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Supraorbital and mini-pterional keyhole craniotomies for brain tumors: a clinical and anatomical comparison of indications and outcomes in 204 cases

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OBJECTIVE The authors' objective was to compare the indications, outcomes, and anatomical limits of supraorbital (SO) and mini-pterional (MP) craniotomies in patients with intra- and extraaxial brain tumors, and to assess approach selection, utility of endoscopy, and surgical field overlap.

METHODS A retrospective analysis was conducted of all brain tumor patients who underwent an SO or MP approach. The analyzed characteristics included pathology, endoscopy use, extent of resection, length of stay (LOS), and complications. On the basis of preoperative MRI data, tumor heatmaps were constructed to compare surgical access provided by both routes, including coronal projection heatmaps for parasellar tumors.

RESULTS From 2007 to 2020, 158 patients underwent 173 (84.8%) SO craniotomies and 30 patients underwent 31 (15.2%) MP craniotomies; 71 (34.8%) procedures were reoperations. Of these 204 operations, 110 (63.6%) SO and 21 (67.7%) MP approaches were for extraaxial tumors (meningiomas in 65% and 76.2%, respectively). Gliomas and metastases together represented 84.1% and 70% of intraaxial tumors accessed with SO and MP approaches, respectively. Overall, 56.1% of tumors accessed with the SO approach and 41.9% of those accessed with the MP approach were in the parasellar region. Axial projection heatmaps showed that SO access extended along the entire ipsilateral and medial contralateral anterior cranial fossa, parasellar region, ipsilateral sylvian fissure, medial middle cranial fossa, and anterior midbrain, whereas MP access was limited to the ipsilateral middle cranial fossa, sylvian fissure, lateral parasellar region, and posterior aspect of anterior cranial fossa. Coronal projection heatmaps showed that parasellar access extended further superiorly with the SO approach compared with that of the MP approach. Endoscopy was utilized in 98 (56.6%) SO craniotomies and 7 (22.6%) MP craniotomies, with further tumor resection in 48 (49%) and 5 (71.4%) cases, respectively. Endoscope-assisted tumor removal was clustered in areas that were generally at farther distances from the craniotomy or in angled locations such as the cribriform plate region where microscopic visualization is limited. Gross-total or near-total resection was achieved in 120/173 (69%) SO approaches and 21/31 (68%) MP approaches. Major complications occurred in 11 (6.4%) SO approaches and 1 (3.2%) MP approach ($p = 0.49$). The median LOS decreased to 2 days in the last 2 years of the study.

CONCLUSIONS This clinical experience suggests the SO and MP craniotomies are versatile, safe, and complementary approaches for tumors located in the anterior and middle cranial fossae and perisylvian and parasellar regions. The SO route, used in 85% of cases, achieved greater overall reach than the MP route. Both approaches may benefit from expanded visualization with endoscopy.

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KEYWORDS supraorbital craniotomy; mini-pterional craniotomy; endoscope; minimally invasive; keyhole surgery; brain tumor; meningioma; glioma; oncology; surgical technique

Minimally invasive neurosurgical techniques have been developed over many decades, fostered in part by endoscopic visualization.[1–8] Keyhole surgery was introduced by Donald Wilson in 1971.[8] Since the 1990s, Axel Perneczky and others have refined the keyhole concept by applying modern microneurosurgical techniques in skull base and vascular neurosurgery.[2,3,5,9] With careful approach selection, such techniques aim to decrease morbidity and length of stay (LOS), accelerate recovery, and enhance functional and cosmetic outcomes.

ABBREVIATIONS GTR = gross-total resection; LOS = length of stay; MP = mini-pterional; NTR = near-total resection; SO = supraorbital; STR = subtotal resection.
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As shown in recent publications, including those by our group, supraorbital (SO) and mini-pterional (MP) craniotomies are two commonly performed minimally invasive procedures for intraaxial and extraaxial pathologies.[4–6,10–18] Both approaches can provide direct, retractorless visualization, which can be expanded with endoscopy to potentially improve resection rates and visualization of tumor interfaces with critical structures.

Recent anatomical studies have compared the SO and MP routes to each other and to traditional pterional craniotomies.[19–21] However, with the exception of the systematic review by Rychen et al., no clinical series have compared these two approaches for brain tumors or assessed surgical field access and the anatomical regions that benefit from endoscopic visualization.[15] Herein, we report our experience using both approaches to treat over 200 brain tumor patients, with a focus on anatomical access visualized with MRI-based heatmaps, and document clinical outcomes.

Methods

Data Collection

After obtaining IRB approval, we retrospectively analyzed all SO and MP craniotomies performed for tumor resection at Providence Saint John's Health Center, Santa Monica, California, by the two senior authors (G.B. and D.F.K.) from October 2007 through October 2020. Per IRB protocol, patient consent was not necessary because data were deidentified, and 2 patients consented to their photographs being shown.

Patient data included age, sex, pathology, tumor location, maximal tumor diameter, prior surgery or radiation therapy, endoscopy use, extent of resection, operative time, complications, LOS, and discharge disposition. As previously published, extent of resection was defined as gross-total resection (GTR) if no residual tumor was seen on immediate postoperative MRI, near-total resection (NTR) if at least 90% of the tumor was removed, or subtotal resection (STR) if < 90% of the tumor was removed.[6,16] Based on the preoperative and intraoperative notes and images, each procedure was defined as having met the surgical goals. The goal was GTR for patients who underwent their first surgery for tumor without vascular encasement. For patients with vascular encasement, the goal was GTR or NTR. For some patients who had undergone prior surgery or radiation therapy or had cavernous sinus invasion, the goal may have been NTR or STR. For some patients, a biopsy (e.g., for lymphoma) or cyst fenestration (e.g., for recurrent craniopharyngioma) was the goal.

Construction of Heatmaps of Tumor Location

To display the surgical reach of the SO and MP routes, composite heatmaps were constructed of the tumor locations. On the basis of the findings on preoperative axial-plane postgadolinium MRI for each patient, the maximal tumor dimensions in the x and y planes and the location of the axial tumor epicenter were projected as ovals onto an idealized axial-plane skull model. A millimeter-to-pixel conversion factor based on standardized anatomical measurements was applied to the MRI measurements to construct the skull model. Given that 54% of tumors had their epicenter in the parasellar region, this subset of tumors was assessed in a similar fashion in the coronal plane. Tumors were classified as parasellar if the axial epicenter on MRI was located within a rectangular region within 1 cm of the anterior and posterior clinoid processes in all directions. The maximal tumor dimensions in the x and z planes, and the coronal epicenter of each parasellar tumor, were projected onto the coronal-plane skull base model through the optic chiasm. The heatmaps of the intra- and extraaxial tumors of the SO and MP groups were compared to display the anatomical distributions of each approach. For tumor resections performed with endoscopy, different shading was used to highlight tumors visualized with endoscopy and if additional tumor was removed endoscopically.

Surgical Technique

For both SO and MP craniotomies, patients are positioned supine under general total intravenous anesthesia and placed in three-point fixation with their head turned 20°–60° depending on tumor location.[6,22–25] Neuronavigation (Brainlab or Stryker) is used in all cases. To optimize healing, monopolar cautery is not used and skin hooks are moved periodically to avoid pressure points that may otherwise lead to retraction injury and scalp breakdown. Since 2016, intravenous fluorescein (2.5–3 mg/kg) has been administered before incision to aid visualization of many intraaxial tumors.[26,27] Ultrasound is used routinely to visualize intraaxial tumors prior to corticectomy. A Doppler probe (Koven Technology Inc. or Vascular Technologies Inc.) is used to localize blood vessels during tumor resection. Lumbar drains are not used.

