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RESEARCH

Individual surgical management of trigeminal schwannomas guided by an extended classification: a consecutive series of 96 clinical cases at a single institution

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Abstract

Trigeminal schwannoma (TS) is a rare intracranial neurinoma that affects the multicompartmental skull base. In recent decades, advancements in skull-base neurosurgical techniques and endoscopic surgery have significantly improved outcomes for TS patients. In this study, we present our experience with surgical resection of TS using a further classification system. We conducted a retrospective analysis of the clinical, surgical, and follow-up data of 96 patients diagnosed with TS at our institution between March 2012 and June 2022. The tumors were classified based on the MPE classification, with Type M further divided into M1 and M2 subtypes according to the origin of the tumor and the patterns of cavernous sinus (CS) invasion. Type MP tumors were divided into M1P and M2P subtypes based on whether the tumors in the middle cranial fossa extended into the anterior CS. Optimal surgical approaches were proposed for each subtype. The outcomes of the case series were collected and analyzed. Based on the further MPE classification, 32 tumors were classified as Type M2P, 21 as Type M1P, 12 as Type ME, 8 as Type P, 8 as Type M1, 8 as Type MPE, and 7 as Type M2. Gross total resection (GTR) was achieved in 88 patients, while five patients underwent subtotal resection (STR), and three patients received partial resection (PR). No deaths occurred during the perioperative period. The extended MPE classification provides specific insights into the features of TS involving the middle fossa, enabling more individualized and tailored treatment strategies, as well as appropriate approach selection. The combination of microsurgery, endoscopic surgery, and stereotactic radiotherapy can lead to satisfactory outcomes in managing complex TS, achieving high rates of GTR while minimizing complications.

Keywords Trigeminal schwannoma · Skull base · Classification · Microsurgery · Endoscopic surgery

Introduction

Trigeminal schwannoma (TS) is the second most common intracranial neuroma after vestibular neuromas. It accounts for less than 1% of all intracranial tumors and 0.8–8% of intracranial neurinomas [5, 22]. TS can originate from different parts of the trigeminal nerve, such as the trigeminal nerve root, Gasserian ganglion, or peripheral divisions, and may involve one or multiple cranial compartments. Before 1956, the fatality rate among 39 patients with TS one year postoperatively was almost 41% [23]. Various classifications have been proposed to categorize TS based on tumor location [8, 9, 14, 22, 28, 32]. Jefferson was the first to classify TS into three types: Type A located primarily in the middle fossa, Type B in the posterior fossa, and Type C in both the middle and posterior fossa [9]. Yoshida and Kawase expanded on this classification system and defined six types:

Qun Xiao and Hao Peng are co-first authors, and contributed equally to this work.

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middle fossa tumor (Type M), posterior fossa tumor (Type P), extracranial fossa tumor (Type E) - including orbital fossa tumor (Type E1) and infratemporal or pterygopalatine fossa tumor (Type E2), dumbbell-shaped middle and posterior fossa tumor (Type MP), dumbbell-shaped middle and extracranial fossa tumor (Type ME), and a middle, posterior, and extracranial fossa tumor (Type MPE) [32].

The development of skull base surgery has substantially reduced disability and mortality rates in TS patients, while also increasing resection rates [1, 2, 4–6, 8, 13, 19, 22, 28, 31–33]. In recent decades, endoscopy has emerged as a powerful tool for managing TS [10, 12, 18, 20, 24, 29, 30].

In this study, we analyzed clinical data from 96 surgically treated TS patients to explore individualized treatment and summarize our surgical experience in managing TS using the further MPE classification system [32]. We propose optimal surgical approaches for each subtype of TS to improve the rate of gross total resection (GTR), long-term quality of life, and reduce postoperative complications.

Methods

Patient population

The clinical, neuroimaging, and follow-up data of 96 patients diagnosed with TS were retrospectively reviewed. The patient cohort consisted of 61 females and 35 males, with an average age of 46.27 years (range: 8–72 years). All patients were treated by the same surgeon between March 2012 and June 2022. Of the 96 patients, 90 underwent first-time surgery and there were six cases of recurrent TS. Among the recurrent cases, four patients underwent gamma knife surgery (GKS) for residual tumors after the initial operation. This study is a retrospective analysis that neither utilizes personal patient information nor involves the execution of clinical trials. Therefore, it is exempt from the requirement for ethics committee review and approval, as well as the necessity for obtaining informed consent from patients.

Clinical data assessment

The most common symptom reported before surgery was face numbness, which was experienced by 53 patients (55.2%). Headaches were reported by 22 patients (22.9%), followed by dizziness (17.7%) and hearing loss (13.5%). Twelve patients (12.5%) had diplopia, with nine cases caused by abducens nerve palsy and three cases caused by oculomotor nerve palsy. Trigeminal neuralgia, although it was atypical in all cases, was reported by 10 patients (10.4%). Other less common symptoms included unstable walking (9.4%), decreased trigeminal nerve motor function (8.3%), tinnitus (7.3%), hoarseness and dysphagia (4.2%), blurred vision (4.2%), exophthalmos (3.1%), taste dysfunction (2.1%), epilepsy (2.1%), ptosis (1.0%), and facial muscle atrophy (1.0%). Preoperative neurological examinations revealed trigeminal nerve signs in 69.8% of patients, while 13.5% presented with CN VIII signs and 11.5% displayed cerebellar signs. (Table 1)

Characteristics and further classification of TS

Of the 96 patients, two had small-sized tumors (< 2 cm), 15 had medium-sized tumors (2–2.9 cm), and the remaining 79 patients (82.3%) had tumors larger than 3 cm in diameter. The majority of the tumors were of the mixed type (42.7%), while cystic tumors without solid parts were less common (18.8%) (Table 1).

The further MPE classification system was employed to categorize all TS cases. Based on our expertise, Type M was further divided into subtypes M1 or M2, depending on the tumor volume that infiltrated the anterior cavernous sinus (CS). Subtype M1 originated from one or more branches of cranial nerve (CN) V or the distal Gasserian Ganglion (GG), occupying the anterior CS or whole CS. Subtype M2 originated from the GG, solely located in Meckel's cave, with/without invasion into the posterior CS. The key distinction between M1 and M2 tumors lay in whether they occupied the anterior CS or not. Type MP was subsequently classified as M1P or M2P, based on whether the tumor extended from the middle cranial fossa into the anterior CS (Fig. 1). Subtype M1P involved the whole CS and posterior cranial fossa, while subtype M2P occupied Meckel's cave and the posterior cranial fossa, with or without involvement of the posterior CS. The remaining types were defined according to the MPE classification system. Among our cases, the most prevalent subtype of TS was Type M2P (33.3%), followed by M1P (21.9%), ME (12.5%), P (8.3%), M1 (8.3%), MPE (8.3%), and M2 (7.3%) (Table 1).

