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CLINICAL ARTICLE - BRAIN TUMORS

Surgical management and outcomes of petroclival meningiomas: a single-center case series of 259 patients

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Abstract
Background Surgical management of petroclival meningiomas is challenging. Various and inconsistent outcome and prognostic factors of the lesions have been evaluated previously. In the present study, the surgical outcome, philosophy, and experience of petroclival meningiomas are detailed based on a large patient series.
Methods A series of 259 patients with petroclival meningiomas (70 males and 189 females) were surgically treated. Clinical charts and radiographs were reviewed. Follow-up results were evaluated.
Results The preoperative Karnofsky Performance Scale (KPS) score was 74.2±10.5. The mean tumor size was 4.3±1.0 cm. The gross total resection (GTR) rate was 52.5 %. During a mean follow-up period of 55.3 months, recurrence/progression (R/P) occurred in 11 patients. The recent KPS score was 78.4±22.7, it improved in 139 (57.2 %) patients and stabilized in 53 (21.8 %) patients, and 201 (82.7 %) patients lived independently. The risk factors affecting the KPS score included (but were not limited to) age≥60, preoperative KPS≤60, and brainstem edema. The adverse factors contributing to R/P-free survival included (but were not limited to) non-total resection and the absence of the subarachnoid space. The R/P-free survival rate was 94.5 % at 5 years and 91.2 % at 9 years. The overall survival rate was 94.7 % at 5 years and 94.7 % at 9 years.
Conclusions Favorable outcomes from petroclival meningiomas could be achieved by microsurgery. Neurological function and quality of life were prioritized, and GTR was attempted. Risk factors should be considered in surgical schemes, and tumor recurrence should be aggressively monitored and treated.

Keywords Meningioma · Microsurgery · Petroclival · Presigmoid approach · Prognosis · Skull base

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Introduction

Approximately 10 % of intracranial meningiomas occur in the posterior fossa, of which clival and petroclival meningiomas account for 3–10 % [35]. The tumors usually grow slowly with benign pathology and involve the cranial nerves (CNs), brainstem, and the basilar artery [52]. The tumors were formerly considered inoperable, and the mortality rate was higher than 50 % [53]. During the past decades, microsurgery of the skull base has rapidly developed; however, the resection of petroclival meningiomas is still challenging. Although the operative mortality rate has decreased to less than 10 %, the rate of permanent postoperative complications is as high as 50 % [35]. Aggressive surgical treatment with surgical morbidity must be weighed against the indefinite natural history of postoperative residual tumors [38].

There are many recent studies of petroclival meningiomas; however, the outcome of these tumors is not well defined in Chinese patients, particularly regarding recurrent cases and long-term prognostic factors. This retrospective study reviews the long-term outcomes in patients after aggressive microsurgical resection of petroclival meningiomas at Beijing Tiantan Hospital, Capital Medical University, from June 2003 to May 2011.

Materials and methods

Patient population

The study included 70 males and 189 females (ratio, 1:2.7) from different regions of China with a mean age of 47.8 years (Fig. 1) (Table 1). Patient flow is depicted in Fig. 2. The preoperative performance status was determined by the Karnofsky Performance Scale (KPS) score, and the mean preoperative score was 74.2±10.5. Seventeen patients (6.6 %) had undergone previous treatment (Table 2). Eight (3.1 %) patients were asymptomatic and 251 (96.9 %) patients complained of various initial symptoms including (but were not limited to) headache (n=82, 31.7 %), dizziness (n=35, 13.5 %), facial numbness (n=30, 11.6 %), and hearing impairment (n=25, 9.7 %). The preoperative symptoms on admission are detailed in Table 3.

Neuroradiological evaluation

All of the patients were evaluated with a preoperative contrast-enhanced magnetic resonance imaging (MRI) scan (Figs. 3, 4, 5, and 6). Twelve patients (4.2 %) had multiple intracranial meningiomas. Tumor size was expressed as the tumor equivalent diameter $(D_1 \times D_2 \times D_3)^{1/3}$, and the tumor volume was defined as $(D_1 \times D_2 \times D_3) \times 1/2$ [35, 41]. Lesions that were limited within the petroclival region were observed in only 27 cases, and 232 lesions extended to other regions (Table 4). A computed tomography scan was also taken to determine the tumor calcification, hyperostosis, the temporal bone anatomy, and the degree of pneumatization.

Surgical strategy

Different surgical approaches were planned for exposing and removing the tumors. Approaches were selected based on tumor location, extent, size, and surgeons' experience and preference. Key points for determining the choice were as follows: presigmoid retrolabyrinth transpetrosal approach (PRT) (n=130, 50.2 %) was preferred in cases with tumor basement below the internal auditory canal (IAC) or reaching to the lower clivus, broad dural attachment to posterior petrosal surface, and main mass in posterior fossa; anterior transpetrosal transtentorial approach (ATPT) (n=93, 25.9 %) was selected in tumors locating in the upper two-thirds of the clivus, and medial and superior to IAC; far lateral approach (n=12, 4.6 %), which was used in the early period due to lesions invading jugular foramen, was replaced by PRT at the later period; retrosigmoid approach (n=10, 3.9 %) was adopted when lesions grew lateral to IAC and created a surgical corridor without a notable supratentorial extension; fronto-temporo-zygomatic with or without supraorbital approach (n=9, 3.5 %) for lesions with significant suprasellar, parasellar, or orbital regions invasion, and combined or extended approaches (n=5, 1.9 %) for lesions with extensive dural attachment were seldom used.

Fig. 1 Distribution of 259 cases of petroclival meningioma. The *numerals in parentheses* indicate the number of treated cases from each region, and the numerals to the right of the slash (/) represent the number of cases lost to follow-up

Table 1 Summary of patients

Variable	
Age, years	
Range	24~70
Median	48.0
Mean ± SD	47.8±10.0
Gender	
Male	70 (27.0 %)
Female	189 (73.0 %)
Duration of symptom, months	
Range	0.5~264.0
Median	24.0
Mean±SD	36.1±45.9
Preoperative KPS	*n*=259
100	7
90	29
80	88
70	81
60	50
50	4
Surgical resection	
GTR (Simpson Grade I/II)	136 (52.5 %)
STR (Simpson Grade III/IV)	105 (40.5 %)
PR (Simpson Grade III/IV)	18 (6.9 %)
Surgical mortality	3 (1.2 %)
Postoperative radiotherapy	
Linear accelerator	2 (0.8 %)
GKS	33 (12.7 %)
Follow-up, months	
Range	4.2~111.3
Mean±SD	55.3±25.7
Recurrence/progression	11 (4.2 %)
Death during follow-up	10 (3.9 %)

GKS gamma knife surgery, *GTR* gross total resection, *PR* partial resection, *SD* standard deviation, *STR* subtotal resection

Neurophysiologic monitoring was routinely performed, including somatosensory evoked potentials and motor-evoked potentials. The tumor consistency, the blood vessel and CN encasement, and the tumor adhesion to the brainstem were also evaluated (Table 5). All of the operations were performed either by or under the supervision of the senior author (J.T.Z). The extent of tumor removal was classified into three degrees, depending on the postoperative MRI scans: GTR (Simpson Grades I/II); subtotal resection (STR) (Simpson Grades III/IV, with 90–99 % excision of the lesion); and partial resection (PR) (Simpson III/IV, with below 90 % excision of the lesion) (Table 1). In 158 (61.0 %) cases with Meckel's cave or cavernous sinus involvement, 116 (73.4 %) tumors were completely removed, and 42 (26.6 %) tumors were incompletely removed. The reasons for non-total resection (NTR) were disappearance of the dissection plane; infiltration of the CNs, brainstem, or vessels; or the tumor characteristics (i.e., a hard consistency or extensive regional involvement) [44].

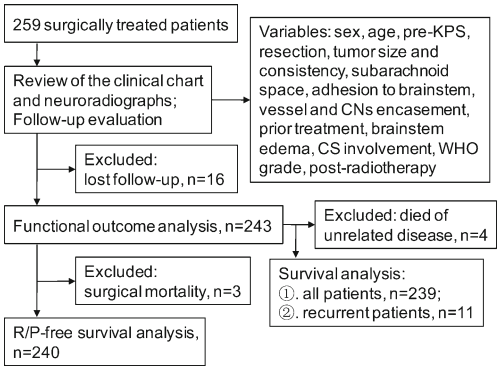


Fig. 2 Participant flow diagram. *KPS* Karnofsky Performance Scale, *CNs* cranial nerves, *CS* cavernous sinus, *R/P* recurrence/ progression

Postoperative radiotherapy

All patients with PR and significant residual lesions evaluated by MRI scans (particularly those lesions involving the cavernous sinus) were recommended for consultation with a radiation oncologist regarding postoperative radiotherapy. Patients with STR or preoperative radiotherapy were not recommended for radiotherapy and were postoperatively followed-up by MRI scans at 3 months, 6 months, 1 year, and then one time per year thereafter, which was called "surviving with tumor." In 123 (47.5 %) patients with NTR, only 35 (13.5 %; STR, *n*=30; PR, *n*=5) patients underwent radiotherapy. Radiotherapy was not considered for the residual tumors that were demonstrated to be unchanged during the follow-up. However, reoperation was advised for patients with evident recurrence/progression (R/P).