The arachnoid cisterns are opened early in intradural dissection for brain relaxation, precluding the need for fixed retractors and creating space for endoscopic visualization. Tumor resection proceeds using standard microsurgical technique, often with an ultrasonic aspirator. In most cases, after maximal microscopic tumor resection, an angled endoscope (4-mm rigid endoscope with a 0°, 30°, or 45° viewing angle [Storz Endoskope North America]) is used to inspect blind spots for residual tumor, such as under the ipsilateral optic nerve, cribriform plate area, or medial sphenoid wing in patients who underwent the SO approach or the anterior cranial fossa or parasellar area in patients who underwent the MP approach. A trained assistant "drives" the endoscope during tumor removal so the surgeon can perform two-handed microsurgical dissection. Video 1 shows 2 case examples.

VIDEO 1. Two case examples of middle fossa meningiomas are shown: a medial tentorial meningioma (Fig. 6A) removed via an SO approach, and a sphenoid wing meningioma (Fig. 6B) removed via an MP approach. Endoscope-assisted tumor resection was used in both cases. Illustrations by Josh Emerson. Copyright Pacific Neuroscience Institute Foundation. Published with permission. Click here to view.

SO Craniotomy

A description of our technique was recently published.[6] An abdominal fat graft site is prepared for use if the frontal sinus is breached. The incision, which is typically 4–5 cm in length, is made within the middle of the thickest part of the eyebrow from just medial to the SO notch to approximately 1 cm lateral to the superior temporal line (Fig. 1). The subcutaneous tissue is dissected sharply to the pericranium and temporalis muscle; the SO nerve is identified medially and preserved. An L-shaped incision in the pericranium is made just lateral to, and parallel with, the SO nerve and extends laterally along the orbital rim to the lateral extent of the skin incision, incorporating the exposed temporalis muscle. The scalp and pericranium are retracted superolaterally with 5–6 skin hooks. A burr hole is placed in the keyhole, and then the craniotomy is turned with a footplate to extend as inferior and superior as possible, resulting in a craniotomy that is at least 2 cm in height and extending from the keyhole to the SO nerve. The orbital rim is not removed, but the inner table of the anterior cranial fossa and any prominences are drilled to expand exposure. The dura mater is opened in a curvilinear fashion and reflected over the brow. After tumor resection and hemostasis are achieved, the dura is closed in a watertight fashion, followed by collagen sponge overlay (Helistat, Integra Life Sciences); the bone flap is replaced with low-profile titanium plates to ensure that the superior and medial gaps are obliterated. The inferior gap between the bone flap and orbital rim is filled with bone cement. Meticulous closure of the muscle and skin is then performed.

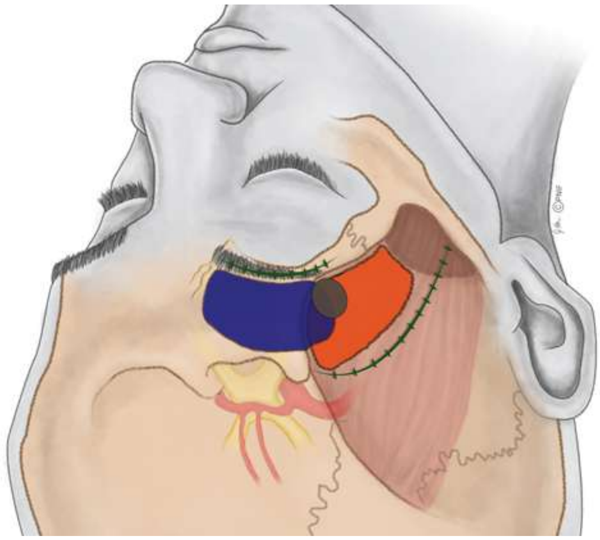

FIG. 1. Illustration of the respective skin incisions (*green lines*) and craniotomies for the SO (*blue*) and MP (*orange*) approaches. The SO incision is made through the middle of the thickest part of the eyebrow, starting just medial to the SO notch and extending laterally just beyond the superior temporal line to provide access to the anatomical keyhole. The SO nerve is identified above the pericranium and defines the medial edge of the craniotomy. The approximate average skin incision length is 5 cm. The skin incision for the MP approach typically extends from just above the root of the zygoma and anterior to the tragus, gently curving superiorly and anteriorly behind the hairline up to the superior temporal line. The approximate average skin incision length is 6 cm. Illustration by Josh Emerson. Copyright Pacific Neuroscience Institute Foundation. Published with permission.

MP Craniotomy

Several variations of MP craniotomy have been described since its introduction by Figueiredo et al. in 2007.[7] Our technique uses a curvilinear incision that is approximately 6 cm in length, centered at the pterion, and without extension above the superior temporal line (Fig. 1). The fascial layers and temporalis muscle are split sharply and reflected anteriorly with 3–4 skin hooks. Burr holes are drilled at the anatomical keyhole and in the inferior temporal bone. After the craniotomy is completed, the sphenoid ridge is drilled down to the meningo-orbital band to maximize exposure. Microsurgical tumor resection proceeds in a standard fashion, in some cases with endoscopic assistance. The dura is closed in a watertight fashion unless the tumor infiltrates the dura. A collagen sponge overlay is extended over the bone edges. The bone flap is secured with titanium plates. The temporalis muscle and overlying fascial layers are reapproximated, and skin closure is performed with subcuticular 4-0 absorbable sutures.

Statistical Analysis

Continuous variables were summarized as mean ± SD and evaluated for normality. Normally distributed data were compared between the SO and MP approaches using the 2-tailed t-tests, whereas nonnormally distributed data were compared using the Mann-Whitney U-test. Ordinal data were summarized as median values and compared using the Mann-Whitney U-test, whereas nominal data were summarized as number (percent) and compared using the chi-square test. All data were analyzed using SPSS version 27.0 (IBM Corp.).

Results

Demographic Characteristics

From October 2007 to October 2020, 158 patients underwent 173 (84.8%) SO craniotomies and 30 patients underwent 31 (15.2%) MP craniotomies (Table 1). Of these 188 patients, 2 underwent both approaches over time owing to disease progression. The mean ages were 59.4 ± 16.9 years for patients who underwent SO craniotomy and 59.5 ± 14.4 years for those who underwent MP craniotomy ($p = 0.706$). For the SO procedures, 64 (37%) and 40 (23.1%) had prior surgery or radiation, respectively; for the MP procedures, 8 (25.8%) and 3 (9.7%) had prior surgery or radiation, respectively ($p = 0.253$; $p = 0.091$). The mean ± SD follow-up durations were 28.9 ± 35.9 months for the SO cohort and 23.4 ± 21.9 months for the MP cohort ($p = 0.96$).