Surgical approach selection

The selection of the surgical approach was guided by the MPE classification system. The pretemporal trans-cavernous sinus approach (PTTC) was chosen for Type M1 and M1P tumors (Fig. 2) (Video 1), while a subtemporal intradural approach (STI) was selected for Type M2 tumors (Fig. 3) (Video 2). Type P tumors were treated using the basic suboccipital retrosigmoid approach (RS). For Type M2P tumors, the STI approach was typically utilized. However, if the posterior cranial fossa tumor extended inferior to the level of the internal auditory meatus (IAM), the retrosigmoid intradural suprameatal approach (RISA) was preferred (Fig. 4) (Video 3). In a case of Type M2P TS, complete resection was achieved using the combined presigmoid supra-infratentorial approach as the tumor extended anteriorly, superiorly,

Table 1 Demographic data of 96 patients with trigeminal schwannomas

	No.	Percentage (%)
Clinical symptom		
Face numbness	53	55.2
Headache	22	22.9
Dizziness	17	17.7
Hearing loss	13	13.5
Face pain	10	10.4
Walking unstable	9	9.4
Tinnitus	7	7.3
Diplopia	12	12.5
Jaw weakness	8	8.3
Hoarseness and dysphagia	4	4.2
Blurred vision	4	4.2
Exophthalmos	3	3.1
Taste disfunction	2	2.1
Epilepsy	2	2.1
Ptosis	1	1
Facial muscle atrophy	1	1
Cranial nerve dysfunction		
CN II	4	4.2
CN III	2	2.1
CN V	67	69.8
CN VI	5	5.2
CN VII	7	7.3
CN VIII	13	13.5
CN IX–XI	4	4.2
Tumor size		
Small (−1.9 cm)	2	2.1
Medium (2.0–2.9 cm)	15	15.6
Large (3.0–3.9)	29	30.2
Extra-large (4.0 cm-)	50	52.1
Tumor characteristics		
Cystic tumor	18	18.8
Solid tumor	37	38.5
Mixed tumor	41	42.7
Further MPE classification		
M1	8	8.3
M2	7	7.3
P	8	8.3
M1P	21	21.9
M2P	32	33.3
ME	12	12.5
MPE	8	8.3

and medially to the hypothalamus and suprasellar cistern, extending down to the jugular foramen (Fig. 5). This made complete resection challenging with just the STI or RISA approach. For Type ME tumors, the PTTC, cranial orbitozygomatic (COZ), or endoscopic endonasal approach (EEA) was selected. Type MPE tumors were typically approached using the PTTC or COZ approach (Fig. 6).

Follow-up

Postoperative follow-ups were conducted starting from the third month after surgery and included outpatient and video follow-ups. MRI imaging data was used to schedule follow-ups, with an annual frequency for patients without tumor recurrence. Increased imaging examinations were recommended if tumor recurrence was suspected. Mean follow-up was 39 ± 12.8 months (range 11 to 136 months) in our series. The follow-up period ended on December 31, 2023.

Results

Surgical outcomes

In this study, GTR was achieved in 88 patients (91.6%), subtotal resection (STR) in five patients (5.2%), and partial resection (PR) in three patients (3.1%) (Table 2). Two patients with Type-M2P TS underwent STR using the RISA. These two tumors primarily occupied the posterior cranial fossa, extending below the IAM, and reaching into the middle cranial fossa. Due to limited visualization of the parasellar region, small residual tumors were left in the cavernous sinus. Five patients underwent STR/PR due to significant adhesions and attachments to the surrounding structures, as well as profuse bleeding. One patient with PR had a recurrent Type-M1P TS and had undergone GKS three times for the residual tumor after the initial microsurgery. They were referred to our hospital for a second operation, and postoperative histopathology revealed a rare low-grade malignant schwannoma. Unfortunately, the patient passed away one year later due to tumor progression causing hydrocephalus. In our cohort, eight patients underwent GKS for residual tumors after surgery. We observed minimal tumor regrowth in two patients who had undergone PR. One of these cases involved a low-grade malignant schwannoma, as previously noted, while the other case is currently under close follow up and does not necessitate surgical intervention (follow-up duration: 2.5 years). The residual tumors in the remaining six patients did not exhibit subsequent enlargement.

Pathological findings

All 96 TS cases were confirmed to be schwannomas based on examination of postoperative paraffin specimens. Among the TS series, one case of malignant schwannoma was reported.

