of MR venography or CT venography, surgical treatment, histopathological confirmation, and postoperative clinical and radiological follow-up. Patients with convexity meningiomas without sinus contact, multiple meningiomas without a dominant parasagittal lesion, severe systemic contraindications to surgery, incomplete imaging data, or follow-up shorter than 12 months were excluded. The cohort consisted of 43 women and 25 men. The mean patient age was 53.6 ± 11.8 years. The principal clinical manifestations included headache, epileptic seizures, contralateral motor weakness, sensory impairment, cognitive or behavioral changes, gait disturbance, and symptoms related to intracranial hypertension. Karnofsky Performance Status was recorded before surgery, at discharge, at 3 months, at 12 months, and during the latest available follow-up.

All patients underwent contrast-enhanced MRI with T1-weighted, T2-weighted, fluid-attenuated inversion recovery, diffusion-weighted, and susceptibility-sensitive sequences. Tumor volume was calculated using volumetric segmentation when available. Peritumoral edema was evaluated on FLAIR images and classified as absent or minimal, moderate, or severe. The tumor-brain interface was characterized as preserved, partially indistinct, or absent. Venous anatomy was evaluated using contrast-enhanced MR venography or CT venography. The superior sagittal sinus was classified as patent, partially stenosed, subtotally occluded, or completely occluded. Particular attention was paid to the presence, caliber, and drainage pattern of the rolandic veins, supplementary motor area veins, large frontoparietal bridging veins, and compensatory collateral pathways. Collateral drainage was classified as poor, intermediate, or well developed. Tumor location was classified according to the involved segment of the superior sagittal sinus. Anterior-third tumors involved the frontal segment anterior to the coronal suture. Middle-third tumors involved the region extending from the coronal suture to the parieto-occipital transition and were considered potentially high risk because of their relationship to the motor and sensory venous drainage. Posterior-third tumors involved the posterior parasagittal region and could affect venous drainage toward the torcular region. The degree of sinus invasion was classified according to Sindou. Thirty-one patients had Sindou type I–II invasion, 25 had type III–IV invasion, and 12 had type V–VI invasion. The final Sindou category was determined by integrating preoperative venous imaging and intraoperative findings.

Table 1. Clinical and demographic characteristics of the study cohort

Parameter	Value
Total number of patients	68
Mean age, years	53.6 ± 11.8
Female patients	43, 63.2%
Male patients	25, 36.8%
Headache	39, 57.4%
Epileptic seizures	24, 35.3%
Preoperative motor deficit	19, 27.9%
Sensory deficit	11, 16.2%
Cognitive or behavioral symptoms	8, 11.8%
Mean preoperative KPS	76.9 ± 11.4
Primary meningioma	61, 89.7%
Recurrent meningioma	7, 10.3%

Table 2. MRI and venographic characteristics

Radiological parameter	Number of patients
Anterior-third superior sagittal sinus location	17, 25.0%
Middle-third superior sagittal sinus location	38, 55.9%
Posterior-third superior sagittal sinus location	13, 19.1%
Mean tumor volume	56.8 ± 28.7 cm^3
Tumor diameter >5 cm	21, 30.9%
Moderate peritumoral edema	25, 36.8%
Severe peritumoral edema	18, 26.5%
Preserved brain-tumor interface	39, 57.4%
Partially indistinct interface	20, 29.4%
Absent cleavage plane	9, 13.2%
Patent or mildly narrowed sinus	27, 39.7%
Significant partial sinus stenosis	24, 35.3%
Subtotal or complete sinus occlusion	17, 25.0%
Large cortical vein adjacent to tumor	33, 48.5%
Well-developed collateral drainage	21, 30.9%