Pathologies

Tumor pathologies are shown in Fig. 2. For the SO and MP operations, meningiomas accounted for 65% and 76.2% of extraaxial tumors, respectively; gliomas and metastases combined accounted for 84.1% and 70% of intraaxial tumors, respectively. Extraaxial tumors were accessed in 110 (63.6%) and 21 (67.7%) of the SO and MP operations, respectively ($p = 0.656$), and meningiomas were accessed in 41% and 51.6% of procedures, respectively. Metastases and gliomas were the most common intraaxial lesions. The mean ± SD maximal tumor dimensions of the pathologies accessed with SO and MP approaches were 32.6 ± 15.1 mm and 34.2 ± 12.7 mm, respectively ($p = 0.246$). Of 12 SO craniotomies performed

TABLE 1. Demographic characteristics and clinical outcomes of patients who underwent the SO and MP approaches

Characteristic	SO Approach	MP Approach	p Value
Demographic & clinical			
No. of operations	173	31	
Age, yrs	59.4 ± 16.9	59.5 ± 14.4	0.706
Female sex	107 (61.8)	20 (64.5)	0.778
Prior surgery	64 (37)	8 (25.8)	0.253
Prior radiation therapy	40 (23.1)	3 (9.7)	0.091
Tumor			
Extraaxial	110 (63.6)	21 (67.7)	0.656
Intraaxial	63 (36.4)	10 (32.3)	0.656
Parasellar*	97 (56.0)	13 (41.9)	0.146
Maximal dimension, mm	32.6 ± 15.1	34.2 ± 12.7	0.246
Procedural			
Endoscope used	98 (56.6)	7 (22.6)	**<0.001**
Additional tumor removal	48 (49)	5 (71.4)	0.251
Surgical goal achieved	161 (93.1)	30 (96.8)	0.384
Extent of resection			0.877
GTR	64 (37)	9 (29)	
NTR	56 (32.4)	12 (38.7)	
STR	53 (30.6)	10 (32.3)	
Op time, mins	338 ± 135	284 ± 102	0.064
Blood loss, ml	190 ± 218	202 ± 152	**0.026**
Major complication	11 (6.4)	1 (3.2)	0.495
Minor complication	5 (2.9)	0	0.338
LOS, days†	3	2	**0.03**
Discharge disposition			0.674
Home	155 (89.6)	27 (87.1)	
Acute rehabilitation	16 (9.2)	3 (9.7)	
Hospice	2 (1.2)	1 (3.2)	
Follow-up, mos	28.9 ± 35.9	23.4 ± 21.9	0.96

Values are shown as number, number (percent), or mean ± SD unless indicated otherwise. Boldface type indicates statistical significance ($p < 0.05$).
* Defined as the axial epicenter lying within 1 cm of the anterior or posterior clinoid processes.
† Median values are shown.

for craniopharyngiomas, 10 (83.3%) were reoperations. Of 11 procedures in the SO group used to access pituitary adenomas, 6 (54.5%) were reoperations after a prior endonasal approach, 2 (18.2%) were a combined endonasal and SO approach for giant adenomas, 2 (18.2%) were first-time SO approaches for exophytic adenomas with predominant lateral and supradiaphragmatic extension, and 1 was for a metastatic pituitary carcinoma that had been previously treated with endonasal and MP approaches.

Heatmap Analysis of Surgical Access

Figures 3 and 4 illustrate the access afforded by the SO and MP approaches for extraaxial and intraaxial tumors, as well as cases that utilized endoscopy. For both tumor subtypes, overall surgical access was greater with the SO route. Specifically, SO access extended along the entire ipsilateral and medial contralateral anterior cranial fossa, parasellar region, ipsilateral sylvian fissure, medial middle cranial fossa, and anterior midbrain. MP access was limited to the ipsilateral middle cranial fossa, sylvian fissure, lateral parasellar region, and posterior aspect of the anterior cranial fossa.

The tumor epicenters were parasellar in 97 (56.1%) SO operations and 13 (41.9%) MP operations ($p = 0.146$). Coronal projection heatmaps demonstrated that parasellar access extended farther superiorly for the SO approach than the MP approach.

The locations of the extraaxial and intraaxial tumors in which endoscopy facilitated additional tumor removal are shown in Fig. 5. For the SO approach, endoscope-assisted tumor removal was performed on 33 (30%) extraaxial tumors that were clustered along the midline cribriform plate and olfactory groove, parasellar area, and sphenoid wing. Pathologies included 24 meningiomas, 3 pituitary adenomas/carcinomas, 2 craniopharyngiomas, 1 schwannoma, 1 sinonasal adenocarcinoma, 1 arachnoid cyst, and 1 epidermoid cyst. For 15 (23.8%) intraaxial tumors, pathology resided in the medial frontal, orbitofrontal, and suprachiasmatic regions and the anterior temporal lobe, including 9 metastases, 5 gliomas, and 1 germinoma. For the MP route, endoscope-assisted tumor removal was performed on 3 (14.3%) extraaxial tumors, including 2 meningiomas and 1 schwannoma, and 2 (20%) intraaxial tumors, which were a metastasis and a glioma.

Utility of Endoscopy and Tumor Resection Rates

Endoscopy was utilized more frequently in SO than MP craniotomies (98 [56.6%] vs 7 [22.6%], $p < 0.001$) and resulted in further tumor removal in 48 (49%) and 5 (71.4%) cases ($p = 0.251$), respectively (Table 1). There were no differences in the rates of GTR, NTR, and STR between the SO and MP groups ($p = 0.877$).

Surgical goals were accomplished in 161/173 (93.1%) SO operations and 30/31 (96.8%) MP operations ($p = 0.384$); 11 of 13 cases in which the surgical goal was not achieved were performed prior to 2015. Of the 12 patients who underwent an SO approach and did not achieve the surgical goal, 11 had intraaxial tumors and 1 had an extraaxial giant pituitary adenoma and had undergone a previous operation. In all but 1 patient with an intraaxial tumor, NTR was achieved with a small remnant that was unintentionally left behind. The 1 patient who underwent an MP operation in which the surgical goal was not achieved had a multifocal glioma; a small remnant was seen on postoperative imaging, resulting in classification of NTR.

Of the 53 (30.6%) operations in the SO cohort that achieved STR, 50 (94.3%) met the surgical goals. Within this subgroup, 26 (52%) had previous surgery and/or radiation therapy. Common reasons for STR as the surgical goal included tumor adherence to critical neurovascular structures, planned debulking or cyst fenestration, tumor invasion into the cavernous sinus or Meckel's cave, eloquent tumor location, and planned biopsy.

Ten (32.3%) MP operations achieved STR, which was consistent with the surgical goals. Of these operations, 3 were planned biopsies, 3 were performed to treat invasion