Table 2 Previous treatment before admission to our hospital

Treatment modality	n (total, 17)
Surgery	
One operation	8
Two operations	2
Surgery+GKS	1
Surgery+linear accelerator	2
GKS	2
Surgery+linear accelerator+GKS+VP shunt	1
Surgery+decompressive craniectomy+GKS	1

GKS gamma knife surgery, *VP* ventriculoperitoneal

Table 3 Main preoperative and postoperative symptoms/CN defects

Symptom	Preoperative (%)	Postoperative at discharge		Recent (%)
		R/A (%)	New onset (%)	
CN II	61 (23.6)	48 (18.5)	15 (5.8)	23 (9.5)
CN III	24 (9.3)	7 (2.7)	99 (38.2)	55 (21.2)
CN VI	23 (8.9)	12 (4.6)	84 (32.4)	32 (12.4)
CN IV	19 (7.3)	6 (2.3)	35 (13.5)	28 (10.8)
CN V: facial numbness	128 (49.4)	68 (26.3)	38 (14.7)	73 (28.2)
Trigeminal neuralgia	23 (8.9)	22 (8.5)	3 (1.2)	2 (0.8)
CN VII: facial palsy	32 (12.4)	9 (3.5)	83 (32.0)	38 (14.7)
Facial spasm	4 (1.5)	4 (1.5)	0	0
CN VIII: hearing deficit	93 (35.9)	65 (25.1)	10 (3.9)	29 (11.9)
Tinnitus	43 (16.6)	38 (14.7)	6 (2.3)	8 (3.1)
CN IX, X, XI: gag reflex	45 (17.4)	38 (14.7)	5 (1.9)	6 (2.3)
Dysdipsia	80 (30.9)	69 (26.6)	7 (2.7)	11 (4.2)
Dysphagia	37 (14.3)	34 (13.1)	9 (3.5)	3 (1.2)
Hoarseness	17 (6.6)	14 (5.4)	9 (3.5)	3 (1.2)
CN XII: atrophy of tongue	3 (1.2)	1 (0.4)	0	1 (0.4)
Tongue deviation	20 (7.7)	13 (5.0)	12 (4.6)	1 (0.4)
Ataxia	33 (12.7)	24 (9.3)	10 (3.9)	9 (3.5)
Dizziness	110 (42.5)	101 (39.0)	0	0
Dysarthria	11 (4.2)	8 (3.1)	31 (12.0)	13 (5.0)
Epilepsy	4 (1.5)	2 (0.8)	5 (1.9)	1 (0.4)
Headache	135 (52.1)	128 (49.4)	3 (1.2)	10 (3.9)
Hydrocephalus	28 (10.8)	27 (10.4)	6 (2.3)[a]	0
Gait	81 (31.3)	67 (25.9)	11 (4.2)	29 (11.2)
Motor	53 (20.5)	29 (11.2)	52 (20.1)	29 (11.2)
Sensory	20 (7.7)	12 (4.6)	11 (4.2)	11 (4.2)

CN cranial nerve, *R/A* recovery or alleviation

[a] Three patients underwent ventriculoperitoneal shunt

Surgical morbidity

In this series, three patients (1.2 %) died within 3 months after surgery (Table 6). CN III defects, which were the most frequent surgical morbidity, was significantly associated with cavernous sinus invasion (χ^2=21.450; odds ratio [OR], 3.730; 95 % confidence interval [CI], 2.109–6.597; p<0.001) (Table 3). Other complications were detected (Table 7), and the majority of these patients improved after treatment. Temporary tarsorrhaphy was performed in five (1.9 %) patients with new-onset CN VII defects to prevent conjunctivitis and corneal injury. Ten patients received hyperbaric oxygen treatment due to neurological dysfunctions. In the ten patients with respiratory difficulty, the mechanical ventilator was applied.

Follow-up

Follow-up evaluations were performed on 243 (93.8 %) patients by clinic consultation, a mailed questionnaire, and/or a telephone interview. The tumor statuses (R/P or unchanged) were determined by comparing the most recent contrast-enhanced MRI scans to the postoperative MRI scans at discharge. Patients with R/P were questioned regarding the treatments before and after R/P and their results. Sixteen patients (four males, 12 females) (Fig. 1) were lost to follow-up, for which the main reasons were relocations to other regions and the upgrading or changing of telephone numbers.

Statistical analysis

Statistical analysis was performed using the IBM SPSS Statistical Package v. 19.0. A p value <0.05 was considered significant. A univariate analysis was used to evaluate the predictors of recent functional status (Chi-square test) and tumor R/P (Kaplan-Meier survival analysis). Statistically significant factors from the univariate analysis were analyzed by multivariate logistic regression or Cox regression.

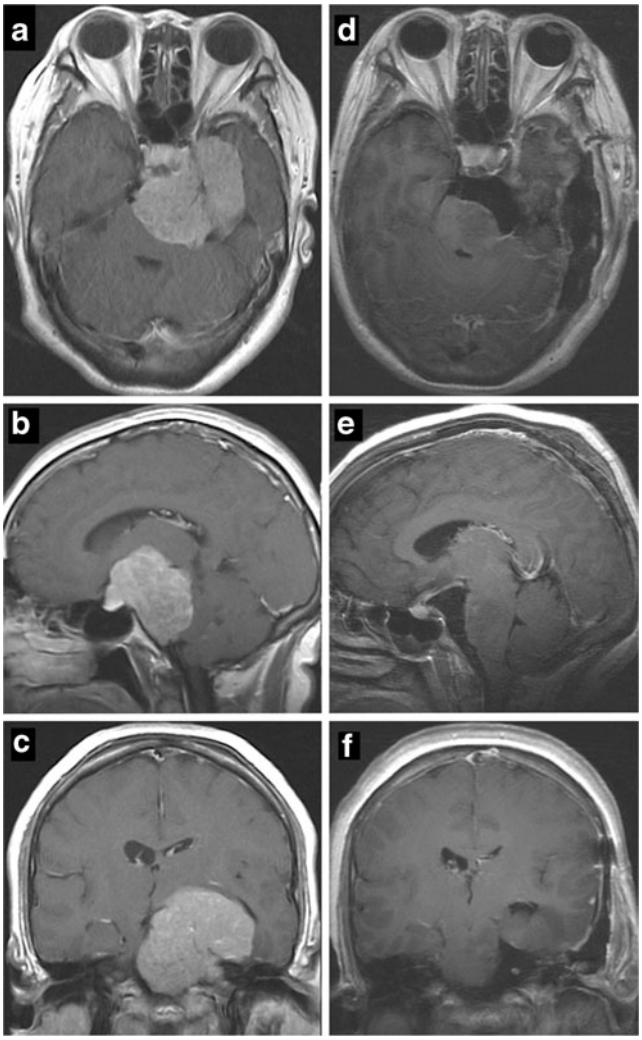


Fig. 3 Case 1: pre- (**a**–**c**) and post-operative (**d**–**f**) magnetic resonance imaging. A female patient aged 53 years with a preoperative KPS score of 90. The tumor size was 5.5×5.9×6.0 cm. The patient underwent a presigmoid approach, and complete resection was achieved. Postoperatively, she suffered hoarseness, abnormal gait, and progression of left oculomotor dysfunction, with a KPS score of 70. After 84 months, she was able to perform household duties—with a most recent KPS score of 80. KPS, Karnofsky Performance Scale

