

Single-Stage Tumor Resection and Immediate CAD/CAM-assisted Cranio-Orbital Reconstruction for Spheno-Orbital Meningiomas: A Standardized Surgical Workflow and Outcome Analysis

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Title: Single-Stage Tumor Resection and Immediate CAD/CAM-assisted Cranio-Orbital Reconstruction for Spheno-Orbital Meningiomas: A Standardized Surgical Workflow and Outcome Analysis

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Keywords: Single-stage surgery, skull base reconstruction, spheno-orbital meningioma, CAD/CAM-assisted

Data availability statement: The data supporting the findings of the study are available from the corresponding author upon reasonable request

Human Ethics approval and Consent to Participate declaration:

This retrospective study was based on clinical data collected during routine patient care at our institution over the past years. Written informed consent for the collection and scientific use of clinical data was obtained from all patients at the time of their treatment. The Institutional Review Board of Clemenshospital Muenster – Alexianer reviewed and approved the study and confirmed that formal ethics committee approval was not required.

Funding:

None

Abstract:

Background:

Spheno-orbital meningiomas (SOMs) are surgically challenging lesions characterized by tumor infiltration and hyperostosis of the sphenoid wing and orbit. Surgical treatment requires tumor resection, drilling of hyperostotic bone, orbital decompression and skull base reconstruction. Traditionally, reconstruction has been performed either free hand or as a delayed second-stage procedure, often resulting in suboptimal skull and facial symmetry. Single-stage resection with immediate CAD/CAM-assisted reconstruction offers a feasible alternative but requires meticulous preoperative planning and a standardized surgical workflow.

Methods:

In this retrospective study of 34 patients with SOMs, we present our institutional standardized protocol for preoperative CAD/CAM planning and single-stage tumor resection with immediate skull reconstruction technique. Clinical, functional and radiological outcomes were also assessed.

Results:

Exophthalmos was the predominant presenting symptom. Gross-total resection was achieved in 73.5% of cases, resulting in a reduction of exophthalmos in 85% of patients and improvement of visual acuity in approximately 70%. CAD/CAM implants demonstrated excellent intraoperative fit without major implant-related complications and with satisfactory orbital and facial symmetry.

Conclusion:

Single-stage resection with immediate CAD/CAM-assisted skull reconstruction for SOMs is feasible, safe and reproducible. The standardized workflow enhances accuracy, reduces operative complexity, and eliminates the need for delayed cranioplasty.

Introduction:

Spheno-orbital meningiomas (SOMs) are characterized by en plaque growth and osseous hyperostosis, typically involving the sphenoid wing and the lateral orbital wall. The main surgical challenge is to achieve complete surgical tumor resection – thus the hyperostotic bone – while simultaneously performing a precise reconstruction of the orbital wall and skull base, preserving both function and aesthetics.

Computer-aid design and manufacturing (CAD/CAM) technology enables submillimetric precision in reconstructive procedures. However, its application in a single-stage surgery – neurooncological tumor resection and skull reconstruction – remains limited, as reconstructive step is often performed as a separate, delayed procedure.

In this retrospective study, we present a standardized stepwise preoperative planning and surgical workflow for single-stage resection and CAD/CAM-assisted reconstruction of SOMs and report the clinical and radiological outcomes based on our institutional experience.

Patients and Methods:

Study Population:

All consecutive patients ≥ 18 years with SOMs who underwent surgery at our institution between 2014 and 2025 were screened for inclusion. Only patients who received a single-stage tumor resection with simultaneous CAD/CAM-assisted skull reconstruction were included. This study adheres to the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines. [1]

Study protocol:

Baseline characteristics of all patients were retrospectively collected and analyzed. Descriptive statistical analysis was performed using RStudio. Continuous variables were reported as mean (SD) or median (IQR) as appropriate, and categorical variables as frequencies and percentages. Exophthalmus was assessed using preoperative and postoperative MRI scans, measured according to the Interzygomatic Line method. Visual acuity (pre- and postoperative at 3 months) was obtained from ophthalmologic examinations and reviewed from patients' records. Extent of tumor resection was determined from postoperative MRI and assessed by the institutional neuroradiology team. Surgical and CAD/CAM implant-related outcomes were documented.