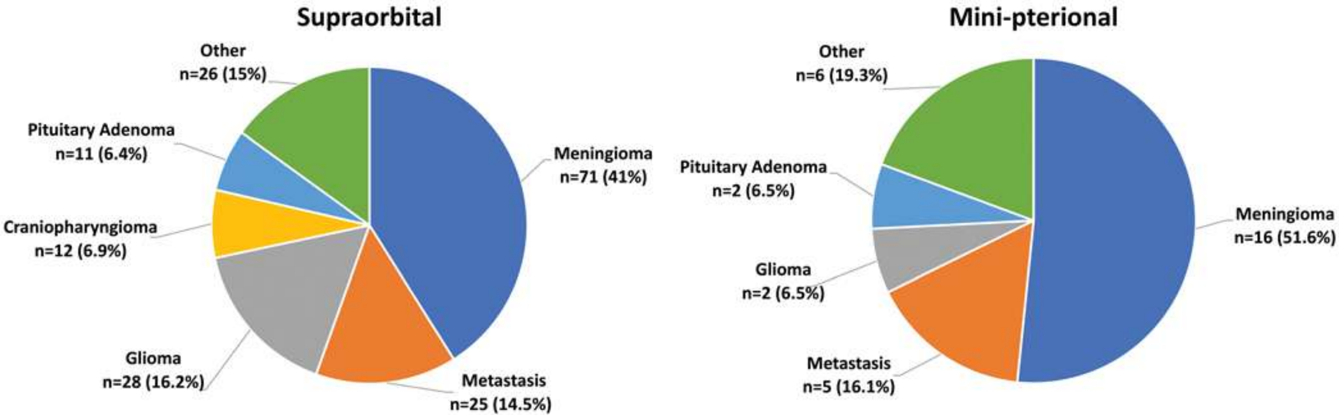

FIG. 2. Tumor pathologies approached using the SO and MP craniotomies. Meningiomas, gliomas, and metastases were the most common tumor types for both approaches. Craniopharyngiomas and exophytic pituitary adenomas were relatively common tumors for the SO route. For SO craniotomy, the other category included solitary fibrous tumor, arachnoid cyst, germinoma, schwannoma, cavernous malformation, radiation necrosis, abscess, dermoid cyst, epidermoid cyst, epithelioid hemangioendothelioma, lymphoma, Rathke's cleft cyst, sinonasal carcinoma, chordoma, and neuroendocrine carcinoma. For MP craniotomy, the other tumor types included solitary fibrous tumor, schwannoma, cavernous malformation, low-grade fibroblastic proliferation, and lymphoma.

into the cavernous sinus or Meckel's cave, 2 were performed to treat tumor extension into the orbital intraconal space, 1 was performed to treat a solitary fibrous tumor that was adhering to the internal carotid and middle cerebral arteries, and 1 was a planned two-stage procedure.

Of 77 (44.5%) operations with a preoperative goal of GTR that were performed with the SO approach, there was no significant difference between the proportion of operations that achieved GTR with only a microscope (24/31 [77.4%]) and the proportion of operations that achieved GTR with endoscope assistance (40/46 [87%]) ($p = 0.273$). In 11 (35.5%) MP cases with a goal of GTR, no difference

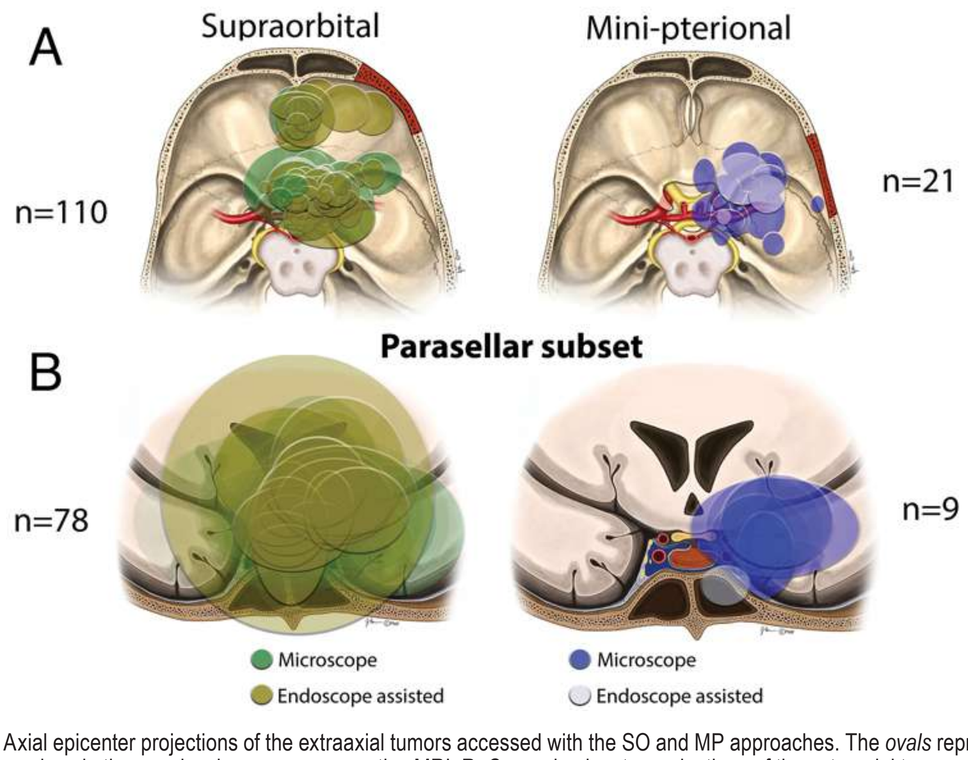

FIG. 3. A: Axial epicenter projections of the extraaxial tumors accessed with the SO and MP approaches. The *ovals* represent the largest dimensions in the x and y planes on preoperative MRI. **B:** Coronal epicenter projections of the extraaxial tumors located within the parasellar region, defined as having an axial epicenter lying within 1 cm of an anterior or posterior clinoid process. *Differential shading* is used to highlight microscopic resection alone versus endoscope-assisted visualization. Magnification is ×2 relative to the axial heatmap. Illustration by Josh Emerson. Copyright Pacific Neuroscience Institute Foundation. Published with permission.

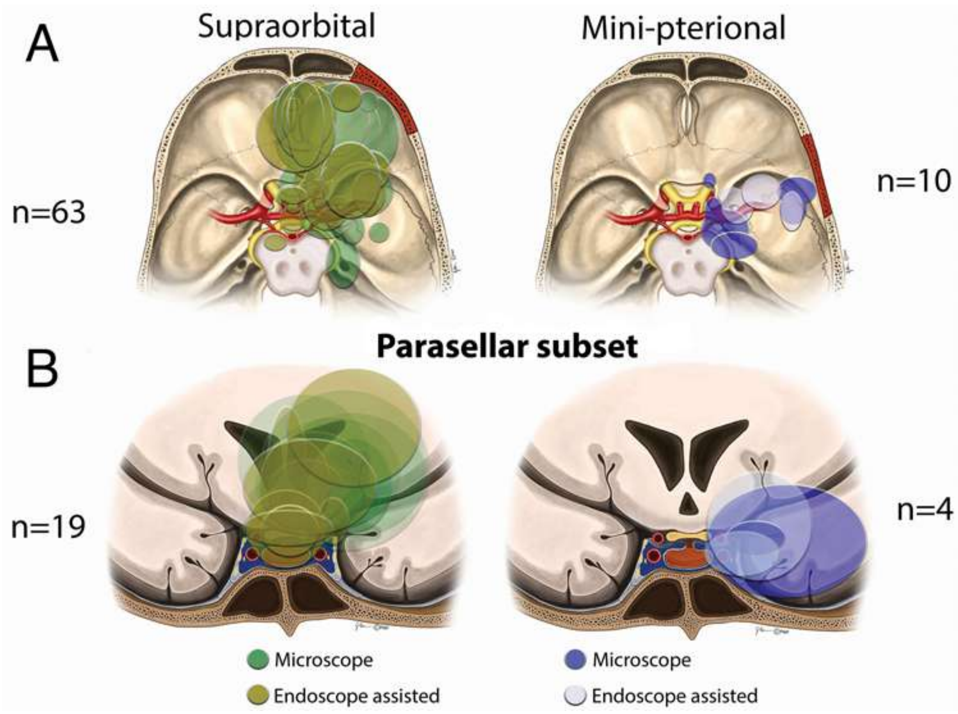

FIG. 4. A: Axial epicenter projections of the intraaxial tumors accessed with the SO and MP approaches. *Ovals* represent the largest dimensions in the x and y planes on preoperative MRI. **B:** Coronal epicenter projections of the intraaxial tumors located within the parasellar region, defined as having an axial epicenter lying within 1 cm of an anterior or posterior clinoid process. *Differential shading* is used to highlight microscopic resection alone versus endoscopic visualization. Magnification is ×2 relative to the axial heatmap. Illustration by Josh Emerson. Copyright Pacific Neuroscience Institute Foundation. Published with permission.