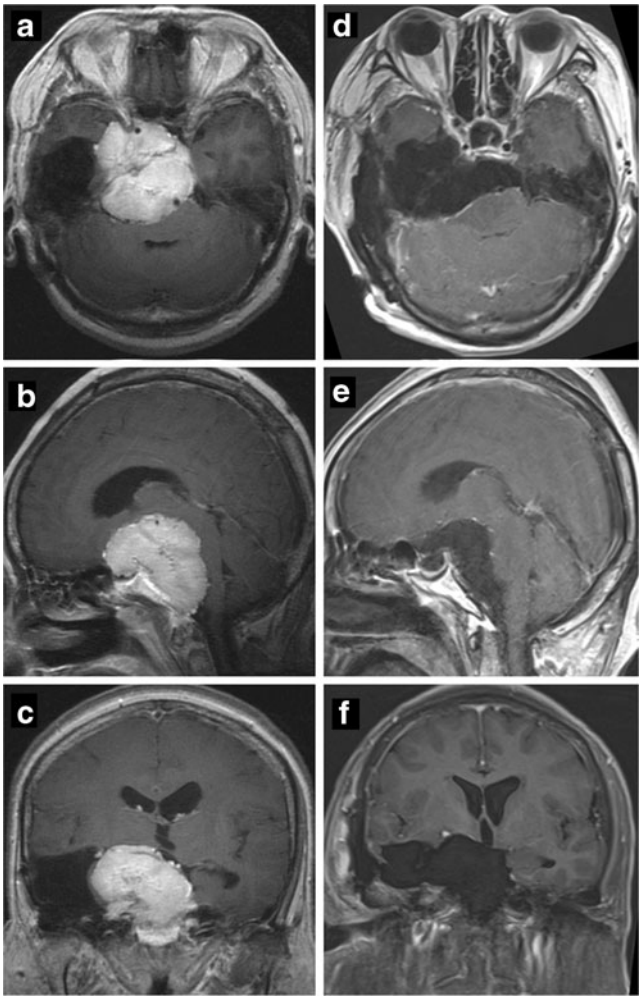


Fig. 4 Case 2: pre- (**a**–**c**) and post-operative (**d**–**f**) magnetic resonance imaging. A 54-year-old female had previous surgery and gamma knife surgery at a local hospital with a preoperative KPS score of 70. Tumor size was 5.6×5.8×6.4 cm. A presigmoid approach was performed, and the tumor was completely removed. The patient's postoperative course was not uneventful: CNs III and VII defects, dysarthria, motor and swallowing dysfunction occurred. The patient's postoperative KPS score was 60. After 28 months, she was living with neurological defects but could perform household duties with a KPS score of 80. *CN* cranial nerve, *KPS* Karnofsky Performance Scale

Results

Tumor characteristics and clinical results

The postoperative histopathology of the tumors revealed WHO Grade I (257 cases, 99.2 %) and WHO Grade II (atypical, $n=2$) (Table 4). The mean tumor volume was approximately 45.4±31.3 cm^3 (range, 0.9–183.8 cm^3). Headaches and dizziness improved significantly after the operations, whereas other symptoms were alleviated to various degrees (Table 3). The postoperative KPS score at discharge was 66.4±11.9 (range, 0–90). The clinical data categorized based on surgical approaches was detailed in Table 8.

Follow-up

At the most recent follow-up evaluation, the mean and median follow-up period was 55.3 months (95 % CI, 52.0–58.5) and 48.8 months, respectively. Ten patients died during follow-up. The symptoms were improved compared with those at discharge, and the major CNs dysfunctions involved CN III (Table 3). The percentage of recovery from the predominant surgical morbidities

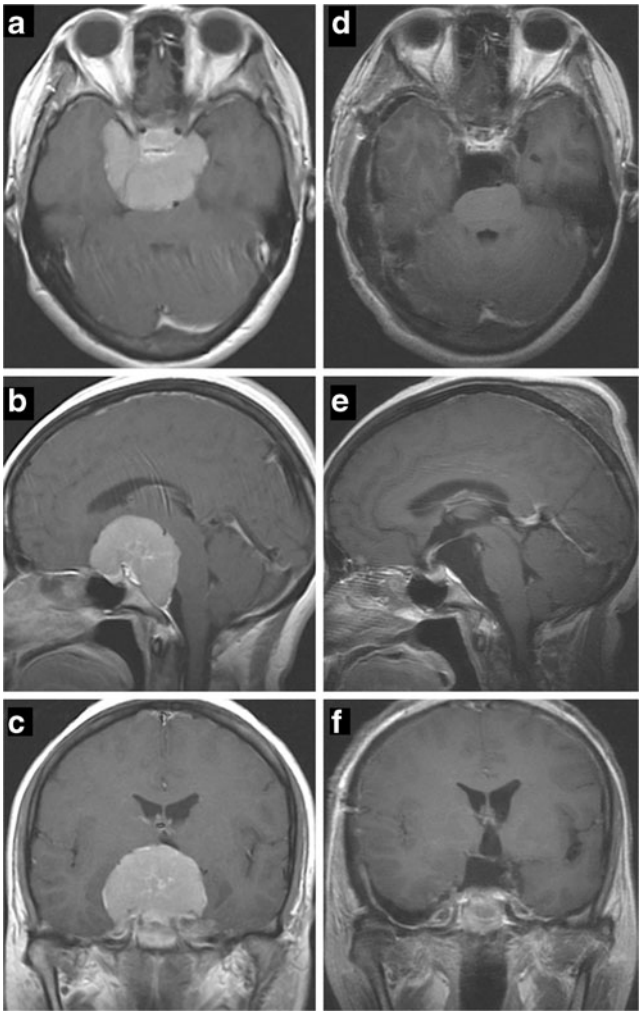


Fig. 5 Case 3: pre- (**a**–**c**) and post-operative (**d**–**f**) magnetic resonance imaging. A 41-year-old female with a preoperative KPS score of 80. Tumor size was 4.9×5.5×5.4 cm. The anterior transpetrosal approach was performed, and the tumor was completely resected. The patient's postoperative, new-onset dysfunctions were oculomotor palsy, diplopia, and right eye ptosis, with a KPS score of 70 at discharge. The ptosis resolved 6 months after the operation. At the 51-month follow-up, she could work full time and experienced mild diplopia, which did not disturb her. Her most recent KPS score was 90, without tumor recurrence. *KPS* Karnofsky Performance Scale

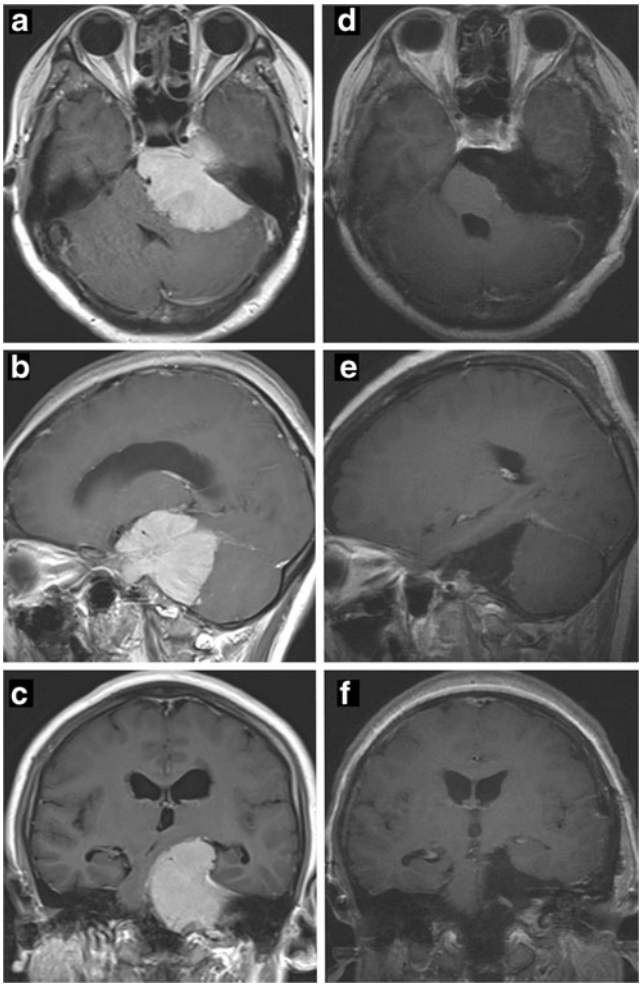


Fig. 6 Case 4: pre- (**a**–**c**) and post-operative (**d**–**f**) magnetic resonance imaging. A female patient was 41 years old with a preoperative KPS score of 60. The tumor was 5.3×5.3×6.4 cm in size. The presigmoid approach was selected to completely remove the lesion. The patient suffered CN V and VII dysfunction, and her other symptoms were unchanged—as was her postoperative KPS score of 60. At the latest follow-up (38 months after surgery), she had noticeably recovered. She was able to work full time and perform household duties, with a most recent KPS score of 90. *CN* cranial nerve, *KPS* Karnofsky Performance Scale

varied (Table 9). Additionally, mild vision impairments and hearing deficits developed in 12 and six patients, respectively, that had not presented preoperatively or at discharge; a series of MRI scans did not detect R/P in these 18 patients. Most of the patients had become accustomed to their neurologic defects or had developed effective coping measures.

The mean recent KPS score was 78.4±22.7 (95 % CI, 75.6–81.3). Compared with the preoperative KPS score, the most recent KPS score improved in 139 (57.2 %) patients, stabilized in 53 (21.8 %), and declined in 51 (21.0 %). Two hundred (82.3 %) patients experienced functional deficits, 201 (82.7 %) patients could perform normal activities or care for themselves (Table 10). Representative cases in our series are presented in Figs. 3, 4, 5, and 6, and each patient exhibited different features in their MRIs and medical histories.

