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Surgical Outcomes, Complications, and Management Strategies for Foramen Magnum Meningiomas

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Abstract

Objectives Foramen magnum meningiomas (FMM) are complex lesions because of their proximity to the brain stem and posterior cerebrovasculature. The objective of this study is to report surgical outcomes and complications after resection of FMM.

Methods A retrospective chart review was conducted on patients with FMM from 1998 to 2015. Univariate logistic regression and recursive partitioning analysis were used to identify risk factors associated with complications and extent of resection (EOR).

Results We identified 28 patients with FMM. Median follow-up was 5.9 years. Tumors were World Health Organization grade I (92.9%) or grade II (7.1%). The vertebral artery was completely encased (25%), partially encased (11%), or not encased (64%). Median size was 11.9 cm^3. EOR was gross total (39%) and subtotal (61%). The observed recurrence rate was 4% ($n = 1$). There were 38 complications in 12 patients (43%), and 6 patients (21%) had complications requiring additional surgery. Complications included cerebrospinal fluid leak/hydrocephalus ($n = 7$, 25%), weakness ($n = 4$, 14%), numbness ($n = 4$, 14%), and cranial nerve deficits: IX, X ($n = 4$, 14%), XI ($n = 2$, 7%), XII ($n = 5$, 18%). Medical complications included pneumonia ($n = 1$, 4%) and meningitis ($n = 1$, 4%). Tumor volume greater than 14 cm^3 (odds ratio [OR] = 21.7, $p = 0.0010$), any vertebral artery encasement (OR 6.1, $p = 0.0386$), and subtotal resection (OR 6.4, $p = 0.0398$) were significantly associated with complications. Tumor volume greater than 14 cm^3 was also significantly associated with subtotal resection (OR 8.3, $p = 0.0201$).

Conclusions Resection of FMM carries perioperative morbidity that increases with larger tumor size. Despite the morbidity, long-term recurrence-free survival is achievable with maximal safe resection and adjuvant radiation.

Keywords
- foramen magnum
- meningioma
- complications
- outcomes
- vertebral artery
- surgical technique
- approach
- management

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Introduction

Meningiomas are the most common primary intracranial tumor, and are typically treated with surgery and/or radiotherapy.[1,2] Foramen magnum meningiomas (FMM), which account for 0.3 to 3.2% of all meningiomas, are particularly challenging due to their anatomical relationship with the brain stem, critical neurovascular structures, and the craniovertebral junction.[3–5] FMMs include all meningiomas arising from the dura within the following anatomical boundaries: ventrally from the inferior third of the clivus to the superior edge of the C2 vertebral body, dorsally from the anterior border of the occipital squamous bone to the spinous process of C2, and laterally from the inferior border of the jugular tubercle to the C2 lamina.[4] FMMs typically present with symptoms due to mass effect on the medulla, the lower cranial nerves (CN) and upper cervical cord, most commonly with dysphagia and/or myelopathy. The mean time from symptom onset to diagnosis is 30.8 months, with the majority of lesions located anterolateral, followed by posterolateral, and posterior.[6] The most common surgical approaches used to resect FMM are the far lateral and midline suboccipital approach. The far lateral approach is typically used during resection of anterior and anterolateral tumors, while posterior and posterolateral tumors are accessible using a suboccipital craniotomy.[7–10] Here, we present our surgical experience with FMM and propose an algorithm for management.

Methods

Study Design, Setting, Size, and Participants

This is a retrospective chart review conducted at a major academic medical center. Patients were identified using an institutional database of all patients undergoing resection of meningioma between 1998 and 2015 at the author's institution. Tumor resection was performed by four neurosurgeons, with the more than half by the senior author. Patients were included in the study based on the following criteria: (1) presence of a tumor in the foramen magnum, (2) underwent surgical resection of the FMM, (3) had adequate surgical documentation and preoperative and postoperative imaging, and (4) had appropriate clinical follow-up and documentation. No subjects were excluded.