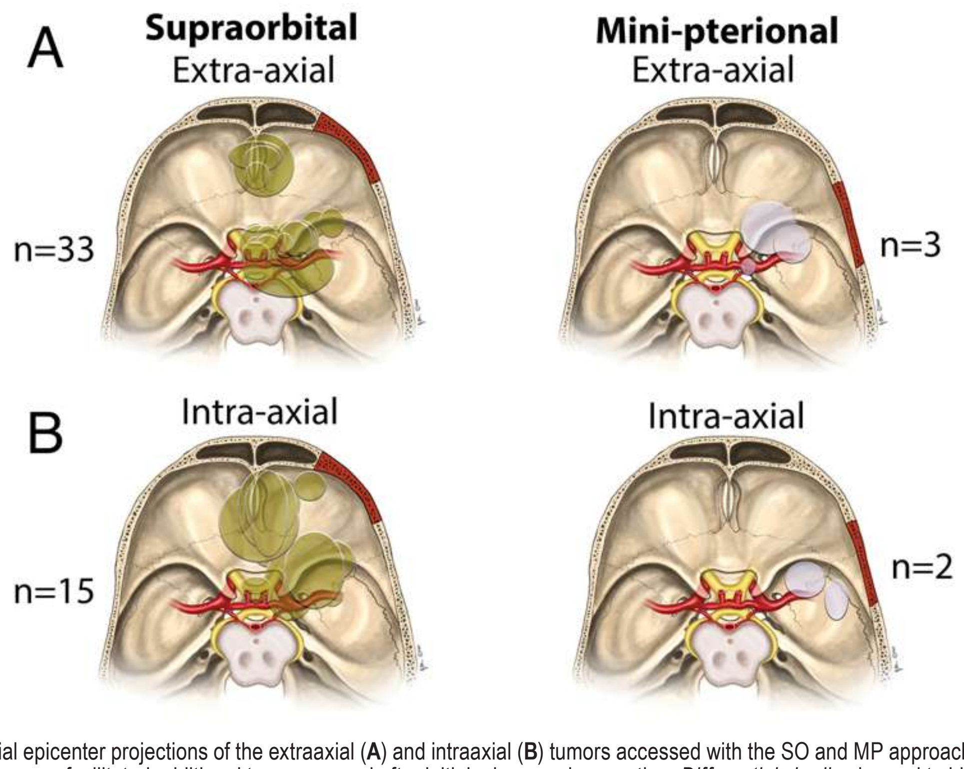

FIG. 5. Axial epicenter projections of the extraaxial (**A**) and intraaxial (**B**) tumors accessed with the SO and MP approaches in which endoscopy facilitated additional tumor removal after initial microscopic resection. *Differential shading* is used to highlight microscopic resection alone versus endoscopic visualization. Illustration by Josh Emerson. Copyright Pacific Neuroscience Institute Foundation. Published with permission.

in GTR was observed between operations that achieved GTR with only microscopy (6/7 [85.7%]) and those that achieved GTR with endoscope assistance (4/4 [100%]) (p = 0.428).

Complications and LOS

Operative complications were classified as major and minor (Table 2). There were no deaths within 30 days. In the SO cohort, 11 (6.4%) operations resulted in a major complication and 5 (2.9%) resulted in a minor complication. In the MP cohort, 1 (3.2%) procedure resulted in a major complication and none resulted in a minor complication. Of 12 major complications, 5/12 were in patients who underwent prior surgery and 6 (3.2%) resulted in permanent neurological deficits.

Of the patients with major complications in the SO group, 1 (0.6%) had undergone multiple previous operations for a craniopharyngioma and had a postoperative CSF leak from a frontal sinus defect that was uneventfully repaired. Four (2.5%) patients had symptomatic strokes, 2 of whom fully recovered during follow-up. Three (1.9%) patients had symptomatic postoperative hematomas, including 2 who returned to the operating room for evacuation. Two (1.3%) patients had deterioration of vision and 1 (0.6%) had a new permanent cranial nerve III deficit after resection of an oculomotor nerve schwannoma. One (3.3%) patient who underwent the MP approach underwent resection of a right-sided temporal lobe metastasis unrelated to the optic apparatus and had postoperative optic neuropathy of unknown etiology. There was 1 minor wound infection (0.5%) in the cohort that was treated with oral antibiotics and debridement.

The median LOS of the SO cohort was 3 days compared with 2 days for the MP cohort (p = 0.03), with 155 (89.6%) SO procedures and 27 (87.1%) MP procedures resulting in discharge to home (p = 0.674). The overall median LOS decreased from 6 days in 2007–2008 to 2 days in 2020. For the last 2 years of the study, the median LOS was 2 days for both approaches. The median LOS was 6 days for the 12 patients with major complications versus 3 days for the 192 patients without major complications (p < 0.001).

Case Examples

Figure 6 and Video 1 show 2 examples of middle fossa meningiomas: a medial tentorial meningioma (Fig. 6A) was removed via an SO approach, and a sphenoid wing meningioma (Fig. 6B) was removed via an MP approach. Both procedures used endoscope-assisted tumor resection.

Discussion

Overview

This series compared the clinical utility and anatomical reach of the SO and MP approaches to brain tumors. Our results indicated that both approaches are most frequently used for meningiomas, gliomas, and metastases, whereas the SO route was also frequently used for recurrent and/or cystic craniopharyngiomas and recurrent and/or exophytic pituitary adenomas; however, a variety of other tumors are accessible with both routes. Used in almost 85% of cases, SO craniotomy was more versatile for both intraaxial and extraaxial tumors and afforded access to a larger intracranial volume than the MP route, despite its shorter incision and smaller craniotomy surface area.

TABLE 2. Major and minor operative complications of the patients who underwent SO and MP approaches

Complication	SO Approach (n = 173)	MP Approach (n = 31)
Major complications	11	1
Mortality	0	0
Stroke*	4	0
Hematoma†	3	0
CSF leak	1	0
Meningitis	0	0
Worsening vision	2	1
New cranial nerve deficit	1	0
Minor complications	5	0
Wound infection	1	0
Deep vein thrombosis	2	0
Urinary tract infection	1	0
Temporalis atrophy	1	0

Values are shown as number of patients.
* Defined as symptomatic stroke. Two patients fully recovered.
† Defined as symptomatic hemorrhage. Two patients required evacuation.

Anatomical Reach of the SO Route Versus That of the MP Route

As shown in Figs. 3 and 4, the SO route provides wide access to both the ipsilateral and medial aspects of the contralateral anterior cranial fossae, parasellar and suprasellar regions, sylvian fissure, anteromedial temporal lobe, medial sphenoid wing, medial tentorium, and anterior midbrain. This extended reach is reflected in our utilization of the SO approach more than 4 times as often as the MP craniotomy. In contrast, the MP route is used predominantly for lesions in the ipsilateral middle cranial fossa, including locations along the entire sphenoid wing, anterior temporal lobe, sylvian fissure, lateral parasellar and perichiasmatic spaces, lateral cavernous sinus, lateral orbit, and posterior aspect of the anterior cranial fossa. Unlike the SO route, the MP route provides minimal access to the contralateral side.