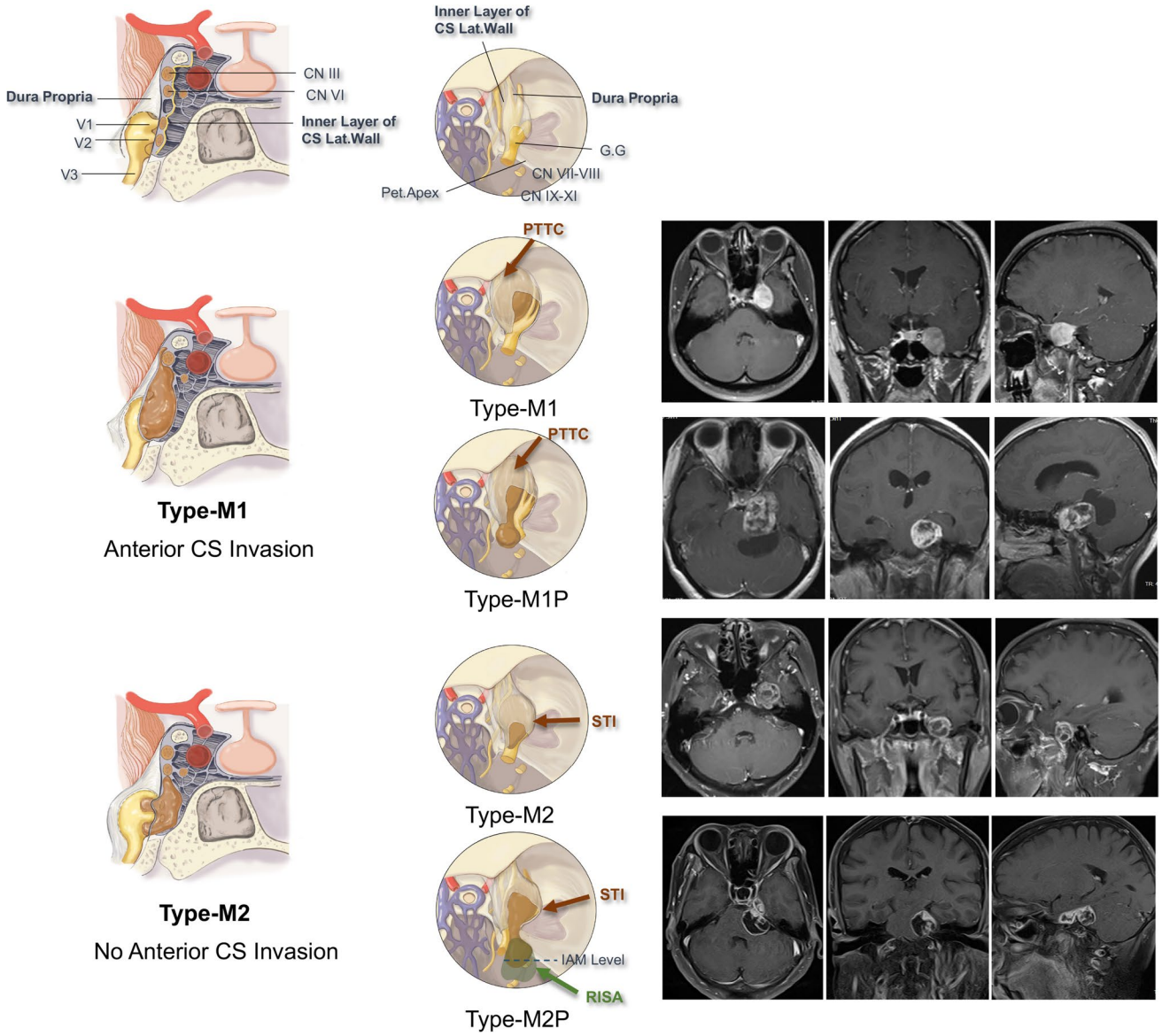

Fig. 1 **(Left) Top**: Schematic diagram illustrating the anatomical relationship of the parasellar region. **Middle**: Schematic diagram of Type-M1 TS invading the anterior cavernous sinus. **Bottom**: Illustration of Type-M2 TS without invasion of the anterior cavernous sinus. **(Center) Top**: Schematic representation of the middle and posterior cranial fossa. Various types of schematic diagrams for Type M1, Type M1P, Type M2, and M2P TS, along with the proposed surgical approaches, are presented sequentially. **(Right)** Axial, coronal, and sagittal MRI T1-weighted images with gadolinium-based contrast for Type M1, Type M1P, Type M2, and M2P TS. TS = trigeminal schwannoma; V1 = ophthalmic nerve; V2 = maxillary nerve; V3 = mandibular nerve; CN VII - VIII = the 7th and 8th cranial nerve; CS = cavernous sinus; Pet.Apex = petrosal apex; IAM = internal acoustic meatus

Postoperative neurofunction and complications

Postoperatively, facial numbness improved in 10 patients (18.9%), persisted in 33 patients (62.3%), and worsened in 10 patients (18.9%) over 1 year (Table 3). Eight patients developed new facial numbness, and among these, three patients had persistent numbness after a follow-up period of over 1 year. Headaches and dizziness were relieved in all cases after surgery. Hearing loss improved in eight patients (61.5%) and persisted in five patients (38.5%). Facial pain resolved in all 10 patients (100%). Walking instability and tinnitus were also resolved. Diplopia improved in 10 patients (83.3%), persisted in one patient (8.3%), and worsened in one patient (8.3%). Two patients experienced transient episodes of diplopia. Jaw weakness resolved in five out of eight patients (93.3%) and persisted in three patients. Resolution was observed for cases of hoarseness, dysphagia, blurred vision, and exophthalmos.

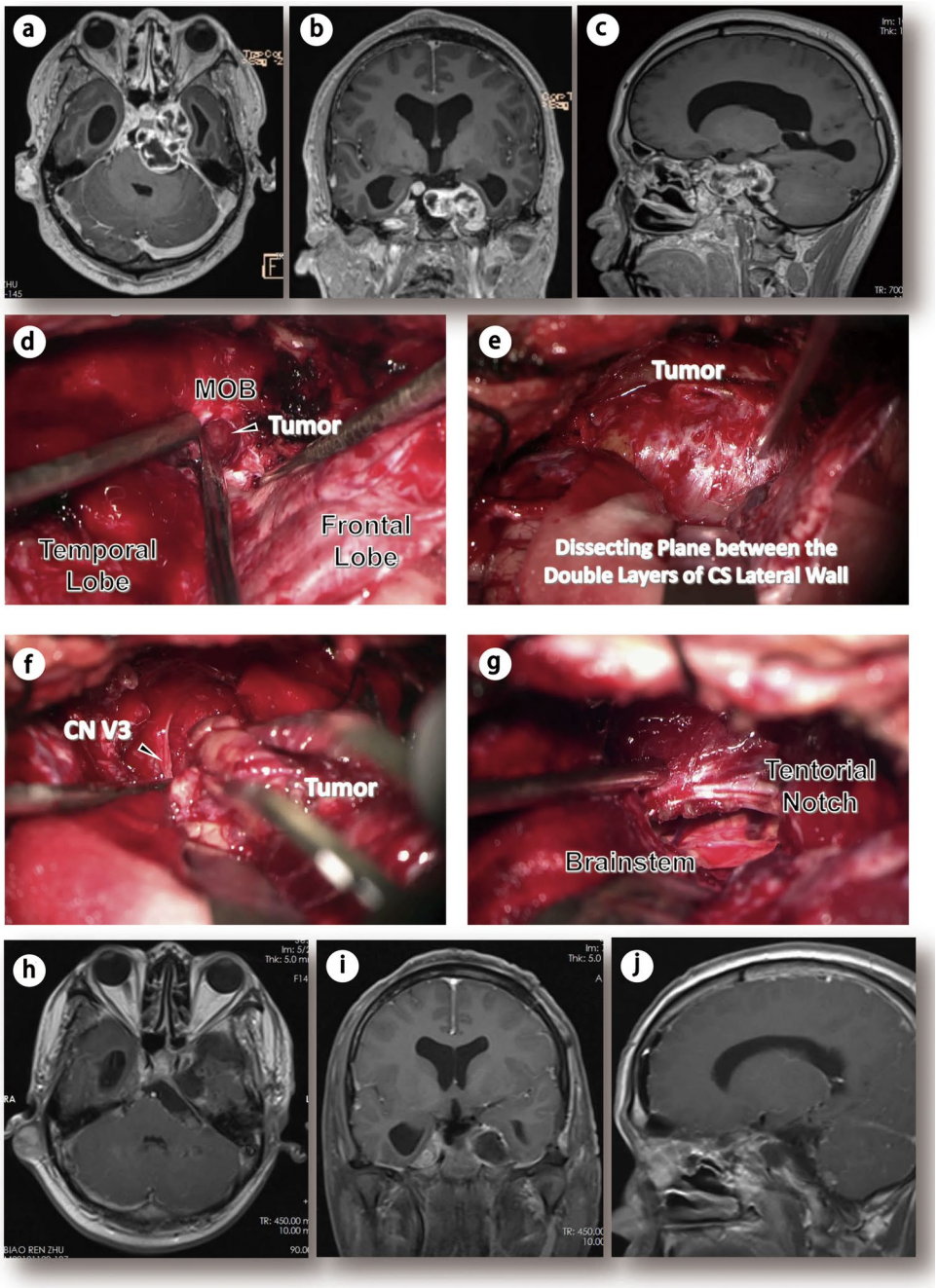

Fig. 2 The pre- and postoperative axial, coronal, and sagittal T1-weighted MR images with gadolinium-based contrast (**a**, **b**, **c**, **h**, **i**, and **j**) and intraoperative pictures (**d**, **e**, **f**, and **g**) depict a patient with Type-M1P TS who underwent resection using a pretemporal trans-cavernous sinus (PTTC) approach. The tumor occupies both the middle (interdural space) and posterior (intradural space) cranial fossa and invades the anterior CS (A, B, and C). During extradural manipulation, the anterior clinoidal process is drilled off, and the meningo-orbital band (MOB) serves as the entry landmark into the interdural space of the CS lateral wall. The tumor within the CS can be fully exposed by peeling off the dura propria, with no infiltration of the inner layer of the CS. The posterior cranial fossa compartment of the TS is removed via the corridor through the porus of Meckel's cave to the intradural space in posterior cranial fossa, providing clear visibility of the tentorial notch and brainstem following total resection (D, E, F, and G). Postoperative gadolinium-enhanced MR images confirm complete tumor removal using a PTTC approach (H, I, and J). CS = cavernous sinus; MOB = meningo-orbital band; CN V3 = mandibular branch of the trigeminal nerve. TS = trigeminal schwannoma

Taste dysfunction improved in one patient (50.0%) but persisted in another patient (50.0%). Facial palsy improved in one patient (100%), and one patient experienced transient seventh nerve palsy, which fully recovered after 3 months. No perioperative mortalities were observed. Two patients developed subdural hematoma; close observation for 3 days followed by a repeat head computed tomography scan showed absorption of the hematoma. Cerebrospinal fluid leakage occurred in one patient but resolved with bed rest alone.