Tumor Location Classification

Preoperative MRI images were used to categorize the tumors as FMM. We further characterized them as either anterior, posterior, lateral, anterolateral, or posterolateral (►**Figs. 1** and **2**). The midpoint of the tumor attachment was considered the site of tumor origin. The largest tumor diameter was recorded and used as a proxy for overall tumor size. Tumor volume was estimated by calculating the volume of a sphere ($V = 4/3\pi r^3$), with half the largest diameter used for the radius.

Surgical Technique

For tumors resected via the far lateral approach, the patients are positioned using techniques described in the previous paper, and briefly summarized as follows.[11] Patients are positioned three quarters prone in a modified park-bench position. Neurophysiologic monitoring of motor evoked potentials, somatosensory potentials, and lower CN

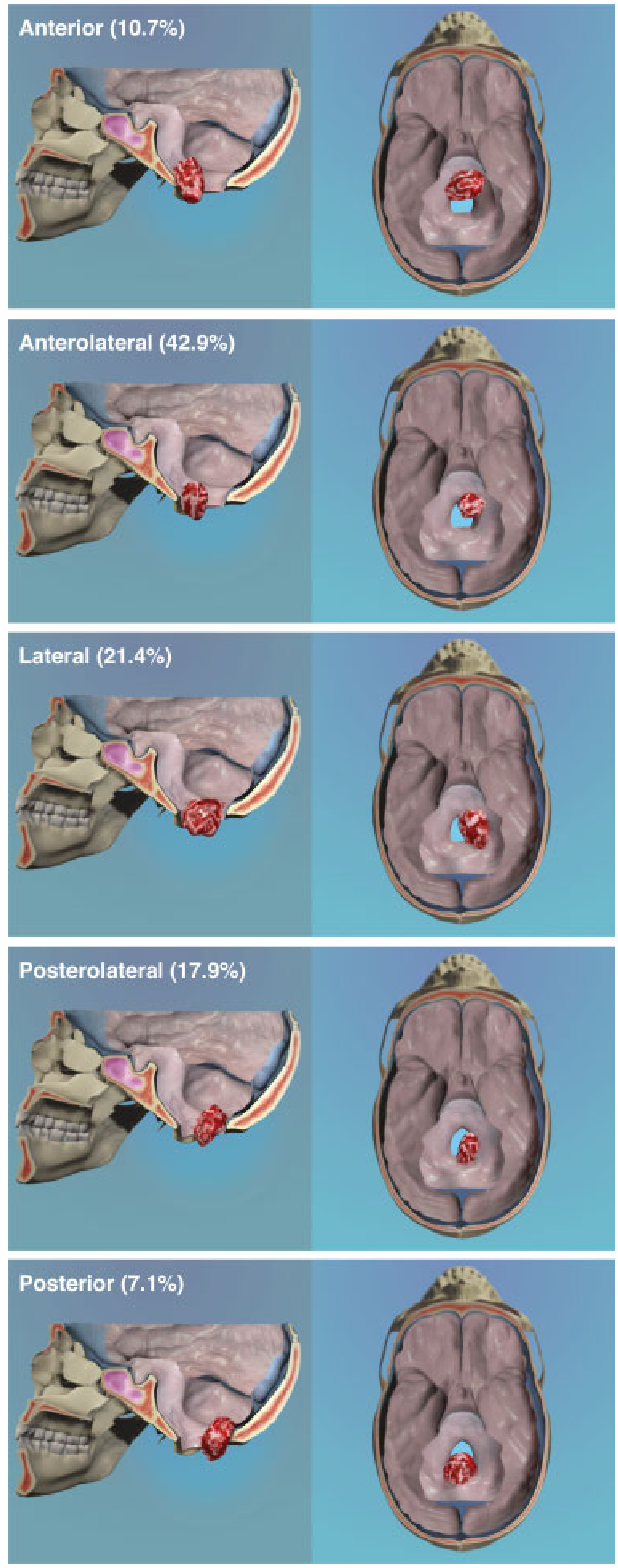

Fig. 1 Schematic of tumor locations within the foramen magnum and frequency of tumors seen at each location in this series. Published with permission. Copyright Kenneth X. Probst.