Recurrence and progression

Tumor R/P occurred in 11 patients (4.5 %), of whom ten patients had experienced incomplete resections (STR, n=7; PR, n=3); moreover, three patients had undergone previous

Table 4 Tumor information

Characteristics	*n* (%)
Size category, cm	
Small, <1	0
Medium, 1–2.4	9 (3.5)
Large, 2.5–4.4	147 (56.8)
Giant, ≥4.5	103 (39.8)
Mean, cm	4.3±1.0
Range, cm	1.2–7.4
Involved regions	
Limited to petroclival	27 (10.4)
CS W/O Meckel cave	158 (61.0)
Cerebellopontine angle	65 (25.1)
Saddle area W/O sphenoid sinus	55 (21.2)
Middle fossa	54 (20.8)
Foramen magnum	44 (17.0)
Contralateral clivus	42 (16.2)
Contralateral CS	10 (3.9)
Orbit	2 (0.8)
Histopathology	
WHO Grade I	
Meningothelial	181 (69.6)
Transitional (mixed)	54 (20.8)
Angiomatous	10 (3.9)
Fibrous (fibroblastic)	6 (2.3)
Secretory	4 (1.5)
Psammomatous	1 (0.4)
Microcystic	1 (0.4)
WHO Grade II	
Atypical	2 (0.8)

TED tumor equivalent diameter, *W/O* with or without, *CS* cavernous sinus

treatment. Four patients received postoperative gamma knife surgery (GKS) before R/P (Table 11). The mean and median durations of the R/P-free period were 40.7±19.9 months (range, 12–78 months) and 39 months, respectively. After R/P, seven patients underwent surgery (STR, $n=5$; PR, $n=2$) and were recommended for postoperative radiotherapy; among these subjects, two patients underwent radiotherapy. One patient underwent a single gamma-knife procedure and responded with the arrest of tumor growth. Three patients declined surgery or radiotherapy and were followed up by observation. Of the 11 patients, five (2.1 %) patients died during the follow-up period. In all the patients, the R/P-free survival rate was 96.7 % at 3 years, 94.5 % at 5 years, 91.2 % at 7 years, and 91.2 % at 9 years; in addition, the overall survival rate was 97.4 % at 3 years, 94.7 % at 5 years, 94.7 % at 5 years, and 94.7 % at 9 years (Fig. 7).

Statistical analysis

The patients with low preoperative KPS scores tended to have low KPS scores at discharge and at the most recent follow-up (Fig. 8). The KPS score at discharge decreased, but the median of the most recent KPS scores improved (Fig. 9h). The recent KPS scores decreased due to the adverse effect of risk factors as follows: age≥60 year (OR, 1.636; 95 % CI, 1.094–2.445; $p=0.016$), preoperative KPS≤60 (OR, 1.639; 95 % CI, 1.041–2.579; $p=0.033$), failure of GTR (OR, 2.281; 95 % CI, 1.270–4.095; $p=0.006$), tumor size≥5 cm (OR, 1.690; 95 % CI, 1.078–2.648; $p=0.022$), severe blood-vessel and CN encasement (OR, 2.141; 95 % CI, 1.109–4.135; $p=0.023$), previous treatment (OR, 4.770; 95 % CI, 1.276–17.830; $p=0.020$), and brainstem edema (OR, 2.178; 95 % CI, 1.482–3.199; $p<0.001$) (Fig. 9).

Table 5 Definition of selected prognostic factors

Factors	*n* (%)	Definition
Vessel and CNs encasement[a] (evaluated by MRI and cerebral angiography)		
No	57 (22.0)	No vessel or CNs encased by tumor, and they surround the tumor surface
Moderate	165 (63.7)	Vessel partially encased by tumor with or without CNs encasement
Severe	37 (14.3)	The tumor perforatedby vital blood vessels and CNs
Adhesion of tumor to brainstem (evaluated by intra-operative findings)		
No	93 (35.9)	It is easy to separate the tumor from the brainstem without adhesion or resistance
Moderate	65 (25.1)	A few adhesions existed between the brainstem and the tumor
Tight	101 (39.0)	Many adhesions existed between the brainstem and the tumor, and it was difficult to separate the tumor from the brainstem
Tumor consistency (evaluated by MRI, CT, and intra-operative findings)		
Soft/crisp	71 (27.4)	Aspiratable
Tough	129 (49.8)	Not aspiratable, but cuttable with scissors
Hard	59 (22.8)	With calcification identified by CT scan and not cuttable with scissors

CT computed tomography, *MRI* magnetic resonance imaging

[a] Vessels include vertebrobasilar artery, internal carotid artery, anterior inferior cerebellar artery, posterior inferior cerebellar artery, superior cerebellar artery, and posterior cerebral artery

Table 6 Surgical mortality

Gender/ age, years	Pre- KPS	Date of Surgery	Approach/ resection degree	TED, cm	Morbility	Postoperative treatment	Death to surgery, days	Cause of death
F/55	70	2004-10-19	Presigmoid/ GTR	5.0	CN III, mild coma	Tracheostomy	63	Respiratory failure
F/45	70	2004-11-4	Presigmoid/ PR	3.6	CN III	Tracheostomy	9	Pulmonary embolism
M/51	60	2009-3-24	Presigmoid/ STR	5.2	Hydrocephalus; Intracranial hematoma	VP shunt; ventricular puncture for external drainage; tracheostomy	52	Intracranial hematoma

CN cranial nerve, *F* female, *GTR* gross total resection, *M* male, *PR* partial resection, *Pre-* preoperative, *STR* subtotal resection, *TED* tumor equivalent diameter, *VP* ventriculoperitoneal

Table 7 Main postoperative complications

	n (%)
Intracranial infection	45 (17.4)
Tracheostomy	41 (15.8)
Cerebrospinal fluid leak	15 (5.8)
Subcutaneous hydrops	14 (5.4)
Pneumonia	13 (5.0)
Intracranial hematoma	6 (2.3)
Cerebral infarction	2 (0.8)
Pulmonary embolism	1 (0.4)

Due to the small number of patients with WHO grade II meningiomas (n=2), the histopathology was not considered for inclusion in the Cox regression analysis. The tumor R/P was significantly related to the following adverse factors: tumor size ≥5 cm (OR, 2.577; 95 % CI, 1.119–5.936; p=0.026), failure of GTR (OR, 4.865; 95 % CI, 1.678–14.106; p=0.004), absence of a subarachnoid space between the brainstem and the tumor (OR, 4.981; 95 % CI, 1.040–23.859; p=0.045), histopathology (WHO grade II) (logrank=147.333; p<0.001), and previous treatment (OR, 13.564; 95 % CI, 2.965–62.054; p=0.001) (Figs. 10, 11, and 12).

Table 8 Clinical data categorized based on surgical approaches

	PRT	ATPT	Far lateral	RS	F/χ^2	*p*
Total	130	93	12	10		
Age, years	47.1±9.6	48.4±10.4	48.7±9.6	52.8±10.3	1.159	0.326
Sex ratio (F/M)	98/32	67/26	10/2	7/3	0.980	0.806
Preoperative KPS	72.6±10.8	77.1±10.4[b]	69.2±7.9	72.0±7.9	4.491	**0.004**
Tumor size, cm	4.6±0.9	3.8±1.0[b]	4.0±1.1	4.4±1.2	11.321	**<0.001**
Surgical resection					10.154	0.118
GTR	62	54	10	6		
STR	59	34	1	4		
PR	9	5	1	0		
Surgical mortality (%)	3 (2.3)	0	0	0		
KPS at discharge	64.1±13.0	69.6±9.9[b]	63.3±13.0	67.0±8.2	4.201	**0.006**
Follow-up duration, m	58.7±29.4	48.4±20.6[b]	66.3±30.1	53.5±22.2	3.427	**0.018**
Available follow-up	118	90	11	10		
Recurrence/Progression (%)[a]	6 (5.1)	3 (3.3)	1 (9.1)	1 (10.0)	0.870	0.833
Recent KPS	75.2±25.7	82.1±16.9	77.3±32.0	79.0±28.5	1.548	0.203
Improved	66	48	8	9		
Unchanged	23	27	0	0		
Worsened	29	15	3	1		

Values in bold were less than 0.05 and statistically significant

ATPT anterior transpetrosal transtentorial approach, *PRT* presigmoid retrolabyrinthine transpetrosal approach, *RS* retrosigmoid approach

[a] Kaplan-Meier survival analysis

[b] Significantly different from the group of PRT (p<0.05) by one-way ANOVA

Table 9 Recovery from the main surgical morbidities

	Recovery/ new onset, *n*	(%)
CN II	5/15	33.3
CN III	57/99	57.6
CN VI	55/84	65.5
CN IV	12/35	34.3
CN V	10/38	26.3
CN VII	54/83	65.1
CN VIII	3/10	30.0
CN XII	10/12	83.3
Dysarthria	19/31	61.3
Gait	4/11	36.4
Motor	36/52	69.2

The tumor R/P and histopathology (WHO grade II) were risk predictors of poor long-term survival. In the 11 patients with tumor R/P, the difference in cumulative survival between the patients with or without treatment was significant (Fig. 7).