Surgical Workflow

1. Preoperative CAD/CAM Planning Workflow

Step 1: All included patients underwent comprehensive preoperative imaging, including contrast-enhanced brain MRI (T2-, T1-MPRage sequences) and thin-slice CT of the skull with neuronavigation-compatible datasets. The CT scan data were transferred to an external medical device manufacturer for CAD/CAM implant planning and production.

Step 2: Following DICOM data processing, a structured planning process was conducted in close collaboration between the neurosurgical team and the engineering partner. Visual surgical planning was performed using a 3D-PDF model during an online session. The planned tumor resection and extent of hyperostotic bone removal were defined. Special consideration was given to the design of the craniotomy. An extended lateral frontotemporal approach was planned. The craniotomy boundaries extended approximately two-thirds into the frontal region up to the mid-orbital rim – this supraorbital extension of craniotomy ensure an optimal surgical corridor to the orbital apex – and one-third into the temporal region.

Step 3: Based on the defined resection margins, a patient-specific CAD/CAM implant was designed. In a subsequent validation step, the implant was reviewed and approved by the operating surgeon. This included detailed assessment of the implant borders and the surgical template, implant thickness and the anticipated postoperative orbital decompression and reconstruction of the skull base and orbital anatomy.

Step 4: After final approval, the implant was manufactured by the external company and delivered to the hospital for sterilization. Upon receipt of the sterilized implant, the surgical procedure was scheduled. A schematic overview of the entire workflow is provided in Figure 1.

2. Surgical Procedure

All patients underwent a standard extra- and intradural approach via a unilateral frontotemporal craniotomy.[2–5] The boundaries of the craniotomy were guided by the preplanned template for the CAD/CAM implant.

Step 1: The procedure began with an entirely extradural phase. The lesser sphenoid wing was drilled down to the level of superior orbital fissure (SOF), and the lateral orbital wall was removed to the level of the foramen rotundum, exposing the maxillary nerve (V2) and the beginning of the inferior orbital fissure. Medial to the SOF, the anterior clinoid process

115 was partially or, depending on tumor involvement, completely removed. The optic canal was unroofed extradurally over
116 a range of approximately 180 to 270°. The extent of orbital access was tailored to the individual case, and the thinned
117 orbital roof was only removed after complete decompression of the orbital apex and the deeper structures.

118 Step 2: This step was performed intradurally and typically involved resection of the small intradural tumor component in
119 the temporal region, along with excision of the involved dura up to the SOF. Dura reconstruction was then performed using
120 interrupted dural sutures along the skull base.

121 Step 3: This step involved opening the periorbita. This resulted in prolapse of intraorbital fat and often limited visualization
122 of deeper structures. Even in cases of suspected muscle infiltration, the intraorbital muscles were preserved and only
123 exophytic tumor components were removed. Residual tumor is frequently present in the orbital apex and should not be
124 aggressively pursued.

125 Step 4: The last step was purely reconstructive. After duraplasty and basal sealing using abdominal fat and fibrin glue,
126 reconstruction focused on the lateral orbital wall and basal sphenoid defect to prevent temporal muscle herniation into the
127 orbit. Cranioplasty was performed using the CAD/CAM implant. This simultaneously restored the lateral orbital wall,
128 part of the lateral orbital roof, the sphenoid base, and the superior orbital contour. If required, the implant was further
129 contoured intraoperatively to achieve smooth adaptation. Careful repositioning and suspension of the temporalis muscle
130 were essential for the final cosmetic and functional result.

131

132 3. Postoperative Assessment

133 Postoperative CT scans were performed to confirm implant position, evaluate the extent of tumor resection, and identify
134 any immediate complications. MRI was performed 3 months after surgery to assess residual tumor and evaluate
135 exophthalmos reduction using the interzygomatic line method.

