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Surgical management of tumors involving Meckel's cave and cavernous sinus: role of an extended middle fossa and lateral sphenoidectomy approach

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Abstract

Objective—To study the indications and outcomes of lateral sphenoidectomy as part of a combined skull base approach in the treatment of tumors involving Meckel's cave (MC) and cavernous sinus (CS).

Study design—Retrospective case series.

Setting—Tertiary referral center

Patients—Twenty-two consecutive patients (mean age: 45 years, range: 16 – 76) who underwent transzygomatic, extended middle fossa approaches for tumors involving MC and CS.

Interventions—Surgical access to MC and CS was achieved via extended middle fossa, trans-clinoid approach. Lateral sphenoidectomy was defined as drill-out of the greater sphenoid wing lateral to foramen rotundum and ovale, decompression of superior orbital fissure, and removal of anterior clinoid process. Reconstruction was achieved using combination of autologous and synthetic materials. Eleven patients (50%) received adjuvant radiation.

Main outcome measures and results—Tumor pathologies included meningioma (16 patients), epidermoid cyst (2), trigeminal schwannoma (2), invasive pituitary adenoma (1), and chondrosarcoma (1). Mean (range) pre-operative tumor size was 4.0cm (1.3 – 9). Mean (range) length of follow-up was 4 years (range 0.1 – 10). Overall tumor control and gross total resection were achieved in 95% and 23% of patients, respectively. Lateral sphenoidectomy was performed in 16 patients (73%) for enhanced surgical access and/or tumor extension to the infratemporal fossa (6 patients). Post-operatively, cranial nerve deficits occurred in 12 (55%) patients (V – 9 patients; III, IV, or VI – 4; VII – 2; VIII – 2). CSF leak and hydrocephalus occurred in 2 and 4 patients, respectively.

Conclusion—In combination with middle fossa-based approaches to tumors involving MC and CS, lateral sphenoidectomy may play a viable role in tumor access and control.

Keywords

Meckel's cave; cavernous sinus; meningioma; schwannoma; lateral sphenoidectomy; middle fossa; greater sphenoid wing

Introduction

Tumors involving the cavernous sinus (CS) and Meckel's cave (MC) continue to pose a formidable challenge for the modern skull base surgeon due to the confluence of critical neurovascular structures surrounded by complex bony topography in these closely associated anatomical areas. Many corridors of access, both extra- and intradural, have been developed based on the specific location of the tumor and its extent of involvement of adjacent structures (1,2). These include frontotemporal (3), anterolateral (1), and lateral (middle fossa) approaches (4), with variations in craniotomy and intracranial bone removal based on specific tumor characteristics. More recently, endoscopic (5–7) and radiosurgical (8) strategies have also emerged as promising modes of therapy for certain tumors. Common to any open surgical approach is the need to gain the most direct route of access to the lesion, provide the exposure necessary to maximize tumor resection, minimize brain retraction, and afford vascular control. For tumors involving MC and the lateral CS, extradural middle fossa approaches have been developed (4,9). Significant tumor extension into the posterior fossa may also necessitate combined posterior and middle fossa approaches (10).

The EMCF approach (11–13) allows for direct, extradural access to the tumor, wide exposure of the skull base including anterior cerebellopontine angle (CPA) when performed in combination with anterior petrosectomy (11,14), reduced temporal lobe retraction by removal of middle fossa bone, facial nerve and hearing preservation, and proximal control of petrous carotid if necessary. EMCF approach alone however, may not provide adequate exposure of lesions in MC and CS. Al-Mefty *et al.* (15) first described a series of patients with trigeminal schwannomas of MC that were surgically resected with variable removal of bone around superior orbital fissure, foramen rotundum, and foramen ovale to allow tumor extirpation. In this study, we investigate the surgical treatment and outcomes in a series of patients with pathologies involving the CS and MC treated at a tertiary referral center using an EMCF approach to access the CS. Specifically, we explore the indications and safety of a lateral sphenoidectomy (LS), defined as wide removal of skull base bone lateral to foramen rotundum and ovale, decompression of superior orbital fissure, and removal of the anterior clinoid process, as a component of the EMCF approach in a subset of patients to help access tumors in CS and MC.