Discussion

Microsurgery of TS through a skull base approach based on further MPE classification

Various surgical approaches have been described for excising TS [1, 4, 5, 7, 22, 32]. In this study, the PTTC approach was employed to treat Type-M1 TS located in the interdural space of the lateral wall of the cavernous sinus.

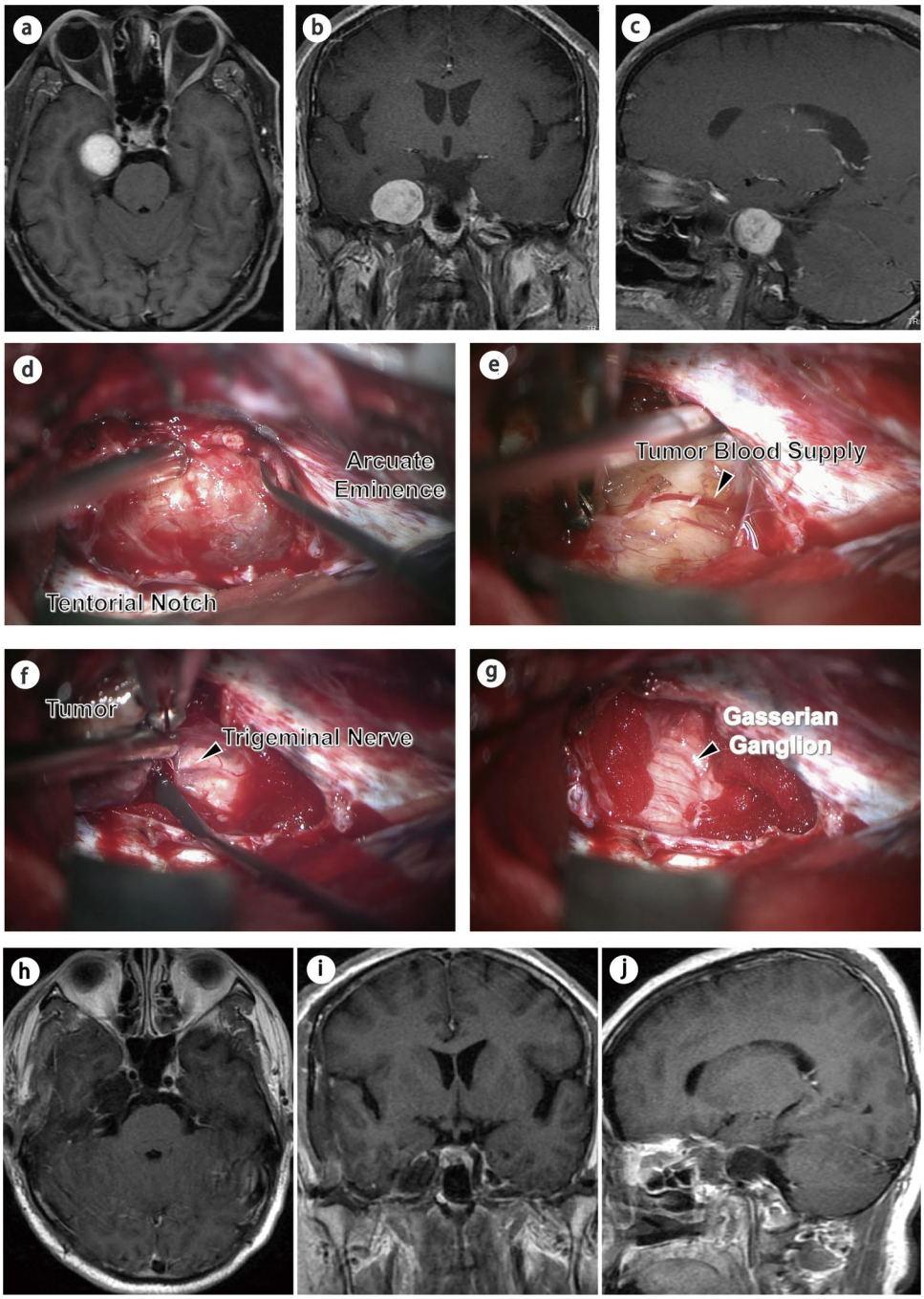

Fig. 3 The axial, coronal, and sagittal T1-weighted MR images with gadolinium-based contrast (**a**, **b**, **c**, **h**, **i**, and **j**) and intraoperative pictures (**d**, **e**, **f**, and **g**) illustrate the case of a patient with Type-M2 TS who underwent resection using a subtemporal intradural (STI) approach. The tumor originates from the Gasserian Ganglion (GG) and is primarily located in Meckel's cave and the posterior CS (interdural space of CS lateral wall) (A, B, and C). Dissection of the tumor along the trigeminal nerve reveals the tumor blood supply originating from the GG, which can be exposed and blocked at early stage, resulting in a clear surface between the tumor and the nerve (F and G). Postoperative gadolinium-enhanced MR images confirm complete removal of the tumor with a STI approach (H, I, and J). CS = cavernous sinus. TS = trigeminal schwannoma

The surgeon could easily separate the dura propria of the lateral wall of the CS from the superior orbital fissure and remove the tumor from its inner membranous layer. The volume of the tumor occupying the anterior CS provided a separation interface between the dura propria and the inner membranous layer of the lateral wall of the CS. The extradural approach provided better tumor visibility and minimized brain retraction compared to the intradural approach [27, 33]. Adequate debulking in a piecemeal manner allowed for flexibility in managing the tumor and its surrounding structures. By separating under the perineurium of CN V branches, we were able to safely resect the tumor while preserving the fibers of the normal and functional trigeminal nerve.

For Type-M2 TS, which occupies the Meckel's cavity and may or may not invade the posterior CS, the preferred approach was the STI approach. This approach allows simultaneous access to the Meckel's cave and the posterior part of the CS, providing a broad exposure of the tumor body, reducing the size of the bone flap, and shortening the

