Neurochirurgie 65 (2019) 55–62

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Original article

Long term surgical results of 154 petroclival meningiomas: A retrospective multicenter study

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ARTICLE INFO

Article history:
Received 12 October 2018
Received in revised form 2 February 2019
Accepted 3 February 2019
Available online 16 May 2019

Keywords:
Meningioma
Microsurgery
Petroclival
Skull base
Oncology

ABSTRACT

Background. – Outcomes of petroclival meningiomas (PCM) (morbidity, permanent cranial nerves deficit, tumor removal and recurrence) are inconsistent in the literature, making it a challenge to predict surgical morbidity.
Methods. – A multicenter study of patients with PCMs larger than 2.5 cm between 1984 and 2017 was conducted. The authors retrospectively reviewed the patients' medical records, imaging studies and pathology reports to analyze presentation, surgical approach, neurological outcomes, complications, recurrence rates and predictive factors.
Results. – There were 154 patients. The follow-up was 76.8 months on average (range 8–380 months). Gross total resection (GTR) was achieved in 40 (26.0%) patients, subtotal resection (STR) in 101 (65.6%), and partial resection in 13 (8.3%). Six (2.6%) perioperative deaths occurred. The 5-year, 10-year and 15-year progression-free survival (PFS) of GTR and STR with radiation therapy (RT) was similar (100%, 90% and 75%). PFS of STR without adjuvant radiation was associated with progression in 71%, 51% and 31%, respectively. Anterior petrosectomy and combined petrosectomy were associated with higher postoperative CN V and CN VI deficits compared to the retrosigmoid approach. The latter had a significantly higher risk of CN VII, CN VIII and LCN deficit. Temporal lobe dysfunction (seizure and aphasia) were significantly associated with the anterior petrosectomy approach.
Conclusions. – Our study shows that optimal subtotal resection of PCMs associated with postoperative RT or stereotactic radiosurgery results in long-term tumor control to equivalent radical surgery. Case selection and appropriate intraoperative judgement are required to reduce the morbidity.

1. Abbreviations

CN	cranial nerve
CPA	cerebellopontine angle
CT	Computed tomography scans
CS	cavernous sinus
ENT	ear, nose and throat specialist (otolaryngologist)
EOR	extent of resection
GKS	gamma knife radiosurgery
GTR	gross total resection
IAC	internal auditory canal
KPS	Karnofsky Performance Status
LCN	lower cranial nerve
MRI	magnetic resonance imaging
OS	overall survival
PCM	petroclival meningioma
PFS	progression-free survival
PR	partial resection
RT	radiation therapy
R/P	recurrence/progression
SRS	stereotactic radiosurgery
STR	subtotal resection

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https://doi.org/10.1016/j.neuchi.2019.02.001
0028-3770/

2. Introduction

The petroclival region is a surgical entity rather than an anatomical one, recognized because of specific diseases, notably petroclival meningiomas (PCM). Defining a tumor as a PCM is challenging. Its rarity has complicated attempts at classifying tumors in this region and large published studies frequently include heterogeneous groups of tumors. PCMs originate or insert in the upper two-thirds of the clivus, the inferior petrosal sinus or the petrous apex around the trigeminal notch, medial or around to the trigeminal incisura. This definition distinguishes PCMs from cerebellopontine angle, posterior petrous bone, sphenopetroclival or midclival tumors which do not entail the same surgical problems [1,2].

Surgery of medium and large PCMs is challenging because of:

- their propensity to engulf nerves and blood vessels, to invade the cavernous sinus (CS), and to extend to multiple cranial fossae and foramina;
- their natural history: owing to the indolent nature and low growth rate of PCMs, the length of follow-up in previous studies has not been sufficient to define the lifelong outcome [3];
- each treatment option — observation, radiosurgery and/or surgery — carries the risk of significant morbidity and must be weighed against the natural history of these tumors.

Patient counselling, as well as pre- and intraoperative decision-making, is difficult. Indeed, patients usually present with mild symptoms at the time of diagnosis, even with large tumors [4–11]. Moreover, the large variance in published surgical outcomes (mortality, morbidity, permanent cranial nerves deficits, tumor removal and recurrence) makes it challenging to predict surgical morbidity. In this study, we retrospectively reviewed our multicenter experience with 154 patients who underwent surgical treatment of PCMs larger than 2.5 cm to provide recommendations regarding their surgical management.