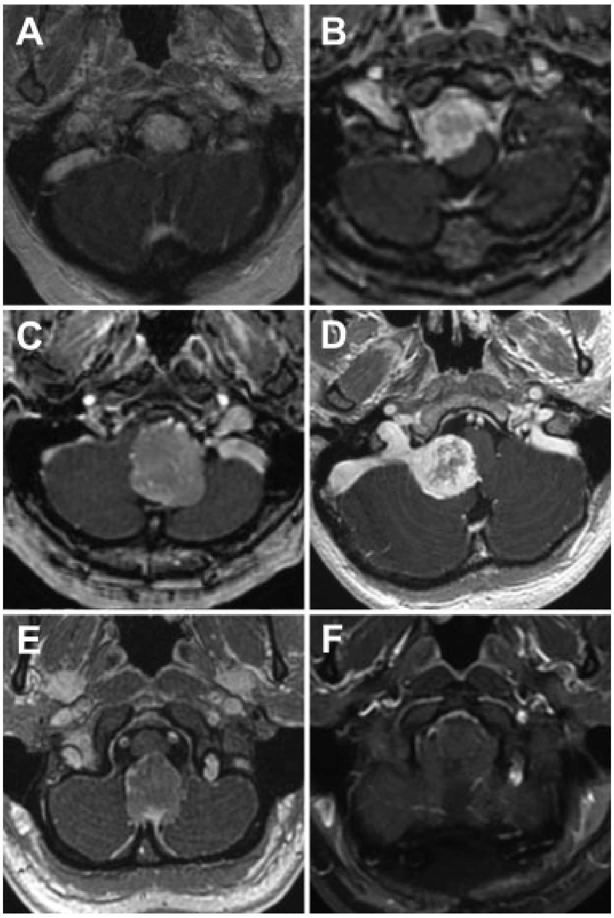

Fig. 2 Case examples with post-contrast T1-weighted magnetic resonance imaging of foramen magnum meningioma locations. (**A**) Anterior, (**B**) anterolateral, (**C**) lateral, (**D**) posterolateral, (**E**) posterior, and (**F**) postoperative scan from the posterior foramen magnum meningiomas.

monitoring is routinely established, which requires no muscle relaxation from anesthesia. After opening the skin, care is taken to detach the suboccipital musculature from the skull and follow the subperiosteal plane to the foramen magnum and the arch of C1. We routinely expose the spinous process and lamina of C2 to assist with the lateral reflection of the myocutaneous flap for optimal exposure. Care is taken not to use electrocautery in the space between the foramen magnum and the arch of C1 to reduce the chance of vertebral artery injury. We then perform a suboccipital craniotomy through the foramen magnum with drilling of the posterior one-third of the occipital condyle completion of a C1 hemilaminectomy. The extent of condyle drilling is limited to the posterior third, or up to the condylar vein. The dura is opened in a curvilinear fashion beginning in the upper cervical region. The inferior extent of the dura is reflected laterally and then the convexity dura is opened separately once the cervical subarachnoid space has been opened and cerebrospinal fluid (CSF) released. The region of the circular sinus is approached from above and controlled with suture ligation or Weck clip techniques. The dura is sutured to reflect it laterally low to the surrounding muscle, and once opened, the arachnoid can be clipped to the dural edges. CN XI and the dentate ligament are followed superiorly to the lower aspect of the cerebellopontine angle to identify the normal and pathological anatomy. The vertebral artery will always be ventral to the last portion of the insertion of the dentate ligament at the base of the skull. Intraoperative navigation with overlaid magnetic resonance angiography images of the vertebral artery can assist with vertebral artery localization along with the use of intraoperative Doppler. Once the vertebral artery is identified, the dural attachments are coagulated with the bipolar and cut with straight microscissors. The tumor is debulked centrally in the standard fashion and anterolateral and anterior dural attachments can be easily coagulated with the CO_2 laser. The dura is closed in a watertight fashion, and if there are dehiscent edges, a pericranial or tensor fascial graft can be secured in place. The dural closure is augmented with fibrin glue. Remaining aspects of the closure proceed in standard neurosurgical fashion. The suboccipital approach was used for posterior and posterior lateral FMM and was performed in the standard neurosurgical fashion with the patient prone.