Materials and Methods

Approval for this retrospective study was obtained from the University of Iowa Institutional Review Board. Inclusion criteria were patients who presented with tumors involving the CS and/or MC and underwent up-front surgical resection via a predominantly middle fossa approach with or without lateral sphenoidectomy between 2006 and 2016. This time range was chosen to limit the search to cases performed by the senior surgeons of this study. Patients who underwent combined middle and posterior fossa approaches (e.g. transpetrosal)

were excluded from analysis as these patients tended to have large petroclival meningiomas where the CS was not a focus of resection. The decision to perform LS as a component of the surgical approach was made preoperatively by the surgical team based on the specific tumor characteristics of each patient.

Based on review of available medical records, relevant clinical data, including demographic, radiographic, pathologic, audiometric data, and postoperative complications were collected and compiled in a database. The index surgery was defined as the first operation performed by our team using the approach under investigation for a particular patient. Available imaging studies and radiologic reports were individually reviewed. Since many lesions in the anatomic area of study are irregularly shaped, the largest distance in any dimension immediately prior to the index surgery was used as the preoperative lesion size. For this review the preoperative imaging for one patient was not available. Facial nerve function was graded using the House-Brackmann (HB) scale. Extent of resection was determined based on analysis of pre- and postoperative imaging. Tumor control was defined as absence of tumor growth on imaging at most recent follow-up. Gross total resection (GTR) was defined as no evidence of residual tumor on imaging, near total resection (NTR) as when residual tumor measures 5mm or less in all dimensions, and subtotal resection (STR) as residual tumor measuring more than 5mm in any dimension. This classification is similar to that used in grading the extent of resection of other skull base pathologies such as vestibular schwannomas (16). Adjuvant radiation therapy was used when there was clinical (e.g. brain invasion) or pathological (e.g. high grade meningioma) concern for aggressive tumor behavior, or radiographic evidence of tumor regrowth after surgical resection. Fractionated Intensity Modulated Radiation Therapy (IMRT, delivered at a cumulative dose of approximately 60 Gy) was the primary modality used, 2 patients received stereotactic radiosurgery (SRS) at a dose of 13 Gy due to previous radiation therapy.

Surgical technique

An anteriorly based pterional skin incision is made beginning in the temporo-frontal hairline, extending posterior to the pinna, and curving to terminate inferiorly in the preauricular crease, which provides exposure to the lateral orbital rim anteriorly, the zygomatic arch inferiorly, and the petrous ridge posteriorly. The skin flap is then reflected inferiorly from the deep temporalis fascia. An incision is made in the fascia just superior to the temporal fat pad and using a freer elevator, a dissection plane is created deep to the fascia and superficial to the fat pad; dissection proceeds inferiorly until the zygomatic arch is reached. Periosteum is then cleared from the superior and deep surfaces of the zygomatic arch along its full span. An oscillating saw is used to create anterior and posterior osteotomies, which are beveled to allow self-stabilization when replaced. The periosteum of the calvarium is then incised and the temporalis muscle is elevated from its fossa and reflected inferiorly, displacing the osteotomized zygomatic arch inferiorly to allow exposure of the greater wing of the sphenoid.

A temporo-pterional craniotomy is created; anteriorly the craniotomy is drilled to the level of the lateral orbital wall. Posteriorly, the craniotomy reaches to the level of the petrous ridge, joining with an EMCF approach. Similarly, dural elevation is begun along the petrous ridge

and proceeds in a medial and anterior direction to identify the arcuate eminence, greater superficial petrosal nerve, porous acousticus, and anterior petrous ridge. Middle meningeal artery emerging from foramen spinosum is ligated and divided. Once trigeminal ganglion is reached, dural elevation is also begun in the keyhole region and proceeds medially until the orbitomeningeal artery is identified, which is ligated and divided. The dura is then further elevated medially until the superior orbital fissure and CS are identified, as are V2, V3, and their respective foramina. This then provides broad exposure of the middle fossa floor including both the greater wing of the sphenoid and temporal bone (Fig 1A).