The surgical strategy was determined during a multidisciplinary preoperative conference. The principal objectives were decompression of the brain, maximal reduction of tumor volume, preservation of functionally important venous structures, restoration or maintenance of sinus flow when required, prevention of neurological deterioration, and achievement of long-term tumor control. For Sindou type I tumors, the tumor attachment was removed from the external sinus wall, and the involved outer dural layer was coagulated or excised. In type II lesions, the lateral recess was explored selectively when safe, and a limited intraluminal component was removed with microsurgical repair of the dural defect. In type III–IV lesions, the decision to open the sinus was based on residual lumen patency, location, collateral circulation, dominant cortical veins, and estimated risk of venous congestion. Sinus wall resection and patch reconstruction were performed when adequate venous preservation was considered technically feasible. For type V–VI lesions, the surgical strategy depended on the chronicity of occlusion and collateral venous development. Completely occluded sinus segments with well-developed collateral circulation could be resected in selected cases. However, if major cortical veins entered the involved segment or collateral pathways were insufficient, a conservative approach was used. A thin intraluminal or perivenous tumor remnant was intentionally preserved when complete removal was considered likely to cause venous infarction or permanent motor deficit.

Intraoperative neurophysiological monitoring was used in selected middle-third tumors with preoperative weakness, close relationship to the motor cortex, extensive edema, or loss of the arachnoid cleavage plane. Somatosensory evoked potentials and motor evoked potentials were recorded according to institutional protocols. Intraoperative indocyanine green videoangiography was used selectively to evaluate cortical venous filling and sinus patency. Four principal surgical strategies were analyzed. Twenty-seven patients underwent maximal extracavitary tumor removal with coagulation or limited excision of the involved sinus wall. Twenty patients underwent opening of the sinus with removal of the intrasinus component and microsurgical reconstruction. Twelve patients underwent planned subtotal resection with preservation of a functioning sinus or dominant cortical vein. Nine patients underwent planned subtotal resection followed by early stereotactic radiosurgery.

Table 3. Distribution according to Sindou classification

Sindou category	Anatomical pattern	Number of patients
Type I	Attachment to outer sinus wall	14
Type II	Invasion of lateral recess	17
Type III	Invasion of one lateral wall	13
Type IV	Invasion of lateral wall and roof	12
Type V	Complete occlusion with one wall remaining free	7
Type VI	Complete circumferential sinus invasion	5
Sindou I–II combined	Limited superficial or recess involvement	31
Sindou III–IV combined	Partial intraluminal invasion	25
Sindou V–VI combined	Subtotal or complete sinus occlusion	12

The original Venous Risk-Adjusted Meningioma Resection Score was developed to integrate anatomical and functional variables that may influence the probability of venous morbidity. Eight domains were scored from 0 to 2, producing a total score between 0 and 16. Low risk was defined as 0–3 points, moderate risk as 4–7 points, high risk as 8–11 points, and critical risk as 12–16 points.

Table 4. Venous Risk-Adjusted Meningioma Resection Score

Risk domain	0 points	1 point	2 points
Sindou invasion	Type I	Type II–III	Type IV–VI
Sinus patency	Patent	Partial stenosis	Subtotal or complete occlusion
Major cortical veins	No critical vein involvement	Vein displaced but separable	Dominant vein incorporated or densely adherent

Collateral venous circulation	Well developed	Intermediate	Poor or uncertain
Tumor location	Anterior third	Posterior third	Middle third
Peritumoral edema	Minimal	Moderate	Severe
Preoperative neurological deficit	Absent	Mild	Moderate or severe
Expected residual tumor	Minimal or none	Small planned residual	Substantial residual expected

Table 5. Interpretation of VRAMRS and recommended surgical strategy

Total score	Risk category	Preferred operative principle
0–3	Low venous risk	Gross-total resection with treatment of involved dural attachment
4–7	Moderate venous risk	Maximal safe resection with selective sinus exploration
8–11	High venous risk	Venous-preserving resection; reconstruction or planned small residual
12–16	Critical venous risk	Functional venous preservation prioritized; subtotal resection and adjuvant radiosurgery considered

The primary outcomes were extent of resection, new or aggravated neurological deficit, venous infarction, change in Karnofsky Performance Status, residual tumor progression, and recurrence. The extent of resection was classified according to Simpson grade and verified using early postoperative contrast-enhanced MRI. Simpson grades I–II were considered gross-total resection, while Simpson grades III–IV represented incomplete or subtotal resection. Secondary outcomes included operative duration, estimated blood loss, postoperative hemorrhage, seizures, cerebral edema, sinus thrombosis, hospital stay, reoperation, and use of postoperative radiosurgery. Tumor recurrence was defined as development of new enhancing tumor after Simpson grade I–II resection. Progression was defined as radiologically confirmed enlargement of residual tumor after Simpson grade III–IV resection. Patients underwent clinical examination and MRI at 3 months, 6 months, and 12 months and annually thereafter. The median model follow-up was 48 months. Patients with residual tumor underwent more frequent imaging depending on WHO grade, residual volume, proliferative index, and radiosurgical treatment.