136 Ophthalmological examination, including visual acuity assessment, was also performed at the 3-month follow-up.

137

Results:

Baseline Characteristics

The mean age was 52.5 years (IQR: 11.25), with a clear female predominance (n=33/34). Exophthalmos was present in 30 patients (88.2%). Reduction of exophthalmos was observed postoperatively in 29/34 patients (85.3%). The remaining 5/34 (14.7%) patients, who demonstrated absent or only minimal preoperative exophthalmos (≤ 2 m), showed no significant postoperative change. Across the entire cohort, the median preoperative exophthalmos measured 5mm (range 0 – 17.5mm) and improved to 2mm (range 0 – 7mm) at 3-month follow-up. Median visual acuity improved from 0.6 preoperatively to 0.8 postoperatively. More specifically, postoperative improvement in visual acuity, ranging from slight to marked, was observed in 24/34 (70.6%) patients. A mild postoperative decline in visual acuity of 0.1 on acuity scale was noted in 7/34 (20.6%) patients. In contrast, 3/34 (8.8%) patients experienced significant postoperative visual deterioration – amaurosis. A comprehensive overview of patient demographics and radiological features is provided in Table 1.

Surgical Data and Perioperative Complications

Gross total resection (Simpson grade I – II) was achieved in 25/34 patients (73.5%) (Figure 2). Subtotal resection was necessary in 9 patients (26.5%) due to infiltration of cavernous sinus. These patients subsequently underwent adjuvant three-dimensional conformal radiotherapy targeting the residual tumor, which was initiated 3 months after surgery.

Histopathological examination revealed meningothelial meningioma in 21 cases (61.8%), transitional subtype in 7 (20.6%) and secretory subtype in 6 (17.6%). In all cases (n=34), a 270° decompression of the optic canal was performed. The overall revision rate was 8.8% (n=3/34). Two patients (5.9%) required revision for early postoperative wound fistula, while one patient (2.9%) underwent reoperation due to increased intraorbital pressure caused by malposition of the CAD/CAM-implant.

Postoperative transient mild cranial nerve III, IV or VI palsies were observed in 19 patients (55.9%), presenting with temporary diplopia. At 3-month follow-up, complete resolution of symptoms was documented in 18 of these patients (94.7%), indicating a predominantly transient postoperative deficit. One patient (2.9%) exhibited a persistent mild oculomotor nerve palsy, with residual ptosis and diplopia still evident at 1-year follow-up. Additionally, 3 patients (8.8%) experienced new-onset focal seizures in the first postoperative days, presenting with language disturbances including global aphasia. All cases were successfully managed with antiepileptic medication, and no further seizure-related complications were reported.

Discussion

Surgical resection of sphenoorbital meningiomas with extensive bony infiltration of the skull base remains highly challenging, as it requires achieving two goals: an adequate tumor resection and simultaneously an aesthetic-functional skull reconstruction. Most published series describe staged procedures or focus on isolated aspects such as tumor debulking or orbital decompression alone, rather than an integrated oncological and reconstructive strategy. The introduction of patient-specific CAD/CAM implants has enabled such a combined approach. However, the application of CAD/CAM implants in a single-stage surgery for sphenoorbital meningiomas remains insufficiently established and underreported in the current literature.

The results of our study demonstrate that the single-stage surgical approach via a frontotemporal craniotomy enabled gross total resection in approximately 75% of patients, whereas complete resection was limited in cases with cavernous sinus infiltration. Patients with residual tumor underwent adjuvant radiotherapy for local tumor growth 3 months after surgery. A significant reduction in proptosis was observed in most patients (ca. 85%), while those with absent or minimal preoperative proptosis remained unchanged postoperatively. Optic nerve decompression resulted in improved visual acuity in 70.6% of patients. Relevant postoperative visual deterioration occurred in only 3/34 patients (8.8%) and was associated with postoperative optic nerve edema on cMRI.