3. Methods

3.1. Data collection

All consecutive adult patients ($\geq$ 18 years old) who underwent surgical treatment of a PCM (diameter $\geq$ 2.5 cm) between January 1984 and September 2017 in one of the Neurosurgery Departments of four French university hospitals (Angers, Marseille, Grenoble and Tours) were included in this retrospective cohort study. PCMs were defined as those originating in the upper two-thirds of the clivus, the inferior petrosal sinus, or the petrous apex around the trigeminal incisura, medial to the trigeminal nerve. The diagnosis of meningioma was confirmed histologically in all cases. Informed consent was obtained from all patients, and our hospitals' local ethics committees approved this study.

The clinical data were recorded from the medical records, location and features of the tumor on imaging examinations, extent of the resection, histopathological characteristics, outcome and follow-up with or without recurrence.

3.2. Neurological examinations

All patients underwent extensive pre- and postoperative neurological examinations with detailed medical history (including major diseases such as thromboembolism, cardiovascular risk, respiratory, cardiac, neoplastic and other neurologic illness), quality of life assessment using the Karnofsky Performance Status (KPS) and detailed cranial nerve (CN) testing. Swallowing was assessed by an ENT.

3.3. Imaging analyses

Computed tomography (CT) scans and magnetic resonance imaging (MRI) were obtained for all patients during the diagnostic work-up except 2 who were operated before 1990 and did not have a preoperative MRI. High-resolution CT scans provided the best images of the petrous bone and surrounding structures (especially the petrous pneumatization and the carotid canal trajectory). Gadolinium-enhanced and T2-weighted MRI sequences were obtained to analyze the main meningiomas insertion and spread of tumor outside the petroclival region. Maximum tumor diameter was measured on a gadolinium-enhanced axial T1-weighted MRI. The area of the involved tumor was calculated including the main insertion (unique/multiple; upper clivus; inferior petrosal sinus; petrous apex around the trigeminal incisura) and the secondary extension (middle fossa; tentorium; CPA; IAC; jugular foramen).

3.4. Surgical strategy

The choice of surgical approach (cisternal or transbasal) was based on multiple factors including:

- the location, size, extent of brainstem compression, involvement of vasculature, extension of tumor outside the petroclival area;
- the patient's condition (age, previous treatments, neurological status, hearing level);
- surgical team experience;
- the goal of surgery.

3.5. Operative reports and follow-up

Operative reports included the surgical approach and the extent of resection (EOR) according to the Simpson grading scale and the postoperative MRI. GTR leaves no visible residual tumor on follow-up MRI and CT scans (Simpson grade I/II). Subtotal removal (STR) (Simpson grade III) was labelled as residual tumor left within the CS, the brainstem or the cerebral peduncle. Partial tumor resection (PR) was defined as residual gross tumor remaining intradurally after surgery (Simpson IV).

Clinical and radiological follow-up was planned in the early postoperative course, at 6 and 12 months after resection, and subsequently at 2, 3, 5, 7 & 10 years after surgery, and then once every 3 years thereafter. Recurrence was defined as in situ regrowth of the tumor after GTR; progression after STR or PR was defined as more than 2 mm increase in maximal residual tumor diameter. Progression-free survival (PFS) was measured from the date of surgery to the date of first radiological evidence of progression.

3.6. Statistical analysis

Analyses were performed using R software v2.15.1 [12]. Results are expressed as mean $\pm$ standard deviation with a range for continuous variables. OS and PFS were plotted by the Kaplan-Meier method, using logrank tests to assess significance when comparing groups. A *P*-value less than 0.05 was considered significant. Student's *t*-test for paired series was used to test the significance of the differences between the values of two groups. A multivariate Cox regression model was used to identify independent prognostic factors affecting the patients' surgical morbidity, OS and PFS. The impact of preoperative data, surgical approach, MRI characteristics, EOR and adjuvant therapy on prognosis was studied.

Table 1
Patient characteristics and clinical presentation.

Patient characteristics	No. of patients (%)
Female (%)	121 (78.6)
Mean age, years (range)	53.6 (11–77)
Previous treatment (%)	14 (9)
Mean preoperative KPS	90.8
Clinical presentation	
Ataxia	42 (27.2)
Proprioceptive ataxia	36 (23.4)
Cerebellar ataxia	24 (15.6)
Hemiparesis	23 (15.1)
Headaches	21 (13.6)
Hydrocephalus	21 (13.6)
Seizure	7 (4.5)
Bed-ridden	6 (3.9)
Diplopia (III-VI)	18 (11.7)
CN deficit (%)	107 (70.4)
CN II	6 (3.9)
CN III	11 (7.1)
CN IV	6 (3.9)
CN V	65 (42.2)
Facial neuralgia	36 (23.4)
Facial hypoesthesia	53 (34.4)
CN VI	10 (6.5)
CN VII	16 (10.4)
CN VIII	61 (39.6)
Hearing loss	59 (38.3)
Vestibular syndrome	37 (24.0)
CN IX-XI	13 (8.4)
CN XII	1 (0.6)

CN: cranial nerve; KPS: Karnofsky performance status.