Discussion

Petroclival meningioma, which is broadly defined as a tumor attached to the lateral sites along the petroclival borderline, is an extremely difficult tumor to tackle [19, 52]. In recent years, the treatment of petroclival meningiomas has undergone notable improvements (Table 12) [11, 20, 23, 24, 28, 30, 32, 35, 37, 42, 45, 50, 57, 61]. For optimal therapy, the natural history, the therapeutic effects of various treatments, and the disease's prognostic factors should be understood.

Table 10 Final outcomes (total, 243)

Recent status	KPS score	*n* (%)
Alive		
Normal, no complaints; no evidence of disease	100	30 (12.3)
Performs normal activity; minor symptoms	90	93 (38.3)
Normal activity with effort; some symptoms	80	64 (26.3)
Cares for self; unable to perform normal activity	70	14 (5.8)
Requires occasional assistance; cares for most needs	60	17 (7.0)
Requires considerable assistance and frequent care	50	9 (3.7)
Disabled; requires special care and assistance	40	3 (1.2)
Deceased		
Surgical mortality	0	3 (1.2)
Died of tumor recurrence/ progression	0	4 (1.6)
Died of surgical morbidity	0	2 (0.8)
Died of unrelated disease	0	4 (1.6)

KPS Karnofsky Performance Scale

Table 11 Treatment and outcomes of the 11 patients with R/P

No.	Gender/age, years	Previous treatment	Approach/ extent	WHO Grade	Post- treatment	R/P-free duration, months	Treatment after recurrence	Duration after R/P, months	Overall life span, months	KPS		Survival	Cause of death
										Pre-	Post-	Recent	
1	F/58	No	Presigmoid/ STR	I	GKS	62	No	1.4	63.4	60	60	0	No	R/P
2	F/46	No	Presigmoid/ GTR	I	No	78	STR+LA	31.2	109.2	80	50	50	Yes	
3	F/32	No	ATA/ STR	I	GKS	60	STR+GKS	37.9	97.9	70	60	70	Yes	
4	M/26	No	Presigmoid/ PR	I	No	40	No	8.0	48.0	60	50	0	No	R/P
5	F/54	No	Presigmoid/ PR	I	No	24	STR	81.8	105.8	60	80	60	Yes	
6	F/30	No	Presigmoid/ PR	I	No	12	Two GKS	41.7	53.7	50	50	60	Yes	
7	F/35	No	ATA/ STR	I	No	39	STR	12.2	51.2	70	60	60	Yes	
8	M/24	Operation+GKS+LA	ATA/ STR	II	No	34	No	7.0	41.0	60	60	0	No	R/P
9	M/33	Two operations	Far lateral/ STR	I	No	46	PR[a]	1.8	47.8	70	60	0	No	OUD
10	F/67	Operation+GKS	Retrosigmoid/ STR	II	GKS	18	PR	10.3	28.3	70	60	0	No	R/P[b]
11	M/40	No	Presigmoid/ STR	I	GKS	35	STR	8.6	43.6	80	70	70	Yes	

ATA anterior transpetrosal approach, *KPS* Karnofsky Performance Scale, *GKS* gamma knife surgery, *GTR* gross total resection, *LA* linear accelerator, *OUD* other unrelated disease, *Post-* postoperative, *PR* partial resection, *Pre-* preoperative, *R/P* recurrence/progression, *STR* subtotal resection

[a] The operation was performed at a local hospital

[b] Continued progression of the tumor after reoperation

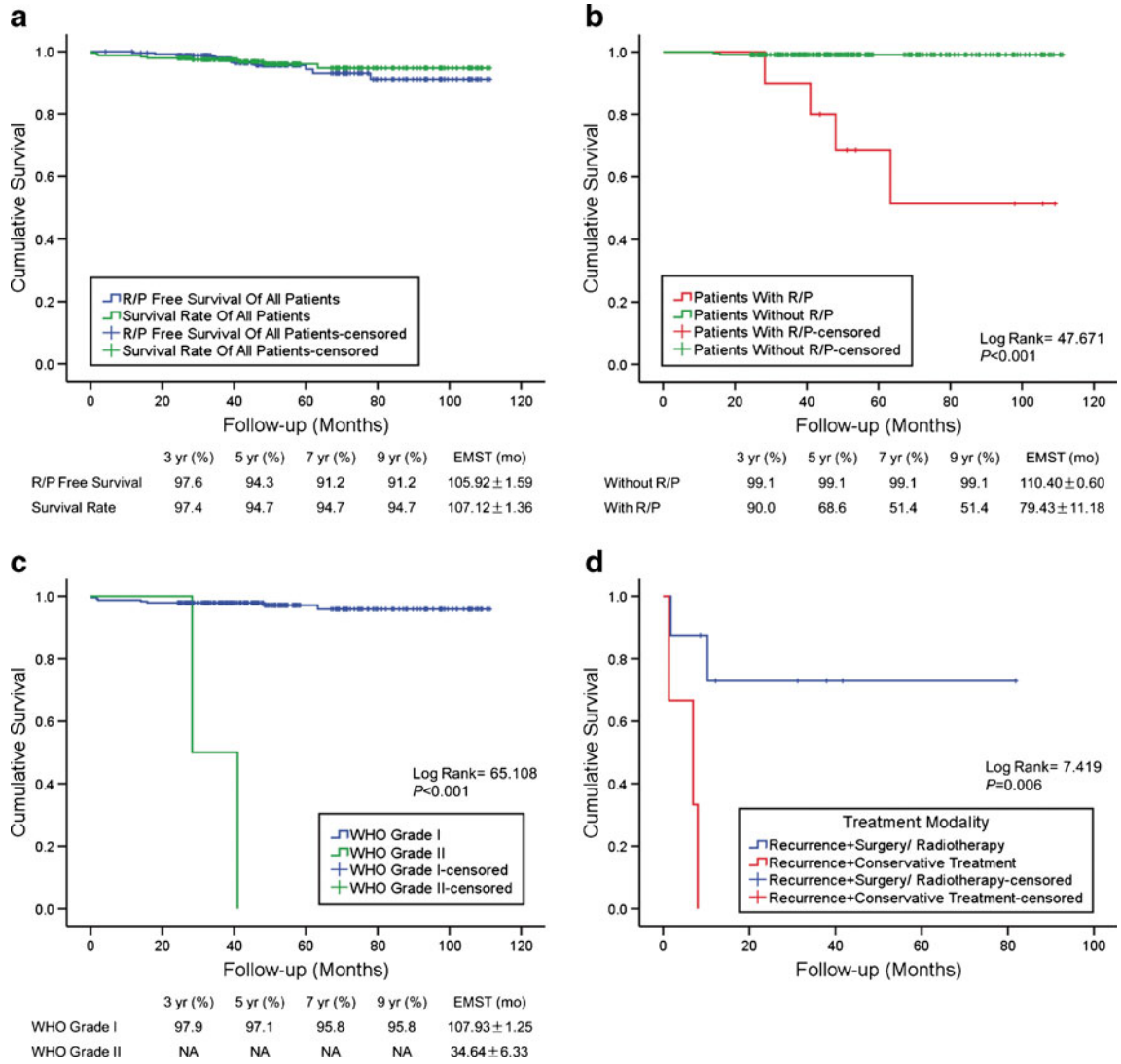


Fig. 7 Kaplan-Meier survival analysis illustrating the R/P-free survival and the final survival of all the patients (**a**), the effect of R/P (**b**), and WHO grade (**c**) on the cumulative survival, and the effect of treatment on the cumulative survival in patients with recurrence (**d**). *EMST* estimated mean survival time, *NA* not available, *R/P* recurrence/progression

Natural history

Few studies have reported the natural history of petroclival meningiomas, of which the main features have been described as unmercifully progressive growth and tragic final outcomes [8, 38, 44, 47, 51–53]. Tumors with initial sizes of 2.5–3 cm can lead to new or deteriorated symptoms [51]. A study of 21 untreated patients demonstrated that tumor growth developed in 76 % of the cases during a follow-up of at least 4 years and that the growth patterns were unpredictable and variable with ultimately poor long-term outcomes [53]. Park et al. [38] followed-up nine cases with a mean of 63 months; eventually, two cases (22.2 %) underwent surgery due to tumor progression. By contrast, arrested or decreased tumor growth rates might occur in many women after menopause [22, 35]. Jung et al. [22] reported the low growth rate in 38 cases of residual tumors; however, the follow-up duration (47.5 months) was not sufficiently long and the tumor growth curve was more useful than the average growth rate per year [33].

Out of the 259 cases in this series, two patients admitted to our hospital rejected surgery, and among them one experienced the deterioration of symptoms with tumor progression and finally died after 84 months; another patient received ventricular-peritoneal shunt and was still alive after 35 months. Furthermore, a large number of untreated patients with long-

term follow-up would guarantee the accurate reporting of the natural history of petroclival meningiomas [43, 53].