These findings are consistent with the current literature. Mariniello et al. in their study on surgical outcomes following different surgical strategies in SOM, identified tumor relationship to the optic nerve and superior orbital fissure (SOF) as the key determinant of resectability and functional outcome. Reported improvements included reduction of proptosis in up to 68% and visual function improvement in approximately 51% of patients, predominately in laterally located tumors.[6] Similarly, several surgical series have demonstrated that meningioma-associated proptosis can be significantly reduced following extensive tumor resection combined with orbital decompression. [7, 8] Improvement in visual impairment has also been reported, although with variable rates across studies, with more favorable outcomes observed in cases with adequate decompression of the orbital walls and optic canal. [7–10] Several reviews have emphasized that comparisons of cranial nerve deficits between staged and single-staged resections remain challenging due to the marked heterogeneity of such lesions, particularly regarding tumor location, involvement of the optic apparatus, and vascular encasement of adjacent neurovascular structures. [11, 12]. In summary, an extensive tumoral bone infiltration and pronounced preoperative hyperostosis involving the sphenoorbital region and optic nerve was associated with worse postoperative visual outcome. [13]

In our cohort, all patients achieved satisfactory cranial symmetry and precise patient-specific reconstruction with excellent implant fitting accuracy. Compared with staged approaches, the presented single-stage strategy provides comparable functional and aesthetic outcomes while avoiding a second surgical procedure and reducing cumulative operative and anesthesia exposure. Earlier studies including smaller SOM cohorts suggested single-stage surgery to be safe and effective approach, enabling precise tumor resection and simultaneous skull reconstruction with optimal fitting while simplifying traditionally complex and time-consuming SOM-surgeries. [14, 15] More recent studies have further confirmed the feasibility of single-stage resection and reconstruction, demonstrating favorable functional and aesthetic outcomes.[16]

Systematic reviews of staged surgeries for complex intracranial meningiomas suggest that these approaches are generally well tolerated with acceptable perioperative morbidity in selected patients, but whether this translates into superior oncologic or functional outcomes compared with single-staged resections is not demonstrated. [12, 17] In the absence of proven clinical benefit of staged approaches, several authors advocate a single-stage strategy when technically feasible, emphasizing potential advantages including reduced cumulative hospitalization, avoidance of repeated surgical and

anesthetic exposure, and minimization of procedure-related risks, particularly in the context of a careful preoperative planning and standardized intraoperative workflow. [18–20]

In our opinion, the implementation of a standardized preoperative planning and intraoperative workflow protocol for SOM surgery enable the establishment of reproductive surgical corridors from virtual planning to the operative field. Systematic integration of imaging data and predefined surgical trajectories facilitated a structured and reproducible operative strategy, allowing a Gross Total Resection and an extended optic nerve decompression of approximately 270° in most cases. This standardized approach improved anatomical orientation for surgeons and reduced inter-case variability.

The importance of standardized workflow protocols in complex skull base surgery has been emphasized in the current literature, particularly for SOMs, where optimization of surgical exposure and integration of reconstructive strategies are essential. [12, 21] Although favorable outcomes with single-stage approaches have been reported, these techniques may not be universally applicable in all cases. Overall, the choice of neurooncological and reconstructive strategy remains dependent of lesion characteristics, surgical goals, and at the end the institutional experience. [18, 22]

Conclusion

Our study demonstrates the feasibility of single-stage surgery for sphenoorbital meningiomas combined with immediate CAD/CAM-assisted reconstruction, achieving favorable outcomes. The presented standardized preoperative planning and intraoperative surgical workflow provide a safe and reproductive technique associated with satisfactory results, including improvement visual acuity and reduction of exophthalmos, while maintaining a low complication rate. To our knowledge, this study represents one of the largest series of patients undergoing single-stage resection and immediate CAD/CAM-assisted reconstruction for SOM, and among the first to report a standardized protocol in this setting.