Clinical Use of SO Versus MP Routes Compared With Anatomical Studies

Although our more frequent use of the SO route over the MP route may be in part related to surgeon preference, our experience is similar to those of others. Rychen et al. recently published a systematic review of SO and MP approaches.[15] The 69 articles on the SO approach and 22 on the MP approach included 4702 (83%) and 952 (17%) patients, respectively. Of all SO and MP approaches, 75% and 97% of lesions were aneurysms, respectively. Notably, in these articles, brain tumors comprised only 1137 (21.9%) and 26 (2.5%) of lesions treated with the SO and MP approaches, respectively, with the absolute numbers of

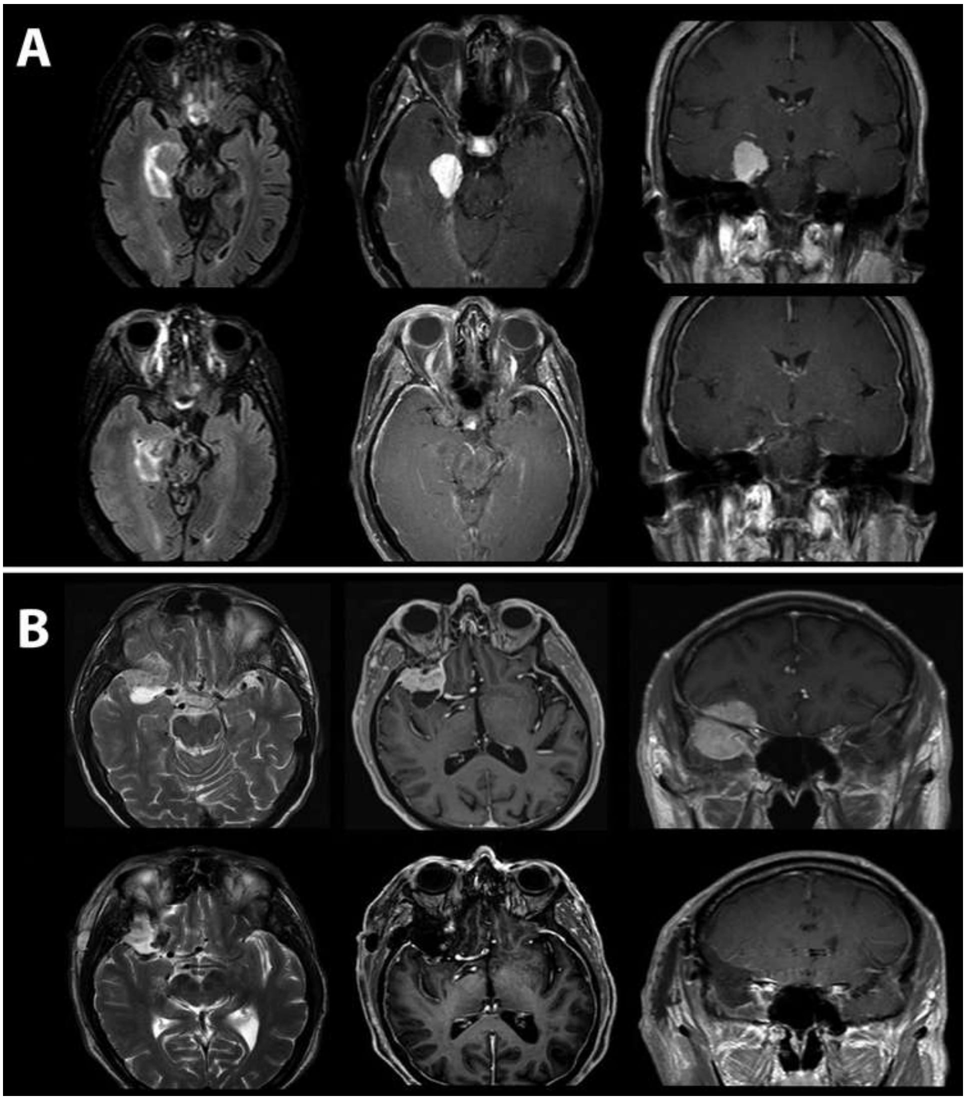

FIG. 6. A: Illustrative case of an SO craniotomy performed on a 70-year-old female with a right-sided tentorial incisura meningioma who presented with temporal lobe seizures. Preoperative MR images with gadolinium enhancement demonstrate the tumor arising from the midportion of the incisura at the level of the cerebral peduncle and exerting mass effect on the medial temporal lobe with surrounding vasogenic edema (*top row*). A right-sided SO approach was performed and achieved GTR with no increased FLAIR signal and no complications (*bottom row*). In this case, endoscopy was critical to accessing the anteroinferior tumor below the plane of the anterior cranial fossa, which is a blind spot of the SO approach. An MP approach would have required significant temporal lobe retraction to reach this tumor. **B:** Illustrative case of an MP craniotomy performed on a 77-year-old man with a right-sided medial sphenoid ridge meningioma. Preoperative MR images with gadolinium enhancement demonstrate extension into both the anterior and middle cranial fossae with a posterior cystic component and moderate vasogenic edema (*top row*). By using an MP approach, GTR was achieved without new FLAIR signal changes and no complications (*bottom row*). Endoscopy was used to better visualize resection of the most anterior part of the tumor in the anterior cranial fossa and sphenoid wing. An SO approach would not have been able to reach the tumor along the middle sphenoid wing and temporal pole region.

brain tumor patients being far greater in the SO cohorts. These numbers suggest that the SO approach is used far more frequently than the MP approach for brain tumors, which is in part likely related to the more expansive anatomical access through the eyebrow route and where the preponderance of brain tumor pathology arises.

The greater use of the SO route in the clinical management of brain tumors provides an interesting contrast to several recent microscope-based cadaveric studies. Martínez-Pérez et al. showed that, for aneurysm surgery, both the area of exposure and surgical freedom afforded by the MP approach were statistically greater than those provided by SO craniotomy.[19] However, in their analysis, SO craniotomy did not extend laterally to the superior temporal line. Another study by the same group compared the MP approach with an "extended SO" approach with a burr hole at the keyhole; this modification is essentially the same as the skin incision and craniotomy used by us.[6] They found equivalent surgical freedom and greater frontal exposure with SO craniotomy, but greater temporal exposure with the MP approach.[20] Similarly, Jägersberg et al. published a target-specific maneuverability evaluation of several keyhole alternatives (SO, lateral SO, and MP approaches) and provided comparisons with traditional pterional craniotomy.[21] They demonstrated deep exposure with all three keyhole approaches that was similar to that provided with a traditional pterional approach, but they also found that MP craniotomy had superior maneuverability relative to other keyhole approaches. This finding was largely due to greater maneuverability with MP craniotomy for accessing perisylvian targets, whereas parasellar targets had similar scores among all approaches. Notably, none of these cadaveric studies assessed the expanded visualization provided with endoscopy.