Using an otologic drill, LS is then performed by removing the greater wing of the sphenoid including the bone between V1, V2, and V3 to the TMJ laterally to expose the soft tissue of infratemporal fossa (Fig. 1B). Foramen ovale and rotundum are thus decompressed, with up to 270 degrees of bony removal in the anterior, lateral, and posterior directions. After removal of skull base bone, the superior extent of lateral pterygoid plate may be removed with drilling. Based on tumor extent, anterior petrosectomy is typically performed by drilling out Kawase's area (14). The internal auditory canal (IAC) is skeletonized 270° medially and a posterior petrosectomy also performed as needed based on tumor extension. The petrous portion of the carotid artery may be decompressed for vascular control.

As part of the LS technique, decompression of the superior orbital fissure is performed by removing the greater wing of the sphenoid located superiorly, proceeding from lateral to medial. Anterior clinoidectomy is then performed by first hollowing out the anterior clinoid process with a drill, followed by carefully removing the thin eggshell of bone remaining. At this location, the dural reflection comprising the lateral wall of the CS forms medial and lateral leaflets, which can be separated from each other and an intervening dissection plane created (Fig. 1C). Excessive bleeding is seldom encountered and can be controlled with hemostatic agents. The lateral leaflet is then elevated posteriorly. The medial leaflet is not elevated to protect the contents of the superior orbital fissure. If tumor is encountered, it is debulked and removed as dissection proceeds. The nerves of superior orbital fissure can usually be recognized through the medial dural leaflet and the leaflet can be incised parallel to the underlying nerves to allow tumor removal from between the underlying nerves. Microsurgical studies have yielded pre-established entry points into the CS (1,17).

To further aid tumor dissection, the superior petrosal sinus may be ligated and divided using hemoclips, the incisura of the tentorium cerebelli is exposed taking care to identify the fourth cranial nerve as it becomes incorporated into the incisura anteriorly. The tentorium is then divided posterior to the 4th cranial nerve. It is important to carry the tentorial opening cephalad to the temporal lobe dura enhancing exposure to the middle fossa and posterior fossa. These dural openings afford enhanced visualization from the third cranial nerve to the lower cranial nerves.

Reconstruction is customized to each surgical defect. Autologous material is used whenever possible, including combinations of abdominal fat, temporalis muscle, temporalis fascia, and split calvarial bone graft.

Results

Twenty-two consecutive patients were identified who met inclusion and exclusion criteria, and their demographic and clinical characteristics are shown in Table 1. Nineteen (86%) were female. The average age at surgery was 46 years (range, 16 – 76), and the average tumor size was 4.0cm (range, 1.3 – 9). Tumor pathology comprised of meningioma (16 patients), epidermoid cyst (2 patients), trigeminal schwannoma (2 patients), invasive pituitary adenoma (1 patient), and chondrosarcoma (1 patient). Six patients had radiographic evidence of tumor extension into the infratemporal fossa at presentation and 15 patients presented with cranial nerve deficits.

Table 2 shows the clinical details of each study patient. A total of 29 surgical procedures directed at tumor control were performed, including in 2 patients (#2 and #3) where an initial surgery (pterional approach in each) was performed elsewhere. Three patients required more than 1 procedure by our team for tumor control. One patient (#4) with atypical meningioma of CS required a second EMCF approach for tumor recurrence 3 years after initial resection. One patient (#9) with a large epidermoid cyst underwent 2 endonasal endoscopic debridements after initial resection followed by a second EMCF procedure that was successful at achieving GTR. Another patient (#11) with petroclival chondrosarcoma required a follow up endonasal endoscopic resection of residual tumor in CS. Adjuvant radiation was used in 11 patients (fractionated IMRT in 9 patients, SRS in 2 patient).

The treatment characteristics and clinical outcomes of study patients are summarized in Table 3. The mean follow-up length was 4 years (range, 0.1 – 10). Tumor control was achieved in 21 patients (95%). Lateral sphenoidectomy was performed in 16 patients (73%); the indications were direct tumor extension into ITF (6 patients) or enhanced access (10 patients). Figures 2 and 3 show two representative lesions with ITF extension treated with EMCF and LS. CS was opened for tumor dissection in 11 patients. Seven patients required at least partial drill-out of the IAC due to tumor extension. Reconstruction of the skull base was achieved using only fascia or synthetic dural matrix in 6 patients, free graft of fat or muscle in 13 patients, and vascularized tissue flap in 3 patients.