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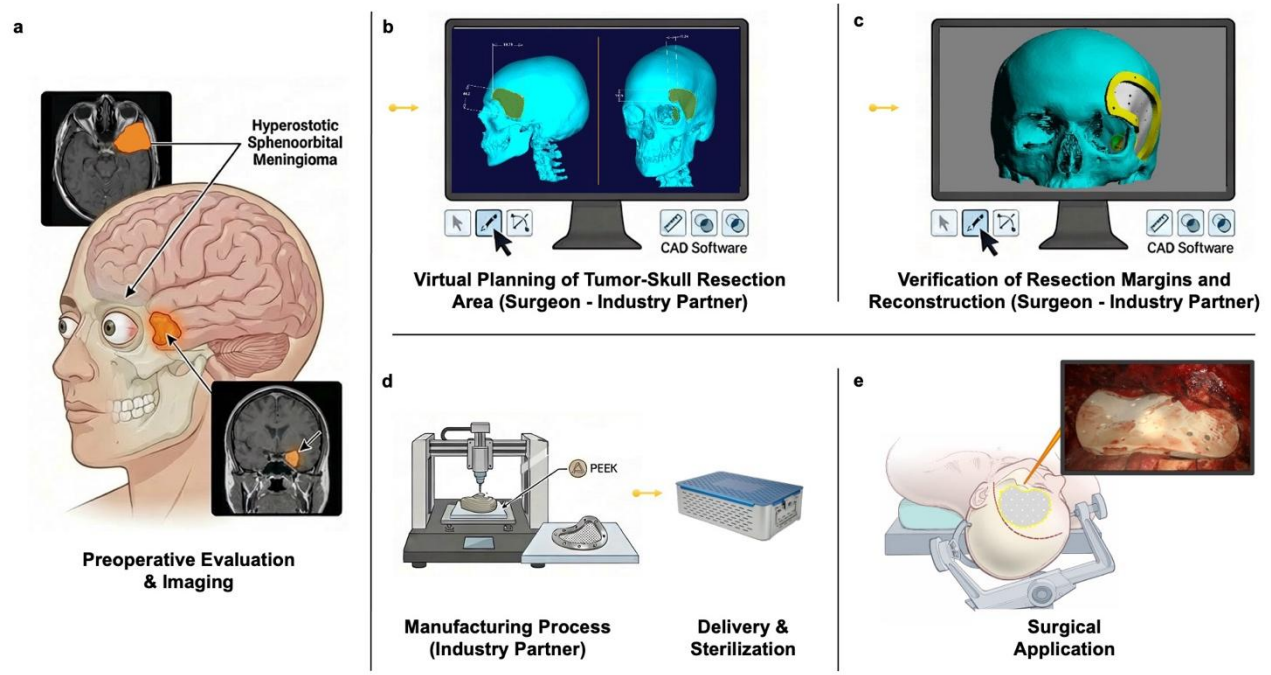
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Tables