4. Results

4.1. Epidemiological and clinical data (Table 1)

During the 33-year study period, 154 patients underwent PCM excision. The mean age at diagnosis was 53.6 years (range 26–77). Females represented 78.6% of all patients ($n = 121$). Forty patients had a major disease previous to the PCM (26%). In terms of clinical presentation, 107 (70.4%) cases developed CN dysfunction and 23 cases developed hemiparesis (15.1%; Table 1). The most common presenting symptom was a trigeminal complaint for 53 patients (34.4%). Other common presenting symptoms included facial pain (23.4%), hearing loss (38.3%), and ataxia (27.2%). The mean preoperative KPS score was 90.8.

Out of the 154 patients, 140 presented with *de novo* tumors while 14 were previously operated in other centers and experienced a recurrence. Four of these 14 patients had sizeable residual tumor after initial resection, and 10 patients had been treated with radiation therapy in addition to initial resection.

4.2. Imaging data (Table 2)

The main insertion component was located medial or around the trigeminal porus in all cases, therefore involving the inferior petrosal sinus ($n = 111$, 72.1%), upper clivus ($n = 81$, 52.6%), and petrous apex ($n = 80$, 51.9%). The main dural insertion was multifocal in 89 cases (57.8%) while secondary extension involved the tentorium, middle fossa, cerebellopontine angle, internal acoustic canal and jugular foramen in 63.0%, 36.4%, 35.1%, 28.6% and 18.2% of cases, respectively.

4.3. Surgical strategy (Table 3)

The most commonly used approach were skull base techniques ($n = 107$, 69.5%) followed by the cisternal ones ($n = 46$, 29.9%).

Table 2
Primary tumor location and extension.

Region	No. of patients (%)
Insertion	
Multiple insertion (> 2 among IPS, Upper clivus, Petrous apex)	89 (57.8)
IPS	111 (72.1)
Upper clivus	81 (52.6)
Petrous apex (around tentorial incisura)	80 (51.9)
Secondary extension	
Tentorium/petroclinoid ligament	97 (63.0)
Middle fossa	56 (36.4)
CPA	54 (35.1)
IAC	44 (28.6)
Jugular Foramen	28 (18.2)

CPA: cerebellopontine angle; IAC: internal acoustic canal; IPS: inferior petrosal sinus.

Table 3
Surgical management used in 154 patients.

Surgical approach	$n = 154$ (%)
Trans-basal approaches	
Anterior petrosectomy (Kawase)	65 (42.2)
Combined petrosectomy	16 (10.4)
Translabyrinthine approach	8 (5.2)
Anterior petrosectomy & pterional approaches	8 (5.2)
Anterior petrosectomy & transcavernous (Kawase + Dolenc)	4 (2.6)
Retrolabyrinthine approach	3 (1.9)
Transcochlear approach	2 (1.3)
Transsphenoidal approach	1 (0.6)
Cisternal approaches	
Retrosigmoid approach (RS)	36 (23.4)
Pterional approach	5 (3.2)
Sub-temporal transtentorial approach	4 (2.6)
Retrosigmoid & pterional approaches	1 (0.6)
No information	1 (0.6)
Extent of resection	
Gross total resection, %	40 (26.0)
Subtotal resection, %	97 (63.0)
Partial resection, %	17 (11.0)
Treatment used	
First line	154
Surgery	122 (79.2)
Surgery + adjuvant therapy	34 (22.1)
Second line (R/P)	40 (26.0)
Surgery	6 (15.0)
Surgery + adjuvant therapy	0 (0)
Radiation therapy	11 (27.5)
Radiosurgery	16 (40.0)
Observation	7 (17.5)
Follow-up	
Mean follow-up, months (range)	76.8 (20–380)
Mortality during follow-up, %	11 (7.1)
Recurrence/progression, %	40 (26.0)

More precisely, anterior petrosectomy was the main approach used ($n = 65$, 42.2%) followed by the retrosigmoid approach ($n = 36$, 23.4%) and combined petrosectomy ($n = 16$, 10.4%). The remaining approaches are listed in Table 3.