No operative mortality occurred, however 3 patients deceased during the follow-up period. Patient #1 was a 76 year-old female with history of dementia who presented with a large, highly aggressive atypical meningioma (WHO grade II) of GSW invading temporal lobe, CS, ITF, orbit, and paranasal sinuses and underwent surgical resection via an orbitozygomatic craniotomy and MCF/lateral sphenoidectomy approach as well as orbital exenteration, with subtotal tumor resection of >50% of tumor bulk. Adjuvant radiation therapy to 61Gy was administered and tumor control was achieved. She presented with worsening dementia and recurrent falls 1 year after surgery. Normal pressure hydrocephalus was diagnosed and a ventriculoperitoneal shunt (VPS) was placed. Due to worsening dementia she was placed into hospice care 3 years after initial surgery. Patient #7 was a 45 year-old female with a history of resection and radiation for pituitary prolactinoma 17 years prior who presented with aggressive radiation-associated meningioma of GSW invading CS and ITF and underwent transzygomatic, EMCF/lateral sphenoidectomy approach. Postoperatively, all cranial nerves were intact except for V3, which had been sacrificed due

to tumor involvement. Despite achieving NTR except for small residual tumor in the medial CS, rapid recurrence occurred within 1 year of surgery and consequently adjuvant IMRT was administered to 54 Gy. Tumor control was achieved for 4 years before she succumbed to an aggressive recurrence. Patient #21 deceased of metastatic mesothelioma after achieving control of a skull base meningioma.

In the study cohort, postoperative cranial nerve deficits occurred in 12 patients (55%). CN V dysfunction was the most common (9 patients), 6 of whom underwent LS and 4 of whom required sacrifice of a CN V division due to tumor involvement. CN III deficit occurred in 2 patients, IV in 3 patients, and VI in 1 patient. In total, extraocular movement dysfunction occurred in 4 patients, 3 of whom underwent LS to aid tumor dissection in CS and MC. Postoperative facial paresis occurred in 2 patients, both in a delayed manner. Patient #17 presented with meningioma of MC and underwent EMCF approach without LS; the medial IAC was skeletonized. Sudden onset facial paralysis (HB 6) was noted on postoperative day 14. Steroid and antiviral therapy was begun and facial function improved to HB 2. In another patient (#16), facial paresis (HB 3) of uncertain etiology occurred several days postoperatively, after undergoing transzygomatic EMCF/LS approach without IAC drill-out for GSW meningioma.

Preoperatively, American Association for Otolaryngology – Head and Neck Surgery class A hearing on the lesion side was present in 20 patients. Two patients had class D hearing as a consequence of previous surgery to treat a neurofibromatosis type II-associated vestibular schwannoma (patient #8) and a posterior fossa meningioma (patient #21). IAC decompression was performed in 7 patients. Preoperative hearing was maintained in all but 2 patients (#14 and 22). Patient #14 presented with a large meningioma of the cerebellopontine angle (CPA) extending into the IAC and CS. A transzygomatic EMCF with LS approach was performed with skeletonization and tumor dissection of IAC. Intraoperative ABR revealed mild amplitude attenuation. Postoperative audiogram revealed 20dB loss with 84% speech discrimination. Patient #22 presented with a trigeminal schwannoma that eroded through cochlea and consequent hearing loss with tumor removal.

Other complications include cerebrospinal fluid (CSF) leak in 2 patients (both successfully managed with lumbar drain), hydrocephalus requiring ventriculostomy catheter placement in 4 patients (2 patients required conversion to VPS), and isolated postoperative seizure in 2 patients. Hematoma, meningitis, and hardware exposure each occurred in 1 patient. Patient #21 presented with an atypical meningioma of the CPA extending to CS in the context of an aggressive meningioma (WHO grade II) of the posterior fossa and jugular foramen that was treated with 2 previous posterior fossa resections followed by adjuvant radiation. A transzygomatic EMCF/LS approach was performed. His postoperative course was complicated by brain edema requiring craniectomy, meningitis, and seizures requiring ventriculostomy and VPS. He required tracheostomy and feeding tube placement due to exacerbation of multiple lower cranial nerve deficits at baseline. During his VPS placement, omental mesothelioma was detected, from which he deceased approximately 6 months after the index surgery.