Treatment selection

In most studies, surgery is theoretically the first optional treatment for most patients with petroclival meningiomas (Table 12), and most surgical treatment series have exhibited satisfactory outcomes [9, 11, 17, 26, 30, 35, 37, 38, 44]. There are few arguments on treatment for large petroclival meningiomas; by contrast, the therapeutic strategy for small lesions has posed a dilemma.

For certain small, asymptomatic lesions that are discovered by routine or occasional health examination, Yano et al. [59] recommended observation. Meanwhile, favorable outcomes from small cranial-base tumors by radiotherapy have been validated [14, 26, 36]. However, deeply located, small meningiomas always exhibit relatively undesirable behavior. A small change in the tumor volume could lead to obvious variations and increases in surgical risk. Given the 8.8 % complication rate of GKS [15], Reinert et al. [40] have reported that the surgical complication rate of small tumors after GTR is 5 %, whereas the radical resection rate is >90 %, in which all the complications are transient [56]. In our series, 21 patients with small tumors (<3 cm) exhibited a 95 % GTR rate and favorable outcomes (the recent KPS, 89.5±10.2) as well as the seven asymptomatic patients (the recent KPS, 91.4±6.9). Therefore, early detection and radical resection, rather than radiotherapy or observation, has been the preferable and optimal method of curing the small lesions (<3 cm) with minimal morbidity [32, 39, 56]. Additionally, patients with tumor R/P trended toward ultimately fatal outcomes in the absence of radiotherapy or other treatments. Thus, active treatment should be recommended for patients with tumor R/P.

Surgical philosophy

The extent of tumor resection is the most important predictor of outcomes [44]. During the past decades, the surgical goal has evolved from radical resection and prolonging the life span to NTR and neurological preservation [1, 5, 30, 34, 35, 43]. Park et al. [38] suggested that intentionally incomplete resection is acceptable because of the low tumor growth rate, the guarantee of good functional status, and the favorable effects of adjuvant treatment for residual tumors, which was implied in other studies [12, 16, 24, 30, 32, 44, 45, 60]. Nevertheless, it is conceivable that if only a small amount of tumor was removed, then a favorable outcome might be achieved, but the patients might subsequently experience a high recurrence rate, which had been verified by our series (Fig. 10) [7]. In our series, the patients' quality of life and the preservation of neurological functions are primarily factored into the surgical strategy, and GTR is attempted at the initial surgery.

Surgical approach

Disagreements remain regarding the optimal approach for petroclival meningiomas that will provide adequate accessibility with minimal invasion and is selected based on the MRI characteristics and the surgeon's experience [9, 13, 28, 43, 47]. Various approaches were reported with different indications, advantages, and pitfalls [4, 5, 9, 10, 18, 21, 23–25, 31, 35, 42, 43, 45–48, 54, 55, 58, 61]. We prefer a single approach, which is parallel to most prior studies [6, 22–25, 28, 37, 38, 45–47, 55, 56], rather than staged operations or combined approaches [4, 29, 35, 43].

The transpetrosal approach has been applied in many studies, among which PRT, compared with the retrosigmoid approach, poses the absolute advantage of exposing the petroclival region, minimal retraction of the cerebellum and temporal lobes, and a shorter distance to the clivus with a low rate of CSF leaking, venous sinus embolism, and Labbe's vein impairment, especially in tumors with large bulks that displayed a significant space-occupying effect, displaced the brainstem, and created a surgical corridor facilitating surgical manipulation; however, PRT required advanced anatomic dissection training. The technique and experience of PRT in our institute was detailed in a prior study [21]. Meanwhile, approaches evolved dramatically in our institute. PRT was once regarded as the optimal approach

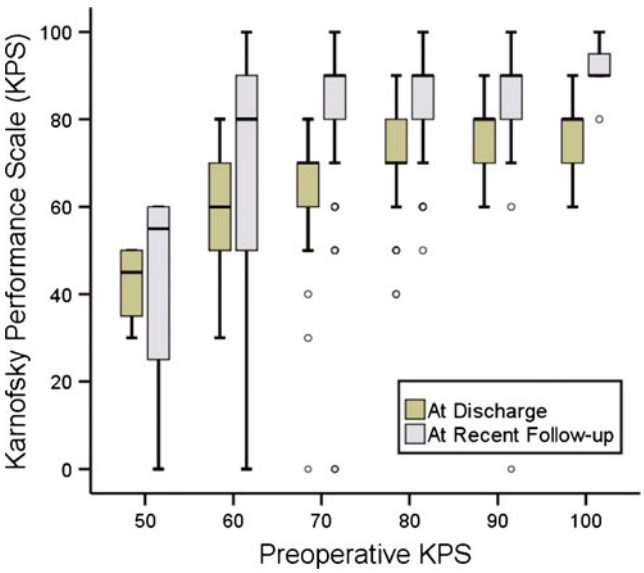


Fig. 8 Patients' KPS scores at discharge and at the most recent follow-up compared with the preoperative KPS scores. *Circles* indicate outliers

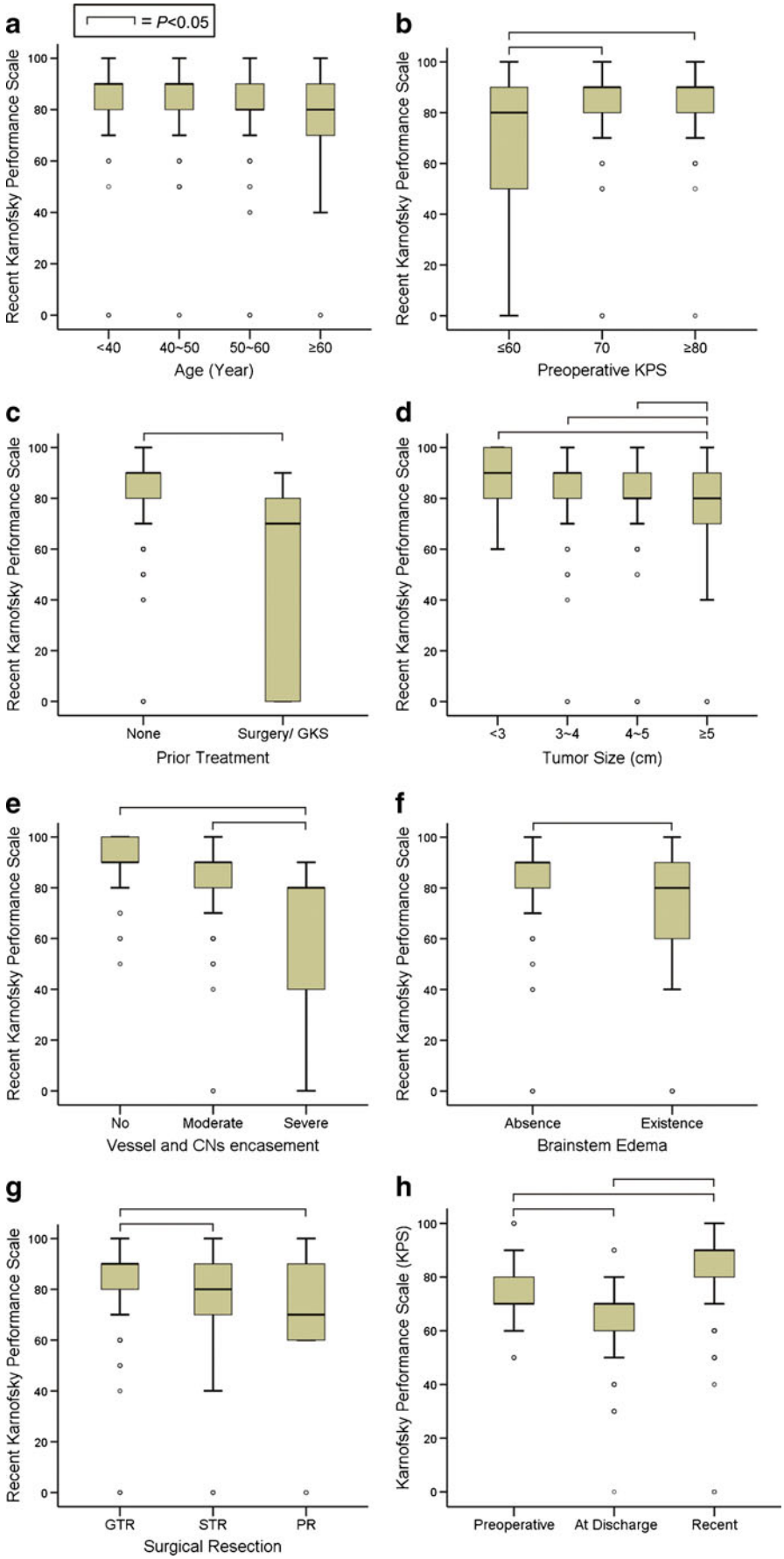
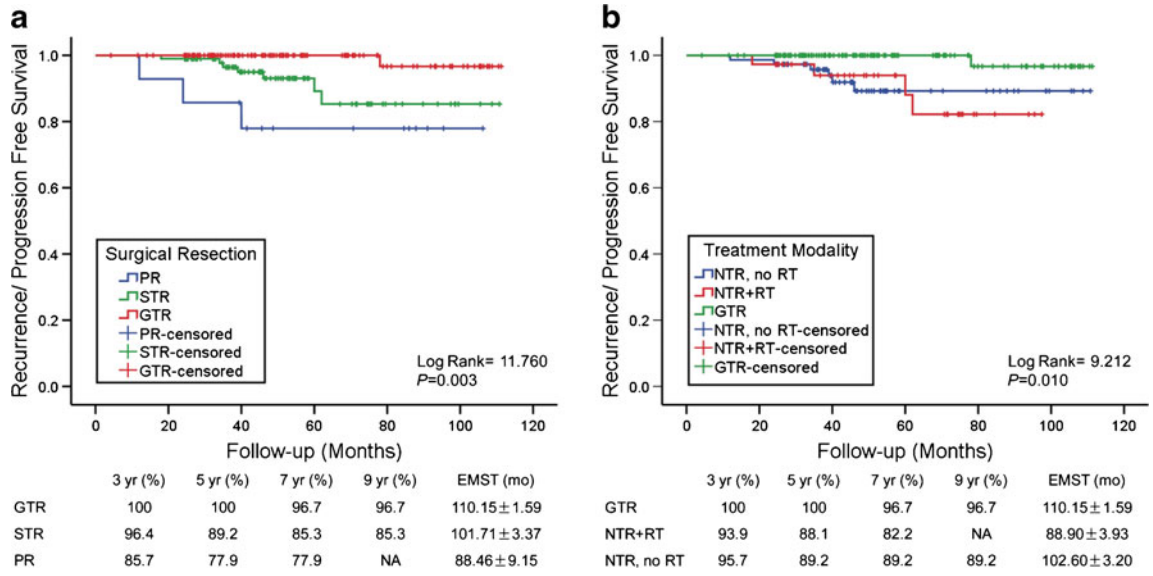