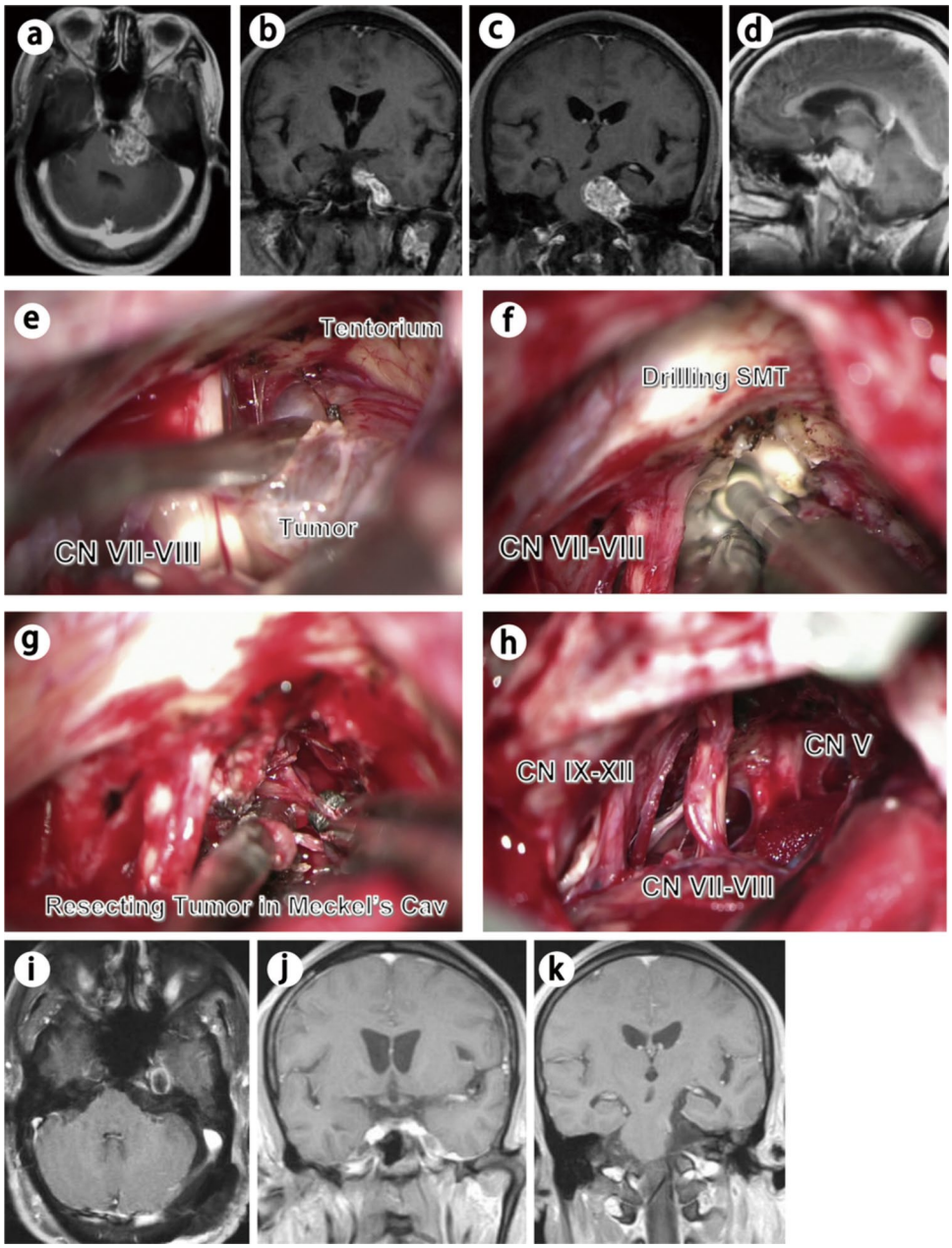

Fig. 4 The pre- and postoperative axial, coronal, and sagittal T1-weighted MR images with gadolinium-based contrast and intraoperative pictures depict the case of a patient who underwent resection for a giant Type-M2P trigeminal schwannoma using a retrosigmoid intradural suprameatal approach (RISA) (**a**, **b**, **c**, **d**, **i**, **j**, and k). The majority of the tumor was located in the posterior cranial fossa within the intradural space and extended into Meckel's cave within the interdural space (A, B, C, and D). The main body of the tumor in the posterior cranial fossa was removed through a piecemeal debulking fashion and sub-perineurium separation. By drilling off the suprameatal tubercle (SMT), access was gained to Meckel's cave for the removal of the remaining tumor in the middle cranial fossa within the interdural space (**e**, **f**, **g**, and **h**). The postoperative gadolinium-enhanced MR images confirmed the complete removal of the tumor using the RISA technique. CN VII-VIII = the 7th and 8th cranial nerve; SMT = superior meatus tubercle

operation distance (Fig. 3). A lower temporal bone craniotomy was performed to minimize excessive retraction of the temporal lobe. Since Type-M2 tumors do not occupy the anterior CS, dura separation from the superior orbital fissure was avoided to protect the nerves controlling the extraocular muscles. Instead, a cruciate incision was made to unroof the superior wall of Meckel's cave. After tumor debulking, the tumor could be mobilized and separated from the peripheral structures. The corridor to the posterior CS was accessed from the anterior Meckel's cave, moving straight forward to the parasella area. Opening the lateral wall CS was unnecessary for achieving GTR.

The tumor body of Type P TS is located entirely in the posterior fossa. Therefore, this type of TS is treated using the RS approach. It is crucial to handle CN IV, VI, VII, and VIII, as well as the vessels (such as the superior cerebellar artery and its perforating vessels), carefully to minimize complications.

Type-M1P TS is characterized by a dumbbell-shaped tumor that extends into the whole CS and posterior cranial fossa. We found that the PTTC approach is the optimal microsurgical approach for Type-M1P TS, as it offers a remarkable view of the middle fossa and provides improved access to the posterior fossa by expanding Meckel's porus