Table 1: Baseline Characteristics

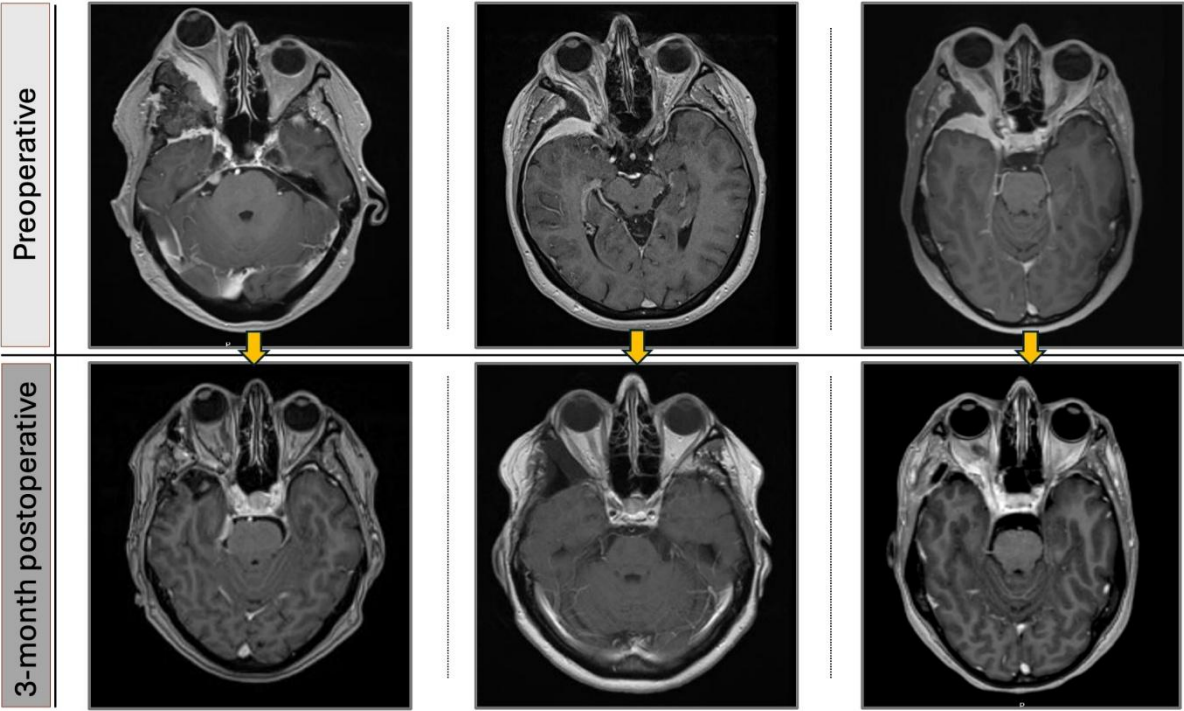
	Overall Cohort
No. of Patients, (n)	34
Patient Characteristics	
Female sex, n (%)	33 (97.0)
Age at diagnosis, median (IQR)	51.5y (12.7)
Clinical Characteristics	
Exophthalmos, n (%)	30 (88.2)
<i>Preoperative exophthalmos, median (IQR)</i>	5mm (0 – 17.5)
<i>Postoperative exophthalmos, median (IQR)</i>	2mm (0 – 7)
Preoperative visual acuity, median	0.6
Postoperative visual acuity, median	0.8
<i>Improvement of visual acuity, n (%)</i>	24 (70.6)
<i>Mild decline in visual acuity, n (%)</i>	7 (20.6)
<i>Major decline in visual acuity, n (%)</i>	3 (8.8)
Tumor Characteristics	
Left Side, n (%)	22 (64.7)
Gross total resection, n (%)	25 (73.5)
270° Decompression of optic canal, n (%)	34 (100)
WHO grade 1, n (%)	34 (100)
Histological Diagnosis	
Meningothelial, n (%)	21 (61.8)
Transitional, n (%)	7 (20.6)
Secretory, n (%)	6 (17.6)
Treatment-related complications	
Surgical revision rate, n (%)	3 (8.8)
Temporary postoperative mild cranial nerve palsies, n (%)	19 (55.9)
Persistent postoperative cranial nerve deficits at last follow-up, n (%)	1 (2.9)
New-onset postoperative seizures, n (%)	3 (8.8)

Figures



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299
300 **Fig.1:** Preoperative planning workflow of patient-specific CAD/CAM implant for skull base reconstruction. a)
301 Preoperative imaging assessment, tumor evaluation and determination of resection margins, b – c) Virtual surgical
302 planning of tumor resection area and CAD-based design and verification of the patient-specific implant using CAD-
303 design software, d) Manufacturing and sterilization of the customized implant, e) Intraoperative application of the patient-
304 specific implant following tumor resection
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Fig 2: Preoperative and postoperative radiological assessment following single-stage tumor resection and immediate CAD/CAM-assisted skull base reconstruction

Supplementary Files

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- [STROBEchecklistcohort.docx](#)