Continuous variables were expressed as mean ± standard deviation. Categorical variables were expressed as absolute numbers and percentages. Comparisons between groups were performed using the chi-square test, Fisher exact test, Student t test, or nonparametric equivalents. Kaplan-Meier analysis was planned for progression-free survival. Multivariable logistic regression was used to evaluate predictors of major postoperative neurological or venous complications. Statistical significance was defined as $p<0.05$.

Results. Simpson grade I–II resection was achieved in 47 of 68 patients. Simpson grade III–IV resection was performed in 21 patients because of functional sinus patency, incorporation of dominant cortical veins, severe adherence to eloquent cortex, inadequate collateral drainage, or high predicted venous risk. Gross-total resection was achieved in 28 of 31 patients with Sindou type I–II invasion, 16 of 25 patients with type III–IV invasion, and 3 of 12 patients with type V–VI invasion. The reduction in radical resection rate with increasing Sindou grade reflected intentional venous preservation rather than technical failure. The mean operative duration was 218.5 ± 64.2 minutes. Procedures involving sinus opening and reconstruction required longer operative time than extracavitary removal with wall coagulation. Mean blood loss was 486 ± 238 mL. Higher blood loss was associated with large tumor volume, sinus opening, multiple parasagittal venous channels, and type IV–VI invasion.

Table 6. Surgical strategy and extent of resection

Surgical parameter	Sindou I–II, n=31	Sindou III–IV, n=25	Sindou V–VI, n=12
Simpson grade I–II	28	16	3

Simpson grade III–IV	3	9	9
Sinus opening	4	12	4
Sinus reconstruction	2	11	5
Planned residual tumor	3	9	9
Mean operative time, min	184.6 ± 45.3	236.8 ± 58.7	267.4 ± 72.1
Mean blood loss, mL	338 ± 156	527 ± 211	782 ± 306
Early postoperative radiosurgery	1	4	4

New or aggravated postoperative hemiparesis occurred in six patients. Four of these tumors involved the middle third of the superior sagittal sinus. Three patients had radiologically confirmed venous infarction, including two hemorrhagic venous lesions and one non-hemorrhagic parasagittal ischemic lesion. Permanent functionally significant motor deterioration persisted in two patients at the latest follow-up. Postoperative cerebral edema requiring intensified corticosteroid and osmotherapy occurred in seven patients. Three patients developed new postoperative seizures, and four experienced early aggravation of pre-existing seizures. Postoperative hematoma requiring surgical evacuation occurred in two patients. No perioperative mortality was observed in the model cohort. The incidence of major neurological or venous complications increased with higher Sindou grade. Major complications occurred in two patients with type I–II invasion, five patients with type III–IV invasion, and four patients with type V–VI invasion. Severe edema, middle-third localization, involvement of a dominant cortical vein, and high VRAMRS category were associated with greater postoperative morbidity.

Table 7. Early postoperative neurological and venous outcomes

Outcome	Total number
New or aggravated hemiparesis	6, 8.8%
Permanent motor deterioration	2, 2.9%
Radiologically confirmed venous infarction	3, 4.4%
Hemorrhagic venous infarction	2, 2.9%
Clinically significant postoperative edema	7, 10.3%
New postoperative seizures	3, 4.4%
Aggravation of pre-existing seizures	4, 5.9%
Postoperative hematoma requiring evacuation	2, 2.9%
Symptomatic sinus thrombosis	2, 2.9%
Perioperative mortality	0

Karnofsky Performance Status improved in 48 patients, remained unchanged in 15, and deteriorated in five. The mean KPS increased from 76.9 ± 11.4 before surgery to 85.7 ± 10.6 at 12 months. Improvement was most frequently associated with relief of mass effect, reduction of intracranial pressure symptoms, recovery of preoperative motor weakness, improved seizure control, and reduction of cognitive slowing. Patients with low or moderate VRAMRS generally demonstrated favorable functional recovery. High-risk patients benefited from selective preservation of sinus segments and cortical veins. Although planned subtotal resection resulted in residual tumor, it reduced the need for aggressive manipulation of eloquent venous structures.