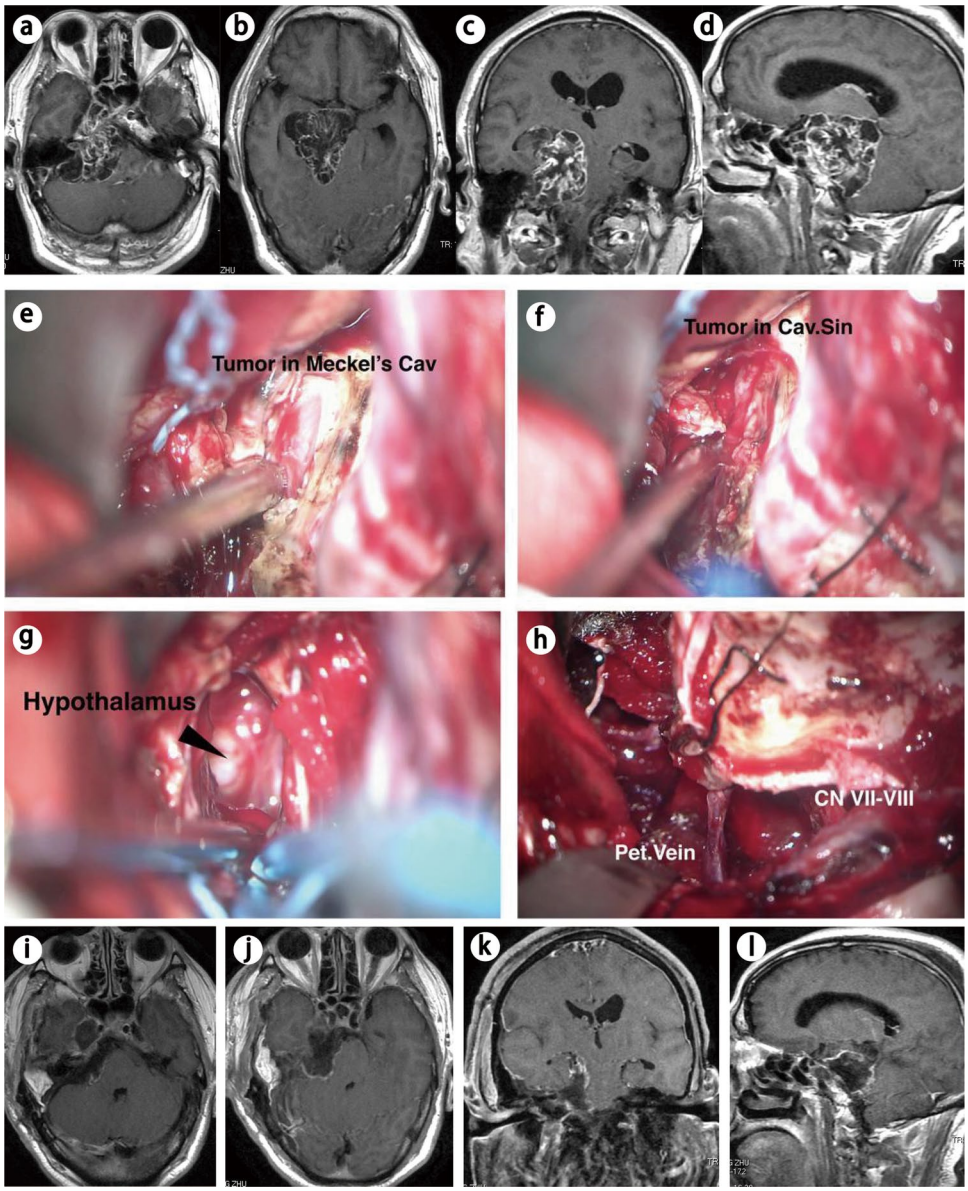

Fig. 5 The pre- and postoperative axial, coronal, and sagittal T1-weighted MR images with gadolinium-based contrast (**a**, **b**, **c**, **d**, **i**, **j**, **k**, and **l**) and intraoperative pictures (**e**, **f**, **g**, and **h**) depict a patient with a giant Type-M2P TS who underwent resection using a presigmoid supra-infratentorial approach. The tumor extends anteriorly, superiorly, and medially to the regions of hypothalamus, suprasellar cistern, and jugular foramen (A, B, C, and D). Drilling off the posterior petrosum exposes Trautmann's triangle. Cutting the tentorium allows for consistent supra- and infratentorial space. The tumor within Meckel's cave and the posterior CS is resected interdurally, while the tumor invading the suprasellar and interpeduncle cistern is removed intradurally, providing satisfactory visualization and manipulation space. The remaining tumor that extends to the jugular foramen can be easily removed in the infratentorial space (E, F, G, and H). Postoperative gadolinium-enhanced MR images confirm complete tumor removal utilizing a combined presigmoid supra-infratentorial approach (I, J, K, and L). Pet. Vein = petrosal vein; CN VII-VIII = the 7th and 8th cranial nerve. CS = cavernous sinus. TS = trigeminal schwannoma

(Fig. 2). The tumor occupying the anterior CS provides an excellent separation interface between the CS lateral and inner walls, which can reduce surgery-induced nerve and internal carotid artery damage in the CS. If the posterior fossa component is relatively large, the tentorium should be resected, and the apex should be drilled. As most TS are soft and suckable, they can be excised even below the level of the IAM [33].

For Type-M2P TS, we employed a STI approach, which could be executed with or without tentorial incision, or alternatively, utilized a RISA technique. If a significant portion of the tumor is situated in the posterior fossa and its lower aspect is below the IAM, we prefer the RISA approach (Fig. 4). This approach provides exposure of the posterior fossa and allows for the removal of the tumor in the middle cranial fossa by drilling off the suprameatal nodules. With advancements in endoscopic techniques, direct observation of the middle cranial fossa during surgery has become possible. In most cases of M2P TS, except for rare exceptions, complete resection can be achieved using either the STI or RISA approach.

Type-ME tumors extend into both intracranial and extracranial spaces, and they can be further classified into two subgroups: tumors of the middle cranial fossa with extension to the orbit (Type ME1) and tumors of the middle cranial fossa with extension to the infratemporal fossa and pterygopalatine fossa (Type ME2) [32]. For Type ME1 tumors, the surgeon can safely remove orbital tumors by increasing the bone removal of the lateral and superior walls of the orbit using the PTTC approach. To achieve a broad