Variables

The following variables were collected: demographic and tumor variables included patient age, gender, tumor size, and tumor grade, (defined by the World Health Organization [WHO] grading system at the time of resection), and extent of vertebral artery encasement (►**Fig. 3**). Presenting symptoms included numbness/paresthesia, ataxia, headache, weakness, neck pain, incidental finding, and CN deficits. Surgical variables included approach and radiographic extent of resection defined radiographically as gross total or subtotal; and postoperative variables included any new postoperative deficit, complications, tumor recurrence, and any adjuvant radiotherapy.

Bias

This is a retrospective study and is limited by selection and observer bias. All subjects treated at the author's institution who had adequate documentation and a FMM were included, limiting selection bias. This study is also limited by observer bias in that only information that was recorded in the electronic medical record could be used.

Statistical Analysis

All statistical analyses were performed in JMP (JMP, Version 13.0. SAS Institute Inc., Cary, North Carolina, United States). Demographic data was assembled and analyzed in the standard fashion. For categorical data, Pearson chi-squared (multiple categories) or Fisher exact (two categories) tests were reported. Univariate logistic regression was performed and used to calculate odds ratios (OR). Recursive partitioning analysis was performed to identify and stratify risk factors associated with postoperative complications and extent of resection. The manuscript was drafted consistent with the STROBE statement.[12] The International Review Board (IRB) at the author's institution approved this study (IRB# 13–12587).

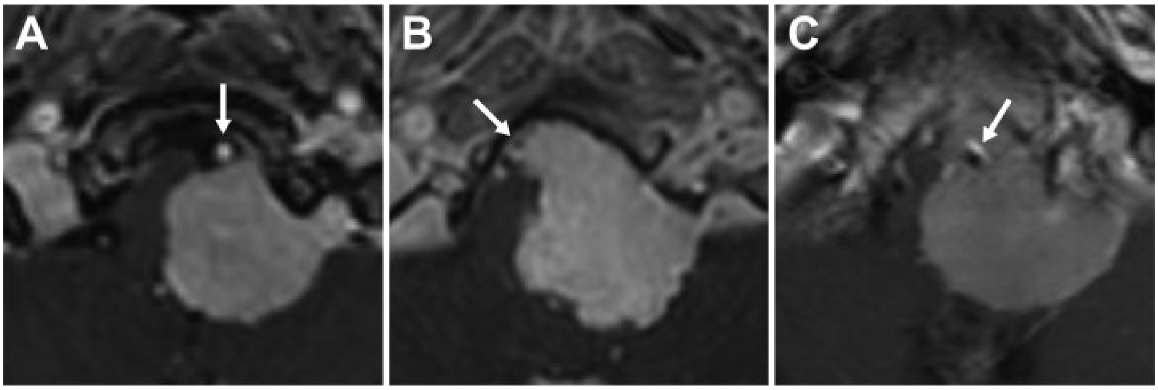

Fig. 3 Case examples showing extent of vertebral artery encasement. (**A**) No encasement, the left vertebral artery does not touch the tumor. (**B**) Partial encasement, the left vertebral artery is aberrantly displaced to the patient's right side, and its flow void can be seen partially encased by the edge of the tumor. (**C**) Complete encasement, the artery is completely surrounded by tumor. Arrows point to the left vertebral artery in each panel.