4.4. Extent of resection and histological data (Table 3)

GTR was performed in 40 patients (26.0%), STR in 97 patients (63.0%), and PR in 17 (11.0%). Based on the World Health Organization scale, 142 tumors in our series were grade I meningiomas and 12 tumors (8%) had atypical pathology (WHO Grade II). Among the 97 STR patients, 24 patients underwent additional SRS (24.7%) and 10 underwent radiation therapy (10.3%).

Table 4
Perioperative deaths (within 60 days) linked to the patient's history and the occurrence of intraoperative complications.

Patient	Cause of peri-operative death	Preoperative neurological status	Intraoperative complication
1	Myocardial infarction (Day 3)	–	No
2	Sylvian stroke (Day 3)	Progression after first surgery Axial sign (ataxia) Intracranial hypertension	Carotid artery injury
3	Cerebral posterior ischemia (Day 21)	Progression after first surgery Hemiplegia Intracranial hypertension	Cerebral posterior artery injury
4	General complications (Day 60)	Multiple operations Radiotherapy Axial sign	No
5	Acute respiratory distress syndrome (Day 13)	Swallowing disorder	No
6	Meningoencephalitis (Day 59)	Multiple operations VP-Shunt for hydrocephalus	No

VP: ventriculoperitoneal.

4.5. Mortality (Tables 3 and 4, Fig. 1A)

Six patients (3.9%) died in the perioperative period (within 60 days). Of these 6 patients, 5 had at least one severe comorbidity (83%), and 4 had a previously surgically treated PCM (28.6%). In the follow-up, 8 deaths occurred, among which 5 patients died of tumor progression. The 3 other patients died from other causes (70, 82, 101 months postoperatively.

4.6. Surgical morbidity (Table 5)

CN dysfunctions were the most common complications and were notable immediately after the operation: 116 (78.4%) of 148 patients had new deficits of one or more CNs postoperatively while 98 patients (66.5%) had persistent CN deficits at last follow-up. CN V deficits improved between 1-month post-operative and the last follow-up ($P = 0.03$).

In the early postoperative course, new transient hemiparesis was noticed in 16 patients (10.4%), transient cerebellar ataxia in 6 (3.9%) and transient proprioceptive ataxia in 7 (4.7%) patients. CSF leakage occurred in 8 cases (5.4%) that required re-operation. The leakage in seven patients led to meningitis. Tracheotomy was performed in 7 cases (4.7%) due to swallowing dysfunction. Five patients had postoperative intracranial hemorrhage accompanied by neurological deterioration. Hematomas occurred in the posterior fossa and required emergent surgical evacuation. Additional complications included stroke ($n = 6$, 4.1%), hydrocephalus ($n = 7$, 4.7%), and aphasia ($n = 17$, 11.0%). Permanent new morbidities remained in 103 patients (66.9%) and included hemiparesis ($n = 17$, 11.9), ataxia ($n = 48$, 33.6%), oculomotor deficit ($n = 27$, 18.9%), facial numbness ($n = 82$, 57.3%), and facial nerve deficit ($n = 39$, 27.3%).

4.7. Variables associated with postoperative neurological deficits

Clinical and radiographic preoperative variables were evaluated for their effects on the rate of postoperative neurological deficits using multivariate analysis. The variables included patient age, previous surgery, preexisting paresis/ataxia, preexisting cranial nerve deficit, evidence of brainstem compression and multiple cranial fossa involvement on preoperative imaging. The surgical approach had a statistically significant effect on the rate of postoperative cranial nerve deficits and paresis/ataxia. In patients with preoperative CN deficits, the rate of definitive new postoperative deficits in previously uninvolved CNs was significantly higher (61.7%) than the rate of new postoperative CN deficits in patients without preoperative CN deficits (44.7%; $P = 0.04$). Among the preoperative variables, the 14 patients with a history of prior PCM resection had significantly higher rates of new or exacerbated CN deficits (70%) and paresis/ataxia (40%), ($P = 0.001$ and $P = 0.001$; respectively).

The risk of new cranial nerve deficits differed from one surgical approach to another. The transpetrosal approaches — anterior petrosectomy and combined petrosectomy — were significantly associated with higher postoperative CN V deficit (hypoesthesia and trigeminal neuralgia) and CN VI deficit compared to the retrosigmoid approach ($P = 0.04$). The latter has a significantly higher risk of CN VII, CN VIII and LCN deficit ($P < 0.05$). Temporal lobe injury (seizures and aphasia) was significantly associated with the anterior petrosectomy approach in the univariate analysis.