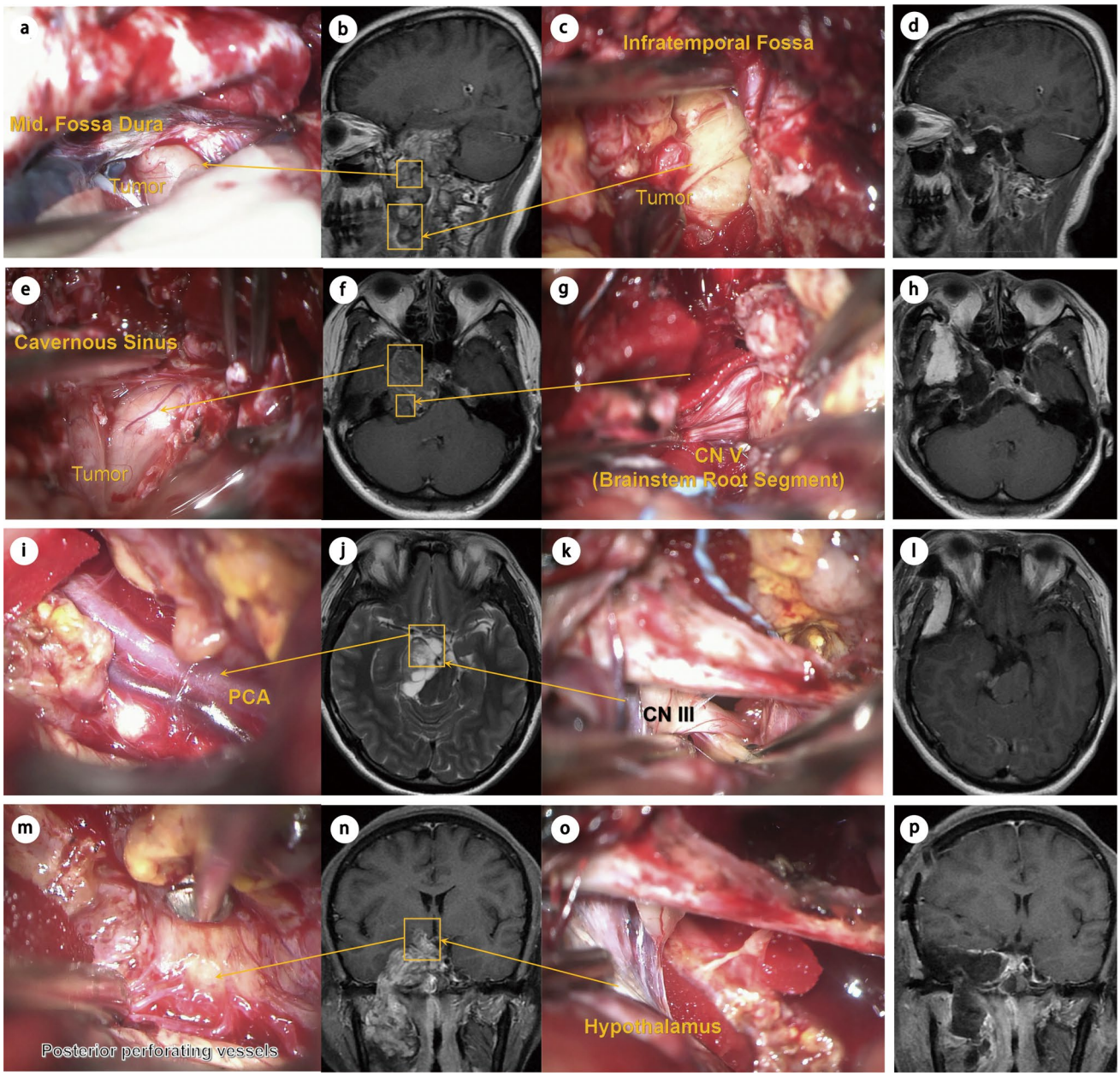

Fig. 6 The pre- and postoperative axial, coronal, and sagittal T1-weighted MR images and axial T2-weighted MR images with gadolinium-based contrast (**b**, **f**, **j**, **n**, d, **h**, **l**, and **p**) and intraoperative pictures (**a**, **e**, **i**, **m**, **c**, **g**, **k**, and **o**) depict a patient with a large Type-MPE TS who underwent resection using cranial orbitozygomatic (COZ) approach. The tumor is located in both the cranial space (middle and posterior cranial fossa) and extracranial space (infratemporal and pterygopalatine fossa). The intraoperative photos demonstrate that the COZ approach can provide excellent exposure and a satisfactory surgical field for both the cranial and extracranial compartments of the tumor. The COZ approach allows for wide visualization and manipulation of the suprasellar and peduncle cistern, enabling safe and careful protection of posterior perforating vessels and the hypothalamus (A, E, I, M, C, G, K, and O). CN = cranial nerve; PCA = posterior cerebral artery

exposure of infratemporal and pterygopalatine fossa tumors, we employed a COZ extradural approach, which minimizes temporal lobe retraction and provides visualization of these regions.

Type MPE tumors have the potential to extend into multiple intracranial compartments and extracranially. In such cases, the PTTC approach and COZ extra-intradural approaches are considered optimal microsurgical approaches (Fig. 6).

Table 2 Appropriate surgical approach and outcomes of 96 patients

Type	No.	Recommend approach	Surgical approach (cases)	Tumor resection		
				GTR	STR	PR
M	8	M1: PTTC	PTTC (8)	8		
	7	M2: ST	STI (7)	7		
P	8	RS	RS (8)	8		
MP	21	M1P: PTTC	PTTC (21)	19	1	1
	32	M2P: ST/RISA	STI (18)	18		
			RISA (13)	10	2	1
			Presigmoid (1)	1		
ME	12	PTTC/COZ/EEA	PTTC (8)	8		
			COZ (1)	1		
			EEA (3)	2	1	
MPE	8	PTTC/COZ	COZ (5)	4		1
			PTTC (3)	2	1	

PTTC pretemporal trans-cavernous sinus approach, *STI* subtemporal intradural approach, *RS* retrosigmoid approach, *RISA* retrosigmoid intradural suprameatal approach, *COZ* cranial orbitozygomatic approach, *EEA* endoscopic endonasal approach, *GTR* gross total resection, *STR* subtotal resection, *PR* partial resection

Table 3 Relationship between preoperative symptoms and postoperative outcomes

Preoperative symptoms	*n*	Postoperative symptoms, *n*			Newly appeared, *n*	
		Disappeared or improved	Persisted	Worsened	Transient	Permanent
Face numbness	53	10	33	10	5	3
Headache	22	22				
Dizziness	17	17				
Hearing loss	13	8	5			
Face pain	10	10				
Walking unstable	9	9				
Tinnitus	7	7				
Diplopia	12	10	1	1	2	
Jaw weakness	8	5	3			
Hoarseness and dysphagia	4	4				
Blurred vision	4	4				
Exophthalmos	3	3				
Taste disfunction	2	1	1			
Epilepsy	2	2				
Ptosis	1	1				
Facial palsy	1	1			1	

Stereotactic radiosurgery

Stereotactic radiosurgery has been utilized as a treatment option for TS patients. Several studies have reported the effectiveness and safety of GKS in this context [21, 25, 26]. In our study, eight patients underwent GKS following surgery. During the follow-up period, we observed two case of residual tumor regrowth in patients who underwent PR. Additionally, the residual tumors in the other six patients remained stable until the end of the follow-up period. These findings indicate that TS patients who undergo PR or STR can benefit from radiosurgery as a viable therapeutic option. Planned STR or PR combined with additional GKRS represents a viable strategy for achieving effective tumor control while minimizing surgical risks. This strategy may be particularly advantageous for tumors with extensive invasion into the CS or infratemporal/pterygopalatine fossa, where radical resection poses significant risks to neurological function. Such strategies have been

shown to yield favorable outcomes in previous studies, supporting their potential utility in selected cases [15–17].

Endoscopic approaches

Tumor resection in the pterygopalatine fossa, inferior temporal fossa, and Meckel's cave has frequently been performed using the endoscopic EEA [20, 24, 29, 30]. Compared to microsurgery, the EEA offers several advantages including no retraction in the temporal lobe, reduced invasiveness, and a precise visual field during the operation [15, 20]. Although the endoscopic route carries a higher risk of cerebrospinal fluid leakage compared to the classic skull base approach through craniotomy, improvements in skull base reconstruction techniques have been made to minimize this serious complication [11]. The EEA has become a complementary and reasonable alternative to traditional microsurgery for Type-ME tumors due to its access to Meckel's cavity from the anterior medial region. In our case series, three patients with Type-ME tumors underwent EEA (Figs. 7 and 8) and achieved favorable outcomes. Based on our knowledge, EEA is suitable for Type-ME2.

The endoscopic transorbital approach (ETOA) has recently been considered a minimally invasive surgical technique for treating TS that provides adequate access for Type-M1 and ME1 tumors [3, 10, 12, 18]. Nevertheless, when tumors are confined to the posterior CS in Type-M2 TS, this presents a difficulty as the ETOA procedure carries the risk of injuring the internal carotid artery during dural dissection of the cranial fossa. Consequently, the EEA technique is considered the most suitable approach for Type-M2 TS [12]. In scenarios where both intracranial and extracranial tumors are large, and complete tumor excision is unachievable via a single endoscopic surgery or a skull base approach, a combined transcranial approach and endoscopic surgery can be used to treat TS. The choice of surgical modality depends on the relationship between the trigeminal nerve and the tumor. Transcranial approaches are more suitable when tumors displace the trigeminal nerve medially, while endonasal techniques are preferred when tumors displace the nerve laterally [17].