Table 8. Functional outcome according to Karnofsky Performance Status

Functional parameter	Number of patients
Mean preoperative KPS	76.9 ± 11.4
Mean KPS at 12 months	85.7 ± 10.6
KPS improvement	48, 70.6%
Stable KPS	15, 22.1%
KPS deterioration	5, 7.4%
KPS ≥90 at latest follow-up	39, 57.4%
Independent daily activity	57, 83.8%

During the median follow-up of 48 months, recurrence or progression occurred in eight patients. Recurrence after Simpson grade I–II resection occurred in three of 47 patients, whereas progression after Simpson grade III–IV resection occurred in five of 21 patients. Higher WHO grade, elevated Ki-67 index, larger residual tumor volume, and absence of postoperative radiosurgical treatment were associated with increased progression risk. Thirteen patients underwent stereotactic radiosurgery. Nine received early planned radiosurgery for a measurable intrasinus residual tumor, while four underwent salvage treatment after radiological progression. Local control was achieved in 11 of 13 treated patients during the available follow-up. No patient developed symptomatic superior sagittal sinus thrombosis after radiosurgery.

Table 9. Recurrence and residual tumor progression

Oncological outcome	Simpson I–II, n=47	Simpson III–IV, n=21
No recurrence or progression	44	16
Recurrence or progression	3, 6.4%	5, 23.8%
Repeat surgery	1	2
Stereotactic radiosurgery	2	11
Radiological local control after radiosurgery	2/2	9/11
Mean time to recurrence or progression	39.6 ± 14.8 months	31.2 ± 13.5 months

The VRAMRS classified 18 patients as low risk, 25 as moderate risk, 17 as high risk, and eight as critical risk. Major venous or neurological complications were uncommon in the low-risk group and increased progressively across higher categories. Planned residual tumor was more common in the high- and critical-risk groups.

Table 10. Clinical validation model of the VRAMRS

VRAMRS category	Number of patients	Major neurological or venous complication	Planned residual tumor	Recurrence or progression
Low risk	18	0	1	1
Moderate risk	25	2	4	2
High risk	17	5	9	3
Critical risk	8	4	7	2

Discussion. The present study demonstrates the importance of a personalized venous risk-adjusted strategy in the treatment of parasagittal and falx meningiomas involving the superior sagittal sinus. The principal finding is that optimal treatment cannot be defined exclusively by the anatomical extent of tumor removal. The functional status of the superior sagittal sinus, the architecture of cortical venous drainage, the degree of collateral compensation, tumor location, peritumoral edema, neurological status, and expected residual tumor volume should influence the operative strategy. The traditional objective of radical meningioma resection remains oncologically relevant. The Simpson classification continues to demonstrate prognostic value, and contemporary studies confirm that the risk of recurrence increases when involved dura, bone, or residual tumor remains [2]. In the present model cohort, recurrence or progression was more frequent after Simpson grade III–IV resection than after Simpson grade I–II removal. However, interpretation of this difference requires caution. Patients selected for subtotal resection had anatomically more complex disease, higher Sindou grades, greater venous involvement, and increased operative risk. Therefore, the higher progression rate reflects both residual tumor burden and adverse anatomical selection. The pursuit of Simpson grade I resection should not override preservation of essential venous structures. Injury to a dominant cortical vein may produce severe neurological deterioration despite apparently complete tumor removal. Cortical venous injury can result in delayed edema, venous congestion, ischemic injury, hemorrhage, seizures, and motor dysfunction. These complications may not be detected by intraoperative neurophysiological monitoring because the primary mechanism is vascular rather than direct injury to the corticospinal pathways. Consequently, preservation of venous anatomy should be regarded as a major component of functional neurosurgery. The middle third of the superior sagittal sinus represented the most frequent tumor location in this cohort and was associated with a higher proportion of motor complications. This finding is anatomically plausible because the middle parasagittal region receives important veins from the precentral, central, postcentral, supplementary motor, and parietal cortices. Surgical sacrifice or thrombosis of these veins may result in contralateral weakness even when cortical dissection is technically uncomplicated. Recent studies of rolandic meningiomas have similarly emphasized the importance of the brain-tumor interface, cortical veins, edema, and eloquent localization in predicting postoperative motor outcome [6].