Discussion

This retrospective case series investigates the role of LS as a component of an EMCF approach to access tumors in the CS and MC. In addition to facilitating exposure of the CS and infratemporal fossa, a key advantage of removal of the lateral wing of sphenoid is that it provides an inferior corridor for tumor dissection and delivery, thereby limiting superior temporal lobe retraction. It provides broad exposure to the middle fossa skull base while also allowing access to the posterior fossa through an anterior petrosectomy, the infratemporal fossa through an LS, and orbit through decompression of superior orbital fissure and orbitotomy, if needed (2 patients in the present study underwent concurrent orbital exenteration), and even the anterior skull base when combined with an orbitozygomatic or supraorbital craniotomy. These locations are frequently affected by tumor extension from MC and CS. The EMCF/LS approach studied here also allows for hearing and facial nerve preservation for tumors that involve the IAC and/or CPA. As an extradural approach, all drilling is accomplished prior to dural opening. Furthermore, vascular control of the petrous carotid may be obtained if needed.

The tumor control rate and incidence of postoperative complications achieved in this cohort were similar to that achieved in another cohort of patients treated with a similar surgical approach (15). The high tumor control rate achieved in the study by Al-Mefty et al. (15) without the use of adjuvant radiation is likely related to the tumor pathology studied, which comprised solely of trigeminal schwannomas. In contrast, pathologies captured in this study were more heterogeneous and aggressive, including a high proportion of WHO grade II meningiomas. Indeed, the tumor control rate in the present study also compares favorably to the rates of 80 – 95% reported in previous series of GSW meningiomas resected using a variety of approaches (18–21).

Despite differences in pathology however, the incidence of new postoperative cranial nerve deficits of 55% demonstrated in this study is similar to those reported in literature using a similar surgical approach (15), although it is higher than other series studying GSW meningiomas (18,19). The retrospective nature and limited sample size of this study hinder root cause analysis of the reported differences in rates of cranial nerve dysfunction, however several factors may be relevant. Firstly, trigeminal dysfunction reported here included patients with trigeminal schwannomas who required necessary sacrifice of at least one trigeminal division. Secondly, although oculomotor dysfunction is an inherent risk to the treatment of tumors in CS and MC, other components of the approach studied here also may place certain cranial nerves at risk. For instance, the 4 patients who suffered from postoperative deficits in extraocular movement function also required division of the tentorium cerebelli and anterior petrosectomy, which may have placed CNs IV and VI at risk, respectively. Thirdly, tumor dissection within the CS places cranial nerves at elevated risk. Of the 4 patients with oculomotor dysfunction, 3 required opening of the CS for tumor removal. As a consequence of the efficacy of radiotherapy, conservative tumor removal in the CS, or not opening the CS at all, has been increasingly advocated by multiple authors in an effort to minimize morbidity without sacrificing tumor control (20–23). However, several patients in the present study had pathologies incompatible with this strategy, such as radiation-associated meningioma and pituitary adenoma, as well as epidermoid cysts. The

decision of whether to open the CS is individualized to each patient and his/her pathology. We are more likely to elect to open the CS and perform intra-CS tumor removal when the tumor is anticipated to be soft, such as in dermoid/epidermoid or schwannoma. The soft texture of these tumors allows them to be easily aspirated using suction and dissected from cranial nerves and the intracavernous carotid. Meningiomas however may be difficult to dissect without neurovascular injury and therefore risks of intracavernous tumor resection outweigh its benefits.

Other complications revealed in this study, such as CSF leak, hydrocephalus, and seizures, are well known risks of intracranial skull base surgery and have also been reported in other series (18,19). It is interesting to note that in the present study, a lumbar drain was preoperatively placed in only 4 patients, and neither of the 2 patients who experienced postoperative CSF leaks. Despite the proximity of the glenoid fossa and TMJ in an LS approach, malocclusion occurred in only 1 patient (#18) in the present study.