Fig. 9 Box-plot (**a**–**g**) illustrating the prognostic factors: age (**a**), preoperative Karnofsky Performance Scale (KPS) (**b**), prior treatment (**c**), tumor size (**d**), blood-vessel and CN encasement (**e**), brainstem edema (**f**), and surgical resection (**g**). **h** The distribution of the preoperative, postoperative, and most recent follow-up KPS scores. *Circles* indicate the outliers. *CNs* cranial nerves, *GTR* gross total resection, *STR* subtotal resection, *PR* partial resection



	3 yr (%)	5 yr (%)	7 yr (%)	9 yr (%)	EMST (mo)
GTR	100	100	96.7	96.7	110.15±1.59
STR	96.4	89.2	85.3	85.3	101.71±3.37
PR	85.7	77.9	77.9	NA	88.46±9.15

	3 yr (%)	5 yr (%)	7 yr (%)	9 yr (%)	EMST (mo)
GTR	100	100	96.7	96.7	110.15±1.59
NTR+RT	93.9	88.1	82.2	NA	88.90±3.93
NTR, no RT	95.7	89.2	89.2	89.2	102.60±3.20

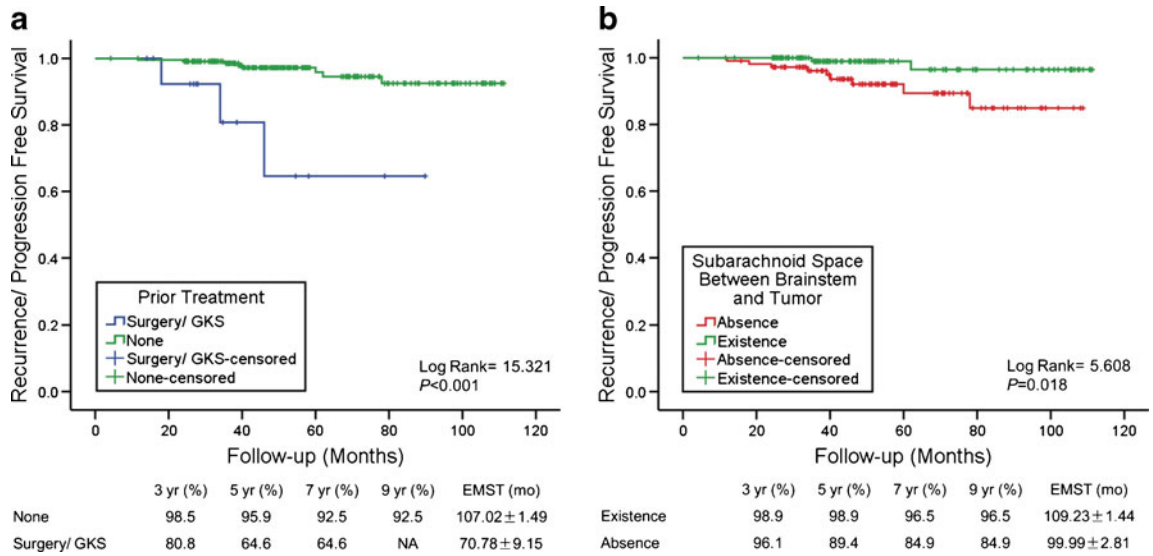
Fig. 10 Kaplan-Meier survival analysis comparing the R/P-free cumulative survival of patients between different treatment modalities. The difference in the R/P-free survival between patients with STR or PR (**a**) was not significant, and neither was the difference between patients with or without radiotherapy after NTR (**b**). *EMST* estimated mean survival time, *GTR* gross total resection, *NA* not available, *NTR* non-total resection, *PR* partial resection, *R/P* recurrence/ progression, *RT* radiotherapy

at the early period; however, after the introduction of ATPT, we found that surgical resection rate and outcomes were similar in both groups (PRT and ATPT); furthermore, ATPT involved less surgical morbidities and were less time-consuming. Consequently, ATPT was used gradually more frequently in recent years and became a preferential approach.

Although all approaches pose advantages and pitfalls based on the various indications and vary in different studies, surgeons who choose their most familiar approach might achieve complete resection and reduce surgical complication rates to a minimum by increasing their clinical experience and constantly improving their surgical technique [9, 21, 27, 35, 43, 58].

Intraoperation

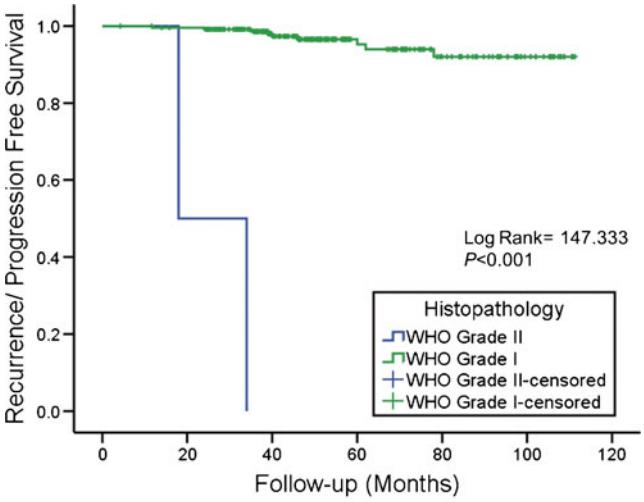
Intraoperative manipulation with gentleness, meticulousness, and appropriate processing methods contribute to the preservation of neurological function [34]. In our series, processing the



	3 yr (%)	5 yr (%)	7 yr (%)	9 yr (%)	EMST (mo)
None	98.5	95.9	92.5	92.5	107.02±1.49
Surgery/ GKS	80.8	64.6	64.6	NA	70.78±9.15

	3 yr (%)	5 yr (%)	7 yr (%)	9 yr (%)	EMST (mo)
Existence	98.9	98.9	96.5	96.5	109.23±1.44
Absence	96.1	89.4	84.9	84.9	99.99±2.81

Fig. 11 Kaplan-Meier survival analysis illustrating the effect of prior treatment (**a**) and subarachnoid space between the brainstem and the tumor (**b**) on R/P-free cumulative survival. *EMST* estimated mean survival time, *GKS* gamma knife surgery, *NA* not available, *R/P* recurrence/progression



	3 yr (%)	5 yr (%)	7 yr (%)	9 yr (%)	EMST (mo)
WHO Grade I	98.6	95.3	92.0	92.0	106.69±1.51
WHO Grade II	NA	NA	NA	NA	26.00±8.00

Fig. 12 Kaplan-Meier survival analysis comparing the R/P-free cumulative survival between patients with WHO grade I or II tumors. *EMST* estimated mean survival time, *NA* not available

main feeders of the tumor base during the early stage was important for achieving a bloodless resection, which contributed to perfect visualization of involved structures and further facilitated the safe resection. Internal tumor decompression was performed, freeing all the blood vessels and CNs was attempted, then tumor capsule was ultimately removed. En bloc removal was not recommended for large lesions that could cause excessive retraction and deformity of the CNs, brainstem, and vital vessels. Tumors involving the cavernous sinus were removed depending on their soft consistency and non-adhesion to the CNs or the carotid artery. Poorly distinguishable anatomy caused by prior operations and blood vessel infiltration or intense adherence due to prior radiotherapy has been frequently observed; meanwhile, fusion of the tunica adventitia of the blood vessel, epineurium, and tumor pial was often encountered, arbitrary dissection or excessive retraction was avoided. The tumors were retained or a thin layer of the tumor was left to prevent the vascular occlusion or functional disturbance.