4.8. Functional outcomes

The mean KPS score on presentation was 90.8; KPS was not available for 27 patients; 10 patients were transferred with a preoperative KPS score less than 70 (Supplemental Table 1). At 1 month after surgery in all patients, the KPS scores decreased significantly (mean of 84.3, $P = 0.008$), but then recovered during the follow-up period (recent KPS of 91.9). Although a higher mean KPS was observed over the long-term follow-up, there was no significant difference between the preoperative and follow-up KPS scores (91.6 vs. 91.9, $P = 0.81$).

4.9. Follow-up and recurrence–oncological results (Fig. 1B)

Ten patients were lost to follow-up. The mean clinical and radiological follow-up was 76.8 months (range 20–380 months). The 5-year, 10-year and 15-year PFS of the GTR group was 100.0%, 90.0% and 75.0%, respectively. The 5-year, 10-year and 15-year PFS rates for patients in the STR group were 100%, 90.0% and 75.2% with radiation therapy, and 71.2%, 51.2% and 30.7% without radiation therapy. Mean long-term KPS for patients in the STR without RT group were similar to patients in the STR + RT group (93.3% and 93.1% respectively). Contrary to the STR group, which had a statistically higher risk of R/P ($P = 0.04$), STR with radiation therapy did not differ from the GTR group in terms of the PFS. Adjuvant treatments were statistically predictive of better tumor control following STR ($P = 0.009$). Neither preoperative radiological characteristics, surgical approach, or WHO grade were predictive of R/P. Patients with R/P ($n = 40$, 26.0%) underwent second-line SRS ($n = 16$, 40.0%), fractionated radiotherapy ($n = 11$, 27.5%), surgical excision ($n = 6$, 15.0%), observation ($n = 7$, 17.5%) (Table 3). Four patients with further regrowth had a third operation; 2 patients with further regrowth underwent radiosurgery.

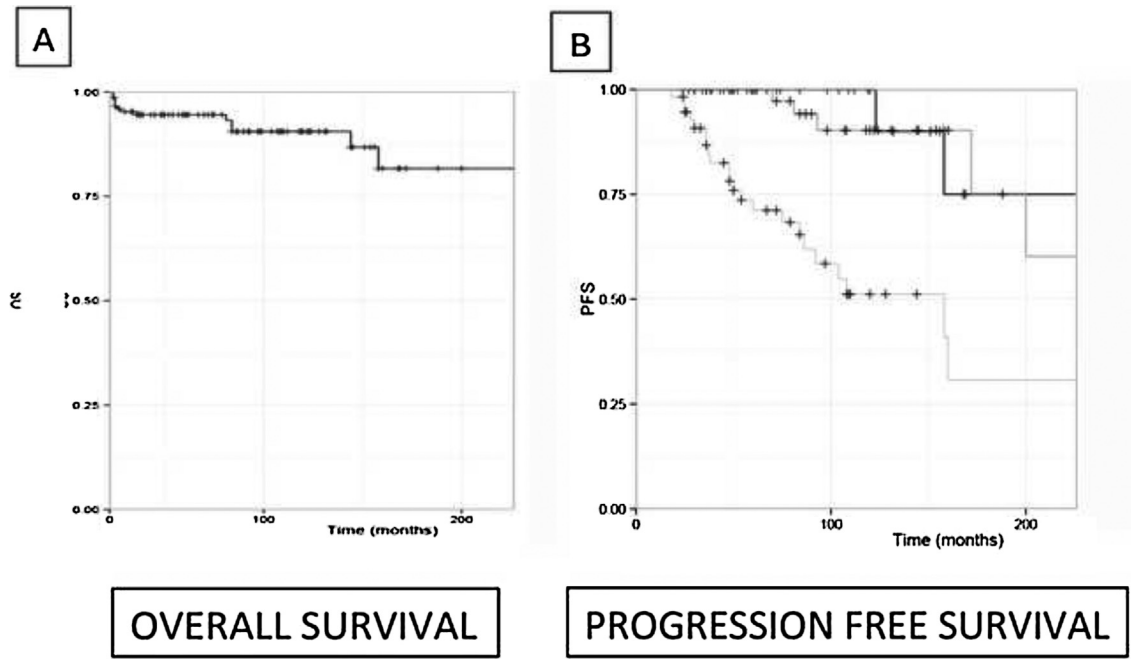

Fig. 1. A: Kaplan–Meier analysis of OS. B: Kaplan–Meier analysis of R/P-free survival. GTR: gross total removal; STR: subtotal removal without adjuvant radiation therapy; STR + RT: subtotal removal with adjuvant radiation therapy. Log rank test: GTR versus STR + RT: $P = 0.81$; GTR versus STR: $P = 0.004$; STR + RT versus STR: $P = 0.009$.