Limitation

This study is a single-institution retrospective chart review, and its strength is inherently limited by being based on the experience of a single surgeon, which may affect the generalizability of the findings. However, this limitation is common in most of the literature on this topic. Additionally, there

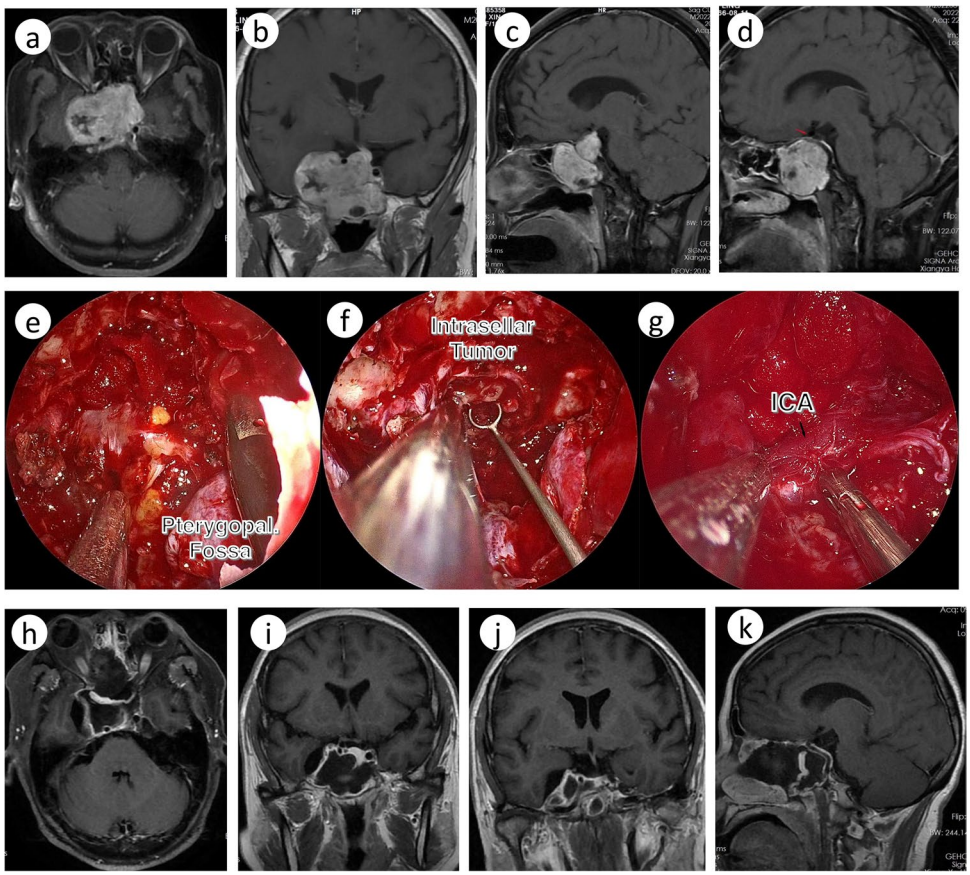

Fig. 7 Pre- and postoperative axial, coronal, and sagittal T1-weighted MR images with gadolinium-based contrast (**a**, **b**, **c**, **d**, **h**, **i**, **j**, and **k**) and intraoperative pictures (**e**, **f**, and **g**) depict a patient with Type-ME TS who underwent resection using an endoscopic endonasal approach (EEA). The tumor is located in middle cranial fossa, extends into sphenoid sinus and pterygopalatine fossa. (A, B, C, and D). Postoperative gadolinium-enhanced MR image shows that the tumor had been nearly completely removed via an EEA (H, I, J, and K). ICA = internal carotid artery

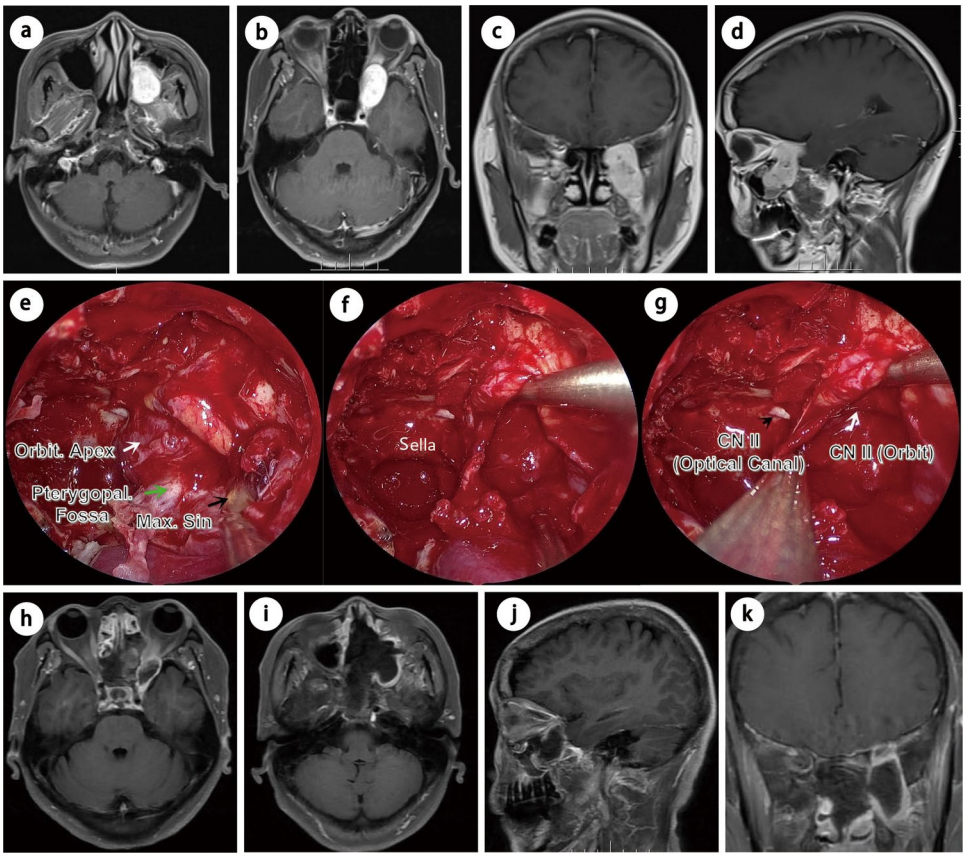

Fig. 8 Pre- and postoperative axial, coronal, and sagittal T1-weighted MR images with gadolinium-based contrast (**a**, **b**, **c**, **d**, **h**, **i**, **j**, and **k**) and intraoperative pictures (**e**, **f**, and **g**) depict a patient with Type-ME TS who underwent resection using an endoscopic endonasal approach (EEA). The tumor is located in middle cranial fossa, orbit, and pterygopalatine fossa (A, B, C, and D). Postoperative gadolinium-enhanced MR image shows that the tumor had been nearly completely removed via an EEA (H, I, J, and K). Max. Sin = maxillary sinus

may be a selection or referral bias, and the study cohort is relatively small.

In our series, the number of cases utilizing endoscopy was limited. Furthermore, the follow-up period for patients undergoing endoscopic procedures was shorter compared to those who underwent craniotomy, indicating the need for further and longer-term follow-up to validate these findings.

Conclusions

The extended MPE classification of TS is primarily based on tumor location, origin, and anterior cavernous sinus invasion. This classification provides a precise guide for preoperative evaluation, rational selection of surgical approaches, and formulation of surgical strategies for TS treatment. a profound understanding of the microanatomy of the skull base, expertise in micromanipulation techniques, and extensive experience are crucial for successful TS management. It is important to recognize that endoscopy and microsurgery should complement each other in the treatment of TS. In cases where GTR cannot be achieved, combining radiotherapy can lead to satisfactory outcomes in managing complex TS cases while minimizing complications.

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Author contributions All authors contributed to the study's conception and design. QX, HP, and WH performed data collection and analysis. QX and CQ wrote the first draft of the manuscript and all authors commented on previous versions. QL, CQ, GT, JY, GP and CZ performed the surgical procedures. QL supervised the entire study. All authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval This is an observational study. The Ethics Committee of Xiangya Hospital has confirmed that no ethical approval is required.

Competing interests The authors declare no competing interests.

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