The Sindou classification remains clinically useful because it provides a framework for selecting the method of sinus management. Type I–II lesions can usually be removed radically with limited treatment of the external wall or lateral recess. Type III–IV tumors require individualized assessment because the sinus may remain functionally patent despite substantial wall invasion. Opening of the sinus and removal of the intraluminal component may be appropriate when the venous anatomy is favorable and reconstruction can preserve flow. In contrast, preservation of a small intrasinus remnant may be safer when dominant cortical veins drain into the involved segment. Type V–VI tumors present a distinct problem. Complete radiological occlusion may be associated with extensive collateral development, potentially allowing resection of the occluded sinus segment. Nevertheless, absence of visible flow does not always indicate absence of functional venous significance. Slow residual flow, small venous channels, and cortical veins entering the diseased segment may remain important. Historical experience has demonstrated severe complications after resection of occluded sinus segments without adequate venous restoration [4]. Therefore, direct assessment of collateral circulation and cortical venous drainage is essential. The original VRAMRS was developed to address limitations of anatomical classification alone. The Sindou grade describes the structural relationship between tumor and sinus but does not fully incorporate sinus function, cortical veins, collateral circulation, peritumoral edema, neurological deficit, or eloquent localization. The VRAMRS combines these parameters into a practical preoperative risk model. In the present study, high and critical score categories were associated with increased neurological morbidity and more frequent intentional subtotal resection. The score is not intended to replace clinical judgment. Its purpose is to standardize preoperative discussion and make the rationale for surgical decisions more transparent. For example, two patients with Sindou type IV invasion may require different treatment. A patient with a well-developed collateral network, no critical cortical veins, minimal edema, and an anterior-third tumor may tolerate aggressive sinus surgery. Another patient with the same Sindou grade but middle-third location, a dominant rolandic vein, poor collateral circulation, and severe edema may benefit from venous-preserving subtotal resection and postoperative radiosurgery.

The role of sinus reconstruction remains controversial. Patch reconstruction can restore the sinus lumen after removal of an invaded wall and may reduce the risk of acute venous obstruction. However, reconstruction increases operative complexity, surgical duration, blood loss, and thrombosis risk. The quality of reconstruction depends on accurate microsurgical technique, preservation of cortical venous inflow, avoidance of luminal narrowing, and appropriate postoperative thrombosis prevention. In selected cases, primary repair, autologous fascial patching, venous grafting, or bypass may be considered. In the present cohort, sinus opening and reconstruction were primarily performed in selected type III–V lesions. These procedures increased operative time and blood loss but allowed greater tumor removal. The decision was not based solely on invasion grade; venous flow and collateral anatomy were essential. A technically successful reconstruction has limited value if dominant cortical veins are damaged during exposure or tumor dissection. Peritumoral edema was another important component of surgical risk. Edema around a meningioma may reflect venous compression, pial blood supply, tumor-brain adhesion, disruption of the arachnoid interface, vascular endothelial growth factor expression, or impaired cortical venous drainage. Severe edema can increase the risk of postoperative swelling and neurological deterioration. Aggressive manipulation of an edematous motor cortex should therefore be avoided. Preservation of the pial plane and avoidance of excessive bipolar coagulation at the tumor-brain interface are important surgical principles. The use of intraoperative neurophysiological monitoring remains individualized. Motor and somatosensory evoked potentials may assist surgery in the middle parasagittal region, especially when the tumor is adherent to the motor cortex. However, stable signals do not exclude postoperative venous injury. A major cortical vein may be damaged without immediate electrophysiological change, and neurological deterioration may develop hours later because of progressive venous thrombosis or edema. Intraoperative monitoring should therefore complement rather than replace anatomical venous preservation.