Utility of Endoscopy

Endoscopy was used in 51% of all operations, but it was used more often in SO procedures after initial microscopic tumor resection and was associated with additional tumor removal in nearly 50% of those cases; a far greater number of SO procedures utilized endoscopy than MP procedures (Figs. 3–5). The regional utility of endoscopy in SO and MP approaches, as highlighted in Fig. 5, demonstrates that most extraaxial tumors that benefitted from endoscopic visualization were in either the olfactory groove/cribriform plate area or parasellar or sphenoid wing region, and that most intraaxial tumors that benefitted from endoscopy were in the medial or orbitofrontal frontal lobe regions or anterior temporal lobe. In general, these locations are either relatively far from the craniotomy site or at an angle that requires endoscopic visualization beyond that afforded by the microscope. Importantly, these regions can be endoscopically visualized by using two-handed microsurgical dissection without brain retraction. The more limited utility of endoscopy in the MP approach may be in part related to the fact that the distance traveled from the craniotomy site is short (compared with that for SO craniotomy) and that there are fewer regions that require angled visualization for tumor access.

The utility of endoscopy has been shown in multiple prior publications, including our recent report on the SO route.[4,6,13,14,28,29] For the SO approach, endoscopy improves visualization of several blind spots, including the cribriform plate, olfactory groove regions, medial side and undersurface of the ipsilateral optic nerve, sella, and the region over the sphenoid ridge that extends into the medial aspect of the middle cranial fossa (Fig. 6).[6] Endoscopy also affords another vantage point for determining if there is residual tumor, as well as for determining if the tumor can be safely resected or if it is too adherent to the cranial nerves, critical blood vessels, or brain itself.

Specific Tumor Types and the Optimal Surgical Approach

For tumors limited to the middle fossa and sphenoid wing, an MP approach is preferred. For tumors of the anterior cranial fossa with lateral extension beyond the optic nerves and supraclinoid carotid arteries, an SO approach is chosen. For midline skull base pathology, an endonasal route can often be considered. For example, we remove a majority (60%) of tuberculum sellae meningiomas via the endonasal transsellar transplanum route, especially if there is medial optic canal invasion; however, we use the SO route for larger tumors (typically > 3 cm) and those with lateral extensions.[16,18] We use the SO route for most clinoidal and olfactory groove meningiomas, whereas sphenoid wing meningiomas are generally approached with an MP route.[16] Although the endonasal transplanum route can be used to access olfactory groove meningiomas, it virtually guarantees anosmia and thus is rarely used in our practice to access such meningiomas. Meningiomas of the medial sphenoid wing and medial anterior tentorium that do not extend too far below the sphenoid ridge can be removed effectively with the SO route; notably angled endoscopy is essential to fully visualize and remove these tumors, as shown in the case example (Fig. 6A).

For gliomas and metastases, the decision to use the SO versus MP route is typically obvious on the basis of the tumor location and the long axis of the tumor; however, either route can be used for some perisylvian lesions. In our experience, over 80% of craniopharyngiomas can be removed with an endoscopic endonasal approach given their frequent retrochiasmal location. In contrast, the SO route can be used for recurrent craniopharyngiomas, particularly those that extend superior or lateral to the chiasm; less often, MP routes can be used.[5,6,10,22,30] The SO route is an effective approach for the rare recurrent pituitary adenoma or carcinoma that grows laterally or anteriorly to the optic apparatus, and we used this route to treat 10 cases.

The transorbital endoscopic approach is increasingly used for middle and anterior cranial fossa pathology and can provide excellent access to orbital and medial sphenoid wing tumors and the lateral parasellar and cavernous sinus regions; however, we have limited experience with this approach.[31–34] Many of the tumors that we approached with an MP approach in this series, and some that were approached with an SO route, could likely have been removed through a transorbital route.

Clinical Outcomes, Functional Recovery, and Cosmesis

Clinical outcomes were comparable between the SO and MP approaches. Extent of resection was similar between approaches and the surgical goal was achieved in 92% of operations, similar to other reports.[5,13,15,28,30,35–37] Notably, 11 of 13 cases in which the surgical goal was not achieved occurred in the first half of the series. Complication rates were generally low, with 3.4% of the cohort sustaining new permanent neurological deficits and 0.5% developing an infection. LOS was short, decreasing to 2 days in the last 2 years of the study for both the SO and MP cohorts.

As recently published, cosmesis and functional recovery are generally excellent for patients who undergo the SO route, with frontalis palsy, forehead numbness, and temporalis atrophy being rare permanent events.[6] Similarly, our patients who undergo MP craniotomy have been pleased with their recovery in general. We attribute these excellent outcomes and infection rate of < 1% to minimal or no use of monopolar cautery when dissecting the scalp, fascia, and muscle; frequent saline irrigation to avoid tissue desiccation; regular rotation of skin hooks to avoid retraction injury; and meticulous scalp closure.

Study Limitations

This study was limited by its retrospective nature and selection bias for one approach over the other. The decision-making for each case was based on surgeon experience, tumor location, and surgical goals. The study population was also heterogenous, with a wide range of tumor types. An additional limitation is the lack of a comparison with other approaches, including endoscopic endonasal, endoscopic transorbital, and traditional pterional routes. Thus, no strong conclusions can be drawn regarding the superiority of one approach over the other. Another limitation is the potentially limited generalizability of our findings because we receive many referrals for parasellar tumors. The distribution of tumor subtypes at other practices may be different, in which case the ratio of SO to MP approaches may differ from ours.

Conclusions

SO and MP craniotomies are complementary keyhole approaches for intraaxial and extraaxial brain tumors. The regions that can be accessed with each approach, although specific, have considerable overlap in the parasellar and perisylvian regions. However, our experience suggests the SO craniotomy has far greater reach and more versatility than the MP route. Endoscopy appears to facilitate visualization of anatomical blind spots and better illuminates neurovascular relationships with tumors, further increasing the utility of both approaches.