Table 5
Pre- and post-operative morbidity.

Deficits	Preoperative (%)	Morbidity at 1 month (%)	Permanent morbidity (%)
Overall	154	148	143
No. patients with CNs deficits	107 (70.4)	116 (78.4)	98 (66.5)
CN II	6 (3.9)	1 (0.6)	0 (0)
CN III	11 (7.1)	41 (27.7)	27 (18.9)
CN IV	6 (3.9)	36 (24.3)	24 (16.8)
CN V	65 (42.2)	96 (64.9)	82 (57.3)
CN VI	10 (6.5)	61 (41.2)	43 (30.1)
CN VII	16 (10.4)	51 (34.5)	39 (27.3)
CN VIII	61 (39.6)	70 (47.3)	58 (40.6)
CN IX-XII	14 (9.0)	29 (19.6)	19 (13.3)
Hemiparesis	23 (15.1)	52 (35.1)	17 (11.9)
Ataxia	42 (27.2)	85 (57.4)	48 (33.6)
Aphasia	0 (0)	17 (11.5)	6 (4.2)
Hydrocephalus	21 (13.6)	7 (4.7)	0 (0)
Coma	0 (0)	5 (3.2)	0 (0)
Corneal ulcer	0 (0)	16 (10.4)	0 (0)
Intracranial hematoma	0 (0)	5 (3.4)	0 (0)
Stroke	0 (0)	6 (4.1)	2 (1,4)
Brainstem contusion	0 (0)	3 (1.9)	0 (0)
Wound infection	0 (0)	2 (1.3)	0 (0)
CSF leak	0 (0)	8 (5.4)	0 (0)
Meningitis	0 (0)	7 (4.7)	0 (0)
Tracheotomy	0 (0)	7 (4.7)	6 (4.2)
Gastrostomy	0 (0)	6 (4.1)	4 (2.8)
Pneumonia	0 (0)	11 (7.4)	0 (0)

CN: Cranial nerve; CSF: cerebrospinal fluid.

5. Discussion

After reviewing our 154 PCM cases, we recommend that surgery be considered cautiously for patient with preoperative KPS scores less than 70, with previous surgical attempts and severe comorbidities given the mortality risk. The quality of life declined at 1 month after surgery but gradually improved during the follow-up period.

5.1. Natural history

The natural history of PCMs is an important issue to consider to better evaluate the risk/benefit balance and the surgical indication. Given the rarity of PCMs, there is little data on this topic. In the largest study, Van Havenbergh et al. [11] found that 76% of 21 untreated PCMs demonstrated radiographic growth over a mean follow-up period of 82 months. More worrisome, 63% of patients whose tumors grew had significant functional decline and 50% of patients who initially had normal CN function developed cranial neuropathy [11]. Although their study had a relatively small patient population, it suggests that PCM treatment is appropriate, either with surgery if the patient can tolerate it or radiation therapy. We agree with this preference for resection, especially for large tumors with brainstem compression in the nonelderly population. However, we only advocate surgery when PCMs become symptomatic or show radiographic evidence of growth. In our study, all patient

were symptomatic, with 70.4% having a cranial deficit, 27.2% ataxia and 15.1% hemiparesis. To determine the optimal resection goal for each patient, the risk of mortality and neurological morbidity must be weighed against the natural history of this lesion and the risk of tumor recurrence.

5.2. Mortality

Once plagued by high mortality and morbidity, the outcome of surgically treated PCM has improved remarkably. In our study, most of the mortality was within 60 days after surgery (3.9%). There were two perioperative deaths linked to intraoperative arterial injury (internal carotid and cerebral posterior artery). These results are comparable to other reports in the literature [1,3,13–17]. EOR was not predictive of surgical mortality. However, preoperative KPS < 70, previously surgically treated PCM, severe comorbidity and patient age > 65 years were significantly predictive of perioperative death ($P < 0.05$). Thus we argue that preoperative patient comorbidities and severe clinical impairments are the main factors affecting mortality. In this high-risk subgroup of patients, surgical resection should be avoided, and alternative approaches such as radiosurgery, ventriculoperitoneal shunt, corticosteroid therapy should be considered on a case-by-case basis. Of note, perioperative mortality is typically assessed over the first 30 postoperative days. However, in an attempt to present results corresponding to our experience, we chose to increase this period to 60 days. Surgery could potentially have been the cause of death, especially due to major delayed complications such as thromboembolism or infection, even after the theoretical period of 30 days.