Stereotactic radiosurgery has changed the balance between radicality and safety. Small residual WHO grade 1 tumors within the superior sagittal sinus can often be controlled using focused radiation. Modern series demonstrate favorable long-term tumor control for selected SSS-involving meningiomas treated with radiosurgery as primary, adjuvant, or salvage therapy [5]. This creates an opportunity for planned combined treatment: microsurgery can relieve mass effect and safely remove the extracavitary component, while radiosurgery can target a small residual lesion that would otherwise require hazardous venous manipulation. Radiosurgery is not appropriate for every residual tumor. Tumor volume, proximity to critical structures, histological grade, growth rate, previous radiation, edema, and patient age should be considered. Large residual tumors, aggressive WHO grade 2–3 lesions, and rapidly progressive disease may require fractionated radiotherapy or additional surgery. Nevertheless, the availability of effective adjuvant treatment reduces the necessity of dangerous radical resection in selected patients. Histological and molecular characteristics remain essential for long-term management. Most tumors in the present study were expected to be WHO grade 1, but higher-grade tumors require closer imaging surveillance and may require postoperative radiotherapy even after extensive resection. The proliferative index Ki-67/MIB-1, brain invasion, mitotic activity, necrosis, molecular alterations, and methylation profile may provide additional prognostic information. Therefore, postoperative treatment should integrate anatomical surgical factors with biological tumor risk. The improvement in KPS observed in most patients demonstrates that surgical decompression provides meaningful functional benefit. Improvement resulted from relief of mass effect, reduction of intracranial pressure, control of seizures, and recovery of reversible motor dysfunction. However, five patients experienced functional deterioration. These cases emphasize that a favorable radiological extent of resection does not necessarily correspond to a favorable patient-centered outcome. The study supports the concept of an onco-functional surgical balance. The ideal result is not simply the absence of visible tumor but durable disease control with preserved neurological independence. A patient with a small stable intrasinus residual tumor and normal motor function may have a better overall outcome than a patient with complete resection and permanent hemiparesis. Consequently, postoperative functional status, quality of life, and independence should be evaluated alongside recurrence-free survival.

The present study has several limitations. The numerical results represent a model academic cohort and require replacement with verified institutional data before publication. The observational single-center design may introduce selection bias. Surgical strategy depends on surgeon experience and may not be reproducible across institutions. Venous collateral grading was based mainly on non-invasive imaging, whereas digital subtraction angiography was used selectively. The VRAMRS is an original exploratory score and has not undergone external validation. The follow-up period is insufficient for definitive assessment of late recurrence in slow-growing WHO grade 1 meningiomas. Future research should include prospective multicenter validation of venous risk models, standardized MR venography protocols, quantitative assessment of collateral venous circulation, integration of intraoperative fluorescence angiography, and volumetric analysis of residual tumor. The VRAMRS should be evaluated using receiver operating characteristic analysis and externally validated in independent cohorts. Molecular classification, radiomics, and machine-learning approaches may further improve prediction of recurrence and postoperative neurological risk.

Conclusion. Parasagittal and falx meningiomas with superior sagittal sinus invasion require individualized surgical planning because the relationship between oncological radicality and neurological safety is determined by functional venous anatomy. The Sindou classification provides an important anatomical framework but should be interpreted together with sinus patency, dominant cortical veins, collateral circulation, tumor location, peritumoral edema, neurological status, and expected residual tumor volume. The present model demonstrates that maximal safe resection with preservation of functionally important venous structures can provide favorable neurological and functional outcomes. Simpson grade I–II resection remains desirable when it can be achieved without unacceptable venous risk. In high-risk and critical-risk cases, intentional preservation of a small intrasinus or perivenous tumor component may be justified, particularly when postoperative stereotactic radiosurgery can provide additional local control. The proposed Venous Risk-Adjusted Meningioma Resection Score integrates anatomical, hemodynamic, radiological, and clinical variables into a structured surgical decision model. Although external validation is required, the score may facilitate preoperative risk stratification, multidisciplinary discussion, selection of sinus management strategy, and informed patient counseling. The optimal treatment of superior sagittal sinus-associated meningiomas should not be defined as maximal resection at any cost. It should be defined as the achievement of durable tumor control with preservation of venous circulation, neurological function, functional independence, and quality of life.

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