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References

1. Garrett M, Consiglieri G, Nakaji P. Transcranial minimally invasive neurosurgery for tumors. *Neurosurg Clin N Am*. 2010;21(4):595-605.
2. Lan Q, Sughrue M, Hopf NJ, Mori K, Park J, Andrade-Barazarte H, et al. International expert consensus statement about methods and indications for keyhole microneurosurgery from International Society on Minimally Invasive Neurosurgery. *Neurosurg Rev*. 2019;44(1):1-17.
3. Reisch R, Stadie A, Kockro RA, Hopf N. The keyhole concept in neurosurgery. *World Neurosurg*. 2013;79(2 Suppl):S17.e9-S17.e13.
4. Igressa A, Pechlivanis I, Weber F, Mahvash M, Ayyad A, Boutarbouch M, et al. Endoscope-assisted keyhole surgery via an eyebrow incision for removal of large meningiomas of the anterior and middle cranial fossa. *Clin Neurol Neurosurg*. 2015;129:27-33.
5. Reisch R, Perneczky A. Ten-year experience with the supraorbital subfrontal approach through an eyebrow skin incision. *Neurosurgery*. 2005;57(4 suppl):242-255.
6. Ansari SF, Eisenberg A, Rodriguez A, Barkhoudarian G, Kelly DF. The supraorbital eyebrow craniotomy for intra- and extra-axial brain tumors: a single-center series and technique modification. *Oper Neurosurg (Hagerstown)*. 2020;opaa217.
7. Figueiredo EG, Deshmukh P, Nakaji P, Crusius MU, Crawford N, Spetzler RF, et al. The minipterional craniotomy: technical description and anatomic assessment. *Neurosurgery*. 2007;61(5)(suppl 2):256-265.
8. Wilson DH. Limited exposure in cerebral surgery. Technical note. *J Neurosurg*. 1971;34(1):102-106.
9. Teo C. The concept of minimally invasive neurosurgery. *Neurosurg Clin N Am*. 2010;21(4):583-584.
10. Wilson DA, Duong H, Teo C, Kelly DF. The supraorbital endoscopic approach for tumors. *World Neurosurg*. 2014;82(6 suppl):S72-S80.
11. Kelly DF, Griffiths CF, Takasumi Y, Rhee J, Barkhoudarian G, Krauss HR. Role of endoscopic skull base and keyhole surgery for pituitary and parasellar tumors impacting vision. *J Neuroophthalmol*. 2015;35(4):335-341.
12. Reisch R, Perneczky A, Filippi R. Surgical technique of the supraorbital key-hole craniotomy. *Surg Neurol*. 2003;59(3):223-227.
13. Perneczky A, Fries G. Endoscope-assisted brain surgery: part 1—evolution, basic concept, and current technique. *Neurosurgery*. 1998;42(2):219-225.
14. de Divitiis E, de Divitiis O, Elefante A. Supraorbital craniotomy: pro and cons of endoscopic assistance. *World Neurosurg*. 2014;82(1-2):e93-e96.
15. Rychen J, Croci D, Roethlisberger M, Nossek E, Potts M, Radovanovic I, et al. Minimally invasive alternative approaches to pterional craniotomy: a systematic review of the literature. *World Neurosurg*. 2018;113:163-179.
16. Thakur JD, Mallari RJ, Corlin A, Yawitz S, Huang W, Eisenberg A, et al. Minimally invasive surgical treatment of intracranial meningiomas in elderly patients (≥ 65 years): outcomes, readmissions, and tumor control. *Neurosurg Focus*. 2020;49(4):E17.
17. Burks JD, Conner AK, Bonney PA, Archer JB, Christensen B, Smith J, et al. Management of intracranial meningiomas using keyhole techniques. *Cureus*. 2016;8(4):e588.
18. Mallari RJ, Thakur JD, Rhee J, Eisenberg A, Krauss H, Griffiths C, et al. Endoscopic endonasal and supraorbital removal of tuberculum sellae meningiomas: anatomical guides and operative nuances for keyhole approach selection. *Oper Neurosurg (Hagerstown)*. 2021;21(2):E71-E81.
19. Martínez-Pérez R, Albonette-Felicio T, Hardesty DA, Prevedello DM. Comparative anatomical analysis between the minipterional and supraorbital approaches. *J Neurosurg*. 2020;134(3):1276-1284.
20. Martinez-Perez R, Beer-Furlan A, Albonette-Felicio T, Hardesty DA, Mohyeldin A, Hara T, et al. The transsylvian corridor through minimally invasive transcranial approaches: a comparative anatomical study. *Neurosurg Rev*. Published online November 18, 2020. doi:10.1007/s10143-020-01439-4
21. Jägersberg M, Brodard J, Qiu J, Mansouri A, Doglietto F, Gentili F, et al. Quantification of working volumes, exposure, and target-specific maneuverability of the pterional craniotomy and its minimally invasive variants. *World Neurosurg*. 2017;101:710-717.e2.
22. McLaughlin N, Ditzel Filho LF, Shahlaie K, Solari D, Kassam AB, Kelly DF. The supraorbital approach for recurrent or residual suprasellar tumors. *Minim Invasive Neurosurg*. 2011;54(4):155-161.
23. Louis RG, Eisenberg A, Barkhoudarian G, Griffiths C, Kelly DF. Evolution of minimally invasive approaches to the sella and parasellar region. *Int Arch Otorhinolaryngol*. 2014;18(2)(suppl 2):S136-S148.
24. Ditzel Filho LF, McLaughlin N, Bresson D, Solari D, Kassam AB, Kelly DF. Supraorbital eyebrow craniotomy for removal of intraaxial frontal brain tumors: a technical note. *World Neurosurg*. 2014;81(2):348-356.
25. Ishii K, Makita T, Yamashita H, Matsunaga S, Akiyama D, Toba K, et al. Total intravenous anesthesia with propofol is associated with a lower rate of postoperative delirium in comparison with sevoflurane anesthesia in elderly patients. *J Clin Anesth*. 2016;33:428-431.
26. Falco J, Cavallo C, Vetrano IG, de Laurentis C, Siozos L, Schiariti M, et al. Fluorescein application in cranial and spinal tumors enhancing at preoperative MRI and operated with

a dedicated filter on the surgical microscope: preliminary results in 279 patients enrolled in the FLUOCERTUM Prospective Study. *Front Surg*. 2019;6:49.
27. Cavallo C, De Laurentis C, Vetrano IG, Falco J, Broggi M, Schiariti M, et al. The utilization of fluorescein in brain tumor surgery: a systematic review. *J Neurosurg Sci*. 2018; 62(6):690-703.
28. Marx S, Clemens S, Schroeder HWS. The value of endoscope assistance during transcranial surgery for tuberculum sellae meningiomas. *J Neurosurg*. 2018;128(1):32-39.
29. Wilson DA, Duong H, Teo C, Kelly DF. The supraorbital endoscopic approach for tumors. *World Neurosurg*. 2014; 82(1-2):e243-e256.
30. Fatemi N, Dusick JR, de Paiva Neto MA, Malkasian D, Kelly DF. Endonasal versus supraorbital keyhole removal of craniopharyngiomas and tuberculum sellae meningiomas. *Neurosurgery*. 2009;64(5)(suppl 2):269-286.
31. Ramakrishna R, Kim LJ, Bly RA, Moe K, Ferreira M Jr. Transorbital neuroendoscopic surgery for the treatment of skull base lesions. *J Clin Neurosci*. 2016;24:99-104.
32. Vural A, Carobbio ALC, Ferrari M, Rampinelli V, Schreiber A, Mattavelli D, et al. Transorbital endoscopic approaches to the skull base: a systematic literature review and anatomical description. *Neurosurg Rev*. Published online January 22, 2021. doi:10.1007/s10143-020-01470-5
33. Miller C, Bly R, Moe KS. Endoscopic orbital and periorbital approaches in minimally disruptive skull base surgery. *J Neurol Surg B Skull Base*. 2020;81(4):459-471.
34. Noiphithak R, Yanez-Siller JC, Revuelta Barbero JM, Cho RI, Otto BA, Carrau RL, Prevedello DM. Comparative analysis of the exposure and surgical freedom of the endoscopic extended minipterional craniotomy and the transorbital endoscopic approach to the anterior and middle cranial fossae. *Oper Neurosurg (Hagerstown)*. 2019;17(2):174-181.
35. Sánchez-Vázquez MA, Barrera-Calatayud P, Mejia-Villela M, Palma-Silva JF, Juan-Carachure I, Gomez-Aguilar JM, Sanchez-Herrera F. Transciliary subfrontal craniotomy for anterior skull base lesions. Technical note. *J Neurosurg*. 1999;91(5):892-896.
36. Tullos HJ, Conner AK, Baker CM, Briggs RG, Burks JD, Glenn CA, et al. Mini-pterional craniotomy for resection of parasellar meningiomas. *World Neurosurg*. 2018;117:e637-e644.
37. Park HH, Yoo J, Yun IS, Hong CK. Comparative analysis of endoscopic transorbital approach and extended mini-pterional approach for sphenoid wing meningiomas with osseous involvement: preliminary surgical results. *World Neurosurg*. 2020;139:e1-e12.

Disclosures

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Author Contributions

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Supplemental Information

Videos

Video 1. https://vimeo.com/569788763.

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