5.3. Morbidity

In our study, age greater than 65 years, preexisting paresis/ataxia, evidence of brainstem compression on preoperative imaging, and multiple cranial fossa involvement had a statistically significant effect on the rate of new postoperative neurological deficits. We found no correlation between EOR and the incidence of complications. We assume the lack of EOR effect on morbidity is because of the low rate of GTR in our series, which did not allow us to test this variable in a robust way. Additionally, Sekhar et al. [17] reported that male gender, diminished KPS, tumor size greater than 2.5 cm, brainstem edema, vascular encasement, and tumor blood supply from the basilar artery were each negative prognostic indicators.

In the literature, the incidence of CN deficits varied between 19% and 66% [30,34,35]. In our study, 98 patients developed a permanent CN deficit (66.5%). Park et al. [18] noted that favorable prognosis of preexisting cranial neuropathies and overall favorable functional outcome were associated with STR. Preoperatively symptomatic CNs are more vulnerable during resection. CN deficits were considered separately: the surgical approach is the main factor contributing to new cranial nerve deficits.

5.4. Surgical approach

The surgical anatomy of the petroclival region is complex and, consequently, one's management of these technically challenging surgical lesions is usually redefined over time. Historically, traditional intradural cisternal routes using suboccipital and pterional approaches have been proposed to remove petroclival tumors [8,10,19,20]. This allows rapid identification of neurovascular structures and shortens the exposure time. However access to the petroclival region is remote, not direct and requires intradural cerebral retraction [2]. In order to improve the access for tumoral dissection, lateral transpetrosal approaches have been proposed [1,5,21–24]. The extradural route shortens the distance to the petroclival region, better preserves the veins, decreases the cerebral retraction, and interrupts the tumor's vascular supply early on [2]. Transpetrosal approaches includes anterior petrosectomy [1,5] (removing the petrous apex), posterior petrosal approach [22,25,26] (removing of presigmoid retrolabyrinthine bone) and translabyrinthine petrosectomy [24]. Although our main surgical approach is the anterior petrosectomy, this preference must be tempered. Indeed, this approach mandates a longer operative time than cisternal approaches, with temporal brain retraction being significantly associated with brain contusion and thus risk of aphasia and seizures. Indeed, temporal deficits were underestimated in previous studies and appear to be significantly associated with this approach. Cognitive outcomes with prospective assessments by a neuropsychologist should be determined to better assess the temporal retraction consequences during transpetrosal drilling.

A presigmoid retrolabyrinthine approach is ideal for larger tumors extending below the internal auditory meatus in patients with serviceable hearing [27]. If hearing is lost, additional exposure may be afforded by a translabyrinthine approach [28]. The combined petrosectomy approach (anterior with retrolabyrinthine petrosectomy) may also be used to access a larger tumor extending across the clival midline, upward to the tentorium or downward to the lower cranial nerves [1,2,28,27].

Alternatively, according to Nanda et al., a retrosigmoid approach may need to be performed to avoid injuring critical draining veins [1,29]. Each approach has its merits and drawbacks. None of the approaches have been definitely proven to be superior. Moreover, risks of new cranial nerve deficits differ from one surgical approach to another. The transpetrosal approaches are associated with significantly higher postoperative CN III, CN IV and CN V deficits compared to the retrosigmoid approach. The latter has a significant higher risk of CN VII, CN VIII and LCN deficits. These results could be explained by the cranial nerve interposition of each approach.

5.5. Surgery: extent of resection

The EOR remains the most salient factor in outcomes for patients with benign meningioma. In our study, 26% of patients had GTR. This is a lower GTR rate than reported in most other studies in which complete resection seemed to be the therapeutic intent, with the rate of total resection varying from 20% to 85% [1,3,8,13–16,18,24,30,31] (Table 6). However, some reports include different subtypes of petroclival region tumors other than the "true" PCMs as studied here, highlighting the importance of a common definition of PCMs [1].

Many other factors have been cited as affecting the EOR: extension into the CS, adhesion to or compression of the brainstem, adhesion to or encasement of neurovascular structures, tumor consistency, and tumor size [14]. These adverse condition affected 60% of patients in our study (PCMs larger than 2.5 cm). We would rather perform STR in these cases to avoid major morbidity with aggressive resection. In their series of 33 patients, Bricolo et al. [30] (1992) reported that total removal was achieved in 26 cases (79%), but in nearly all cases in their series, the patients were in worse clinical and neurological condition after surgery than before. Although stereotactic radiosurgery (SRS) was first developed in 1949 by the Swedish neurosurgeon Lars Leksell, in France the radiosurgery era began in 1992. Before 1992, as radiosurgery did not exist, the surgical philosophy was likely more aggressive. In the largest study of surgically treated PCMs, GTR was achieved in 55.8% of cases [13]. Park et al. [18] reported a GTR rate of 20% with a morbidity rate of 29%.