No single surgical approach is able to provide access to all compartments of CS; therefore the therapeutic strategy must be selected based on the specific tumor characteristics of each patient. GTR may not be achievable (or a wise goal) in certain compartments of CS (1,20) and the high tumor control rate demonstrated in this study serves as verification of the utility of incomplete resection in view of minimizing morbidity, especially when coupled with a multidisciplinary treatment paradigm that includes adjuvant radiation and/or complementary surgical approaches, such as endonasal endoscopic resection of the medial CS compartment (patients #9 and 11).

Although heterogeneity in the study cohort, sample size, retrospective nature, and length of follow-up are inherent limitations, this study illustrates LS as a safe and viable tool as part of an EMCF approach in the treatment of CS and MC tumors. The decision to perform LS was at the discretion of the surgical team based on individual tumor characteristics, and this study represents an evolution in technique as LS became increasingly utilized at our center to minimize brain retraction, improve access, and reach disease in the ITF. Indeed, the treatment of complex skull base tumors continues to be predicated on customizing any approach based on the specific tumor and clinical characteristics of each patient. Despite favorable tumor control rates, quality of life and functional status measures were not collected, which are important factors of consideration in evaluating any medical treatment.

Conclusion

EMCF with LS provides is a safe and wide approach to complex lesions of the CS, ITF, CPA in the MC and CS. This study demonstrates the importance of a multidisciplinary team comprised of neurosurgeons, otolaryngologists, radiation oncologists, ophthalmologists, neuroradiologists, and others in the care of patients with skull base tumors.

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Figure 1.

Artist rendering of surgical technique. After a transzygomatic temporo-pterional craniotomy (A, inset) is performed, middle fossa dura is broadly elevated to expose the middle fossa floor and greater sphenoid wing, including superior orbital fissure, anterior clinoid process, foramen rotundum and ovale, and petrous ridge (A). Orbitomeningeal and middle meningeal vessels are ligated and divided. Extradural bone removal is then performed (B) including drill-out of internal auditory canal and Kawase's area in an extended middle fossa approach (red), and a lateral sphenoidectomy (blue) by removing anterior clinoid process and decompression of superior orbital fissure and foramen rotundum and ovale. A plane is then developed between the medial and lateral dural leaflets at superior orbital fissure to access Meckel's cave and lateral cavernous sinus (C). The medial dural leaflet can be incised to allow tumor resection within the lateral cavernous sinus and superior orbital fissure. Illustrations created by, and published with permission from, Cheney Medical Illustration.

Figure 2.

Preoperative axial (A) and coronal (B) contrast-enhanced magnetic resonance imaging of a rapidly growing right trigeminal (V3) schwannoma in a 16 year-old female (#8) with Neurofibromatosis type 2 with concurrent left vestibular schwannoma and previous resections of right vestibular schwannoma via translabyrinthine approach and right intraventricular meningioma (both performed elsewhere). She underwent transzygomatic, extended middle fossa approach with lateral sphenoidectomy. Postoperative axial (C) and coronal (D) images demonstrate near total resection of tumor. Reconstruction was via fat and

fascia grafts. Postoperatively, she experienced V3 paresthesia and exposure of craniotomy hardware requiring revision cranioplasty.

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Figure 3.

Preoperative contrast-enhanced magnetic resonance imaging of greater sphenoid wing meningioma with axial section (A) demonstrating invasion of orbit, cavernous sinus, and Meckel's cave, and coronal section (B) demonstrating invasion of infratemporal fossa in a 50 year-old male (#12) who presented with vision loss and cranial nerves III and VI palsy. Transzygomatic, middle fossa approach with lateral sphenoidectomy and orbitotomy was used to achieve subtotal resection with only residual tumor in the cavernous sinus postoperatively. Reconstruction was performed using synthetic dural matrix and fat graft, shown on nonfat-suppressed postoperative axial (C) and coronal (D) images. Adjuvant

radiation therapy was delivered. He experienced numbness in cranial nerve V distribution postsurgically, without evidence of tumor progression.