Outcomes and prognostic factors

A study by Little et al. [30] revealed that the risk of CN deficits is significantly associated with prior resections, preoperative CN function [49], tumor adherence to neurovascular structures, and a fibrous tumor consistency; some of these factors (similar to cavernous sinus involvement and the tumor size) also influence the complete resection rate. The duration of symptom was confirmed to be related to the outcomes [38]. Adachi et al. [2] established a new scoring system for predicting the extent of tumor removal and neurological outcome. Some lesions often invade the arachnoid layer and then the adhesion to the brainstem and tumor feeders from the brainstem developed. Greater extension of the brainstem edema indicates a higher degree of invasion or adherence. Adverse factors of the recent KPS score in our series were parallel to prior studies. Moreover, cavernous sinus invasion was observed in 61.0 % of patients. Although we attempted to obtain only STR of the tumors involving the cavernous sinus, the procedure still disturbed the patients' CNs function. Fortunately, the majority of the deficits were recovered to normal function by the most recent follow-up.

The probability and reasons for R/P of petroclival meningiomas are undefined [35]. The recurrence rates in published studies vary, ranging from 0 to 26 % [1, 6, 11, 30, 35, 38, 42, 47, 55, 56]. Natarajan et al. [35] claimed that it was useless to compare the published studies because of the various durations of follow-up and the definition of R/P as radiographic or symptomatic. Jung et al. [22] verified that age, radiation, and menopause were related to the growth rate of the residual tumors. Factors related to R/P in our series were similar to other studies and additional attention should be paid to patients with high potentiality of R/P. Favorable outcomes can be achieved in selected patients without such adverse factors.

Although postoperative radiotherapy was not significantly relevant to the outcomes in our series, it did positively affect incompletely resected tumors. In the five patients who died with recurrent tumors (Table 11), the predominant reason for the outcomes was the ineffectiveness of observation and the passive attitude toward treatment. Because GTR cannot be achieved in all patients and R/P will invariably occur during follow-up, MRI follow-up was imperative and postoperative radiotherapy should be administrated to the patients with NTR, if necessary. Therefore, the treatment in the recent series was as follows: 1. Surgery was suggested for patients with age ≤75 years, including asymptomatic and small tumors; 2. Radiotherapy was reserved for patients with advanced ages (>75 years) and significant co-morbidities, for patients with PR or mild R/P after NTR, or for patients who rejected surgery; 3. If the tumor size after R/P was significant and substantially larger than that of the residual tumor, reoperation was recommended instead of radiotherapy.

Limitations of the recent study

Limitations of the recent study are as follows: 1. Surgical approaches were not selected randomizedly; 2. The follow-up time was not long enough; 3. The study was unable to identify differences between GKS and surgery treatment. Therefore, we suggested that a prospective randomized controlled trial with multiple treatments should be performed to improve research results. Attention should be focused on tumor growth or regrowth curve based on series of MRI

Table 12 Previous series

Series	*n*	GTR (%)	STR (%)	Major morbidity (%)	Mortality (%)	Mean follow-up (m)	R/P (%)	Death of follow-up (%)	Main surgical approach (%)
Abdel et al. 2000 [1]	35	37	31	9	0	51	3		CP (71)[a]
Al-Mefty et al. 1988 [2]	13	85	15	8	0	26	8		TP (100)
Bambakidis et al. 2008 [3]	46	43	41	41	0	43	16	0	RS (59)
Bricolo et al. 1992 [5]	33	79	12	76	9	52	23	9	RM (70)
Carvalho et al. 2000 [6]	70					53			
Chen et al. 2011 [8]	82	56	34		2		9		RS (51)
Cho and Al-Mefty 2002 [9]	7	71	29		0	24	0	0	CP (100)
Couldwell et al. 1996 [10]	109	69	31	32	4		13		SR/RA (55)
Erkmen et al. 2005 [12]	97								CP (35)
Goel 1999 [15]	24	67				14	0		ELST (100)
Goel and Muzumdar 2004 [16]	28	75	25		7	48	4	0	RS (100)
Javed and Sekhar 1991 [19]	52	73	21		4		4		
Jung et al. 2000 [21]	64	41		16	1.5				
Kawase et al. 1991 [22]	10	70	30	90	0		10	0	ATPT (100)
Kawase et al. 1994 [23]	42	76	24		0	54	7	2	ATPT (100)
Kusumi et al. 2012 [26]	111								
Li et al. 2010 [27]	57	58	21	42	1.8	34	12	1.8	RS (40)
Little et al. 2005 [29]	137	40	40	26	1	8.3	18		CP (39)
Mathiesen et al. 2007 [30]	29	41	59		0	66	7	3	CP (100)
Mayberg and Symon 1986 [31]	35	26	74	86	9	34	23	15	SO (54)
Nanda et al. 2011 [33]	50	28		44	6	22	19	0	TP (32)
Natarajan et al. 2007 [34]	150	32	43	22	0	102	5	12	TPLPA (67)
Nishimura et al. 1989 [36]	24	71	29	100	8	60	36	13	TP (75)[b]
Park et al. 2006 [37]	49	20		29	2	86[c]	22	0	PP (51)
Roberti et al. 2001 [40]	110	45		90	1				
Samii et al. 1989 [41]	24	71	29	46	0				RM (54)
Samii and Tatagiba 1992 [44]	36	75			0				RM (42)
Samii et al. 1999 [45]	70								TPS (50)
Seifert 2010 [46]	93	37	39	32	0		16		SSR (52)
Seifert et al. 2003 [47]	19	63	37	63	0		11		TP (100)[d]
Sekhar et al. 1994 [48]	48								TPS
Tahara et al. 2009 [51]	15	50	30		13		8	0	RS (53)
Watanabe et al. 2011 [54]	37								LST (70)
Yamakami et al. 2011 [55]	32	59		31	0	65	9	6	AP (46)
Yang et al. 2011 [56]	41	61	37	66	0	35	15	0	
Yang et al. 2011 [57]	39	64	28	64	0				STA (64)
Zentner et al. 1997 [59]	19	68	32	33	5	18	0	0	PP (58)
Zhu et al. 2006 [60]	25	56	32	48	4		0	0	CRS (100)
Present series	259	53	41	54	1	55	5	4	PRT (50)

AP anterior petrosal approach, *ATPT* anterior transpetrosal transtentorial, *CP* combined petrosal approach, *CRS* combined retrosigmoid and subtemporal approach, *ELST* extended lateral subtemporal approach, *GTR* gross total resection, *LST* lateral supracerebellar transtentorial approach, *PP* posterior petrosal approach, including retrolabyrinthine, translabyrinthine, transcochlear, and transotic, *PR* partial resection, *PRT* presigmoid retrolabyrinthine transpetrosal approach, *RM* retromastoid approach, *R/P* recurrence/progression, *RS* retrosigmoid approach, *SO* suboccipital approach, *SSR* standard suboccipital retromastoidal approach, *STA* subtemporal transpetrosal apex approach, *STR* subtotal resection, *TP* transpetrosal, *TPLPA* transpetrosal partial labyrinthectomy petrous apicectomy, *TPS* transpetrosal presigmoid

[a] The combined petrosal approach comprised anterior petrosal approach and posterior petrosal approach

[b] 38% patients with transzygomatic and 38 % patients without it

[c] The time was a median follow-up time

[d] The approach was conservative (labyrinth-preserving) transpetrosal approach

scans and changes of patients' life quality and neurological function after different treatments.

Conclusions

The selection of a therapeutic strategy for petroclival meningiomas should be individualized and should also take account the preoperative variables. Surgery is the initial treatment for petroclival meningiomas, even for asymptomatic or small tumors; moreover, an R/P-free survival rate of 91.2 % at 9 years and an overall survival rate of 94.7 % at 9 years can be achieved. Aggressive treatment is important for recurrent cases.

Conflicts of interest None.

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Comment

This impressive series illustrates a nationally centered approach to a formidable surgical problem. It is important for surgeons to realise that we may make our patients worse (see Table 9) but these tumors may remain unchanged for a long time without intervention. The skill is to realize which patient to select for surgery and then by which method.

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