As in previous studies, the variable that most frequently led to STR rather than GTR in our study was the presence of CS tumor extension [32,33]. Despite aggressive attempts and the associated greater risk of neurological or vascular injury, GTR was achieved

Table 6
Literature review.

Authors & year	n	Follow-up (months)	Inclusion period	Extent of resection	CN dysfunction (%)	Motor paresis (%)	Tumor control (%)	Perioperative mortality (< 30 days) (%)	Overall mortality rate (%)
Little et al., 2005 [21]	137	30	1993-2002	GTR (40) STR (40) PR (20)	23	7	83	1	NA
Natarajan et al., 2005 [3]	150	101	1991-2004	GTR (32) STR (43) PR (25)	20	4	95	0	12
Seifert et al., 2010 [25]	93	4-242	1998-2008	GTR (37) STR (39) PR (24)	17	4.3	84	0	0
Nanda et al., 2011[22]	50	22	1993-2008	GTR (28)	32	2	88	0	6
Al-Mefty et al., 2014 [1]	64	72	1988-2012	GTR (64)	33	5	78	1.56	9.37
Li et al., 2016 [20]	199	171	1993-2003	GTR (56) STR (33) PR (11)	19	5.5	83	3	29
Our study	154	76.8 (20–380)	1990-2017	GTR (26) STR (97) PTR (17)	66.5	11.9	72.7	4	7.1

CN: cranial nerve; GTR: gross total removal; PR: partial removal; STR: subtotal removal.

in only 60% to 80% of cases in the literature [33–35]. Furthermore, patients in whom total intracavernous resection was achieved have 5-year recurrence rates of 5% to 19%. With STR, 5-year recurrence rates have ranged from 20 to 38% [33–35]. Alternatively, studies involving adjuvant or primary radiosurgery for CS meningiomas have reported exacerbation of CN deficits in 2 to 8%, with a tumor control rate above 90% at 10 years [32,36–38]. For all these reasons, with the availability of SRS, we believe the risks associated with attempted resection are not justified. In our study, STR with adjuvant radiation (gamma knife or radiotherapy) was significantly better than STR alone in terms of the recurrence risk ($P = 0.09$). With improvements in radiosurgery and fractionated radiotherapy techniques, we advocate aggressive, but careful resection with adjuvant radiotherapy for residual meningioma as optimal in most cases.

5.6. Limitations

The retrospective study design means there is a possibility of missing data, but it is also the length of the study period which could be problematic. Indeed, the practices evolved in the 33-year period and we did not test the results according to the different eras. Similarly, the center effect was not tested. Showing that the results are equivalent regardless of the hospital in which the patients are treated would have been interesting. The natural history has to be studied prospectively. The cognitive impact of the treatment was not determined. As this was a multicenter study, the PCM management and clinical results are quite heterogenous, thus a framework for the management of PCMs cannot be provided. Pre- and postoperative tumor volumes were not measured. As the study period lasted three decades, the surgical practice evolved over time for the surgical approach, the development of electrophysiological intraoperative cranial nerves stimulation, peri-operative care and radiosurgery.

6. Conclusion

Based on a retrospective analysis of data retrieved from a large number of patients with large PCMs and managed in specialized centers our results suggest that the surgical approach does not influence mortality. However the surgical approach influenced the morbidity (e.g. cranial nerve deficits), which should be taken into consideration when counseling patients and selecting the approach. Early postoperative mortality was linked to improper patient selection suggesting that there is a time window in which to operate and one in which to adopt conservative management in cases of severely disabled patients. PFS is the same for total resection versus subtotal plus radiation, which suggest that additional RT is strongly advised in case of obvious remnant tumor to optimize long-term control. As the postoperative outcome is linked to the surgical approach, we advise that this rare entity be managed in specialized skull base tumor care centers.

Author contributions

Author contributions to the study and manuscript preparation include the following. Conception and design: PHR, HDF. Data acquisition: FB, LT, PHR, HDF, EG. Analysis and interpretation of data: all authors. Drafting the article: FB, LT, HDF, PHR, JML. Critically revising the article: all authors. Statistical analysis: JML. Study supervision: PHR, HDF.

Compliance with ethical standards

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. For this type of study (retrospective study), formal consent is not required.

Funding

No funding was received for this study.

Disclosure of interest

The authors declare that they have no competing interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.neuchi.2019.02.001.

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