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Table 1

Demographic and clinical characteristics of study patients (N=22)

Female gender, n (%)	19 (86)
Mean age (range)	46 years (16–76)
Mean tumor size ^I (range)	4.0 cm (1.3–9)
Pathology, n (%)	
Meningioma	16 (73)
Epidermoid cyst	2 (9)
Trigeminal schwannoma	2 (9)
Invasive pituitary adenoma	1 (5)
Chondrosarcoma	1 (5)
Infratemporal fossa extension, n (%)	6 (27)
Preoperative cranial nerve deficit, n (%)	15 (68)

^I At presentation, largest dimension

Table 2

Cohort of patients with tumors of Meckel's cave and cavernous sinus who underwent EMCF with or without LS

Patient	Gender	Age at surgery, years	Size, cm	Pathology (WHO grade for meningioma)	Location	Surgery ¹	LS	Intra-CS tumor dissection	IAC drill-out	Extent of resection ²	Adjuvant radiation	Facial nerve outcome, HB score	Hearing outcome	Preop deficits	New CN deficit	Adverse event(s)	Outcome	Follow up, months
1	F	76	6	Meningioma (II)	CS, ITF, orbit, maxillary sinus	Orbitozygomatic, orbital exenteration	Y	Y	N	STR	IMRT	I	No change	V, III, IV, VI, proptosis, dementia, blindness	none	none	Stable disease without progression Deceased from dementia	35
2	F	54	9	Meningioma (II)	CS, orbit, ITF, parasal sinus	Orbital exenteration, paramasal sinus resection	Y	N	N	NTR	IMRT	I	No change	APD, EOM restriction, V intact	none	CSF leak, LD	Stable disease without progression	126
3	M	61	5	Epidermoid cyst	CPA, CS, suprasellar	Previous temporal craniotomy	N	N	Y	NTR	None	I	No change	III, IV, VI	none	hydrocephalus, VP shunt	Stable disease without progression	13
4	F	17	5	Meningioma (II)	MC	EMCF x2 due to recurrence	Y	Y	Y	STR	IMRT	I	No change	V	III/IV	keratopathy	Stable disease without progression	59
5	F	69	4.2	Meningioma (I)	CS, ITF		Y	N	N	GTR	None	I	No change	none	V	none	No evidence of disease	23
6	F	47	2.6	Meningioma (I)	CPA, MC, CS		N	Y	Y	NTR	None	I	No change	Headache, VI	none	none	Stable disease without progression	68
7	F	45	N.A. ³	Meningioma	CS, ITF		Y	Y	N	NTR	IMRT	I	No change	none	none	jaw pain	Recurrent tumor, deceased	48
8	F	16	2.5	Trigeminal schwannoma (NF2)	MC, CS		Y	N	N	NTR	None	V1 (Preop)	No change (Preoperative hearing loss)	R vision/hearing loss, VII paresis (h/o translab)	V	exposed hardware	Stable disease without progression	42
9	F	18	4.3	Epidermoid cyst	MC, CS, ITF, orbit	1 EMCF with cyst wall in CS	Y	Y	N	GTR	None	I	No change	headache, syncope	V	seizure, CSF leak, mild cognitive difficulties, nonorganic hearing loss	No evidence of disease	105
						2 EEA for recurrence in CS												
						3 Revision EMCF for definitive resection of cyst wall from CS												
10	F	55	4.5	Pituitary adenoma (invasive)	CS, orbit, sella		Y	Y	N	STR	SRS	I	No change	ear pain, CSF leak	III, VI	DI, edema, hematoma	Stable disease without progression	67
11	F	25	5.1	Chondrosarcoma	MC, CS	EMCF followed by EEA for tumor in medial CS	N	Y	N	STR	IMRT	I	No change	VI	V	none	Stable disease without progression	33
12	M	50	3.5	Meningioma (I)	CS, ITF, orbit		Y	Y	N	NTR	IMRT	I	No change	II, III, VI	V	none	Stable disease without progression	34
13	F	39	3.2	Meningioma (I)	CS, MC		N	N	Y	NTR	None	I	No change	headache	IV	strabismus surgery	Stable disease without progression	87
14	F	69	4.5	Meningioma (I)	CS, MC	Concurrent posterior petrosectomy	Y	N	Y (ABR)	STR	None	I	20dB loss	Headache, diplopia, balance problems	V	hydrocephalus, EVD	Stable disease without progression	9
15	F	32	4	Meningioma (I)	CS, MC, clivus		N	Y	Y	NTR	IMRT	I	No change	Headache, VI	V	hydrocephalus, EVD	Stable disease without progression	35
16	F	44	3.5	Meningioma (I)	CS, MC	Resection of Eustachian tube	Y	N	N	STR	None	III	No change	Headache, VI, hearing decreased,	V	none	Stable disease without progression	3

Patient	Gender	Age at surgery, years	Size, cm	Pathology (WHO grade for meningioma)	Location	Surgery ¹	LS	Intra-CS tumor dissection	IAC drill-out	Extent of resection ²	Adjuvant radiation	Facial nerve outcome, HB score	Hearing outcome	Preop deficits	New CN deficit	Adverse event(s)	Outcome	Follow up, months
17	F	47	1.3	Meningioma (I)	CPA, CS	Frontotemporal craniotomy with superior and lateral orbitotomy	N	N	Y (ABR)	GTR	None	II	No change	V	none	none	No evidence of disease	38
18	F	47	3.8	Meningioma (II)	CS		Y	N	N	NTR	adjuvant FRT	I	No change	VI, IV	none	trismus, malocclusion	No evidence of disease	102
19	F	51	3.1	Meningioma (I)	CS, orbit	Lateral orbitotomy	Y	Y	N	NTR	IMRT	I	No change	proptosis, VI	none	neurocognitive	Stable disease without progression	95
20	F	42	2.8	Meningioma (I)	CS, MC	Frontotemporal craniotomy	Y	Y	N	GTR	None	I	No change	cognitive deficits	IV, VI	midbrain CVA	No evidence of disease	1
21	M	45	4.1	Meningioma (II)	CS, MC, CPA		Y	Y	N	NTR	SRS	VI (Preop)	No change	IX, X, XI	none	edema/craniectomy, pseudomeningocele, meningitis, seizures, VP shunt, trach/PEG	Stable disease without progression Deceased of metastatic mesothelioma	6
22	F	69	2	Trigeminal schwannoma	CS, MC		Y	N	N	GTR	None	I	Total loss (tumor eroded into cochlea)	none	V3	none	No evidence of disease	1

Y, yes; N, no; HB: House-Brackmann; LS: lateral sphenoidectomy; CS: cavernous sinus; ITF: infratemporal fossa; MC: Meckel's cave; GSW: greater sphenoid wing; IAC: internal auditory canal; CPA: cerebellopontine angle; EEA: expanded endonasal endoscopic approach; IMRT: intensity modulated radiation therapy; SRS: stereotactic radiosurgery; DI: diabetes insipidus

¹ All patients underwent EMCF as primary surgical approach

² GTR: gross total resection, no evidence of residual tumor on imaging; NTR: near total resection, residual tumor measures 5mm or less; STR: subtotal resection, residual tumor measuring more than 5mm in any dimension

³ Imaging not available

Table 3Treatment characteristics and outcomes of study patients (N=22)¹

	n (%)
Tumor control	21 (95)
Deceased of disease	1 (5)
Extent of resection	
GTR	5 (23)
NTR	11 (50)
STR	6 (27)
Adjuvant radiation	11 (50)
Lateral sphenoidectomy, n (%)	16 (73)
Reconstruction	
Fascia or synthetic dura only	6 (27)
Fat or muscle free graft	13 (59)
Vascularized tissue ²	3 (14)
New postoperative cranial nerve deficit	12 (55)
III, IV, or VI	4 (18)
V	9 (40)
VII	2 (9) ³
VIII	2 (9)
CSF leak	2 (9)
Hydrocephalus	4 (18)
Seizure	2 (9)

GTR: Gross total resection, NTR: Near total resection, STR: Subtotal resection

¹Mean length of follow up (range): 4 years (0.1–10)²Pericranial flap in 1 patient, temporalis muscle flap in 1 patient, free flap in 1 patient³House-Brackmann 2 and 3