Results

Demographics and Presenting Symptoms

We identified 28 patients that fit our inclusion criteria. Patient demographics and presenting symptoms are listed in ►**Table 1**. The average age was 57.2 years old and 71.4% ($n = 20$) were female. Median radiographic and clinical follow-up time was 5.9 years. The majority ($n = 25$, 89.3%) of patients with FMM were symptomatic at presentation, while 10.7% ($n = 3$) presented incidentally. The most common symptom was extremity numbness 60.7% ($n = 17$). Other common presenting complaints included gait impairment ($n = 10$, 35.7%), headache ($n = 10$, 35.7%), extremity weakness ($n = 9$, 32.1%), and neck pain ($n = 8$, 28.6%).

Table 1 Demographics

Patients (#)	28
Median age (years, range)	57.2 (30.6–74.4)
Median follow-up (years, range)	5.9 (0–16.9)
% Female	71
Initial presenting symptoms (*n*, %)	
Extremity numbness	17 (61)
Gait impairment	10 (36)
Headache	10 (36)
Extremity weakness	9 (33)
Neck pain	8 (29)
Balance	5 (18)
Facial numbness	3 (11)
Coordination	3 (11)
Dizziness	2 (7)
Nausea/vomiting	1 (4)
Dysphagia	1 (4)
Hearing loss	1 (4)
Incidental	3 (11)

Tumor Characteristics and Treatment Outcomes

Tumor characteristics and treatment outcomes are presented in ►**Table 2**. The median tumor size was 11.9 cm^3, and the mean was 18.4 cm^3. The mean largest tumor diameter was 3.0 cm (1.2–4.7 cm). WHO grading was reported using the diagnostic criteria at the time of resection, with 92.9% ($n = 26$) of tumors being WHO Grade I, while the remaining 7.1% ($n = 2$) were WHO Grade II. There were no WHO Grade III tumors. Tumor location was most frequently anterolateral ($n = 12$, 42.9%), followed by lateral ($n = 6$, 21.4%), posterolateral ($n = 5$, 17.9%), and anterior ($n = 3$, 10.7%) and posterior ($n = 2$, 7.1%). Example tumors are shown in ►**Fig. 2**. Vertebral artery encasement was absent in 64.3% ($n = 18$), while 25.0% ($n = 7$) had complete encasement and 10.7% ($n = 3$) had partial encasement. The most common surgical approach was the far lateral ($n = 22$, 78.6%), while the remaining 21.4% ($n = 6$) tumors were resected using a midline suboccipital approach. Subtotal resection was achieved in 60.7% ($n = 17$) of cases, while gross total resection was achieved in 39.3% ($n = 11$) patients. There were no recurrences in patients who received a gross total resection. Preoperative symptoms improved in 63% of patients. The recurrence rate was 3.6% ($n = 1$). Adjuvant radiation was performed after subtotal resection in eight patients (28.6%), all of whom were treated with fractionated external beam radiotherapy, except for one patient who received Gamma Knife stereotactic radiosurgery for a small residual. For external beam radiotherapy, we treated most patients with 50.4 Gy in 28 fractions. One patient had tumor recurrence 12 years after subtotal resection of a WHO Grade I tumor and adjuvant fractionated radiotherapy. The recurrence was treated with repeat subtotal resection followed by Gamma Knife stereotactic radiosurgery with the extend frame over five sessions for a total dose of 22.5 Gy to the 50% isodose line. The residual tumor was controlled at last radiographic follow-up 3.5 years after treatment.

Morbidity

The surgical complications are presented in ►**Table 3**. There were no perioperative deaths, strokes, or vascular injuries. Of the 28 patients, 42.9% ($n = 12$) experienced a postoperative complication. CSF leak/pseudomeningocele/hydrocephalus was the most common complication ($n = 7$, 25.0%). Of those

Table 2 Tumor characteristics and treatment outcomes

	n (%)
World Health Organization **Grade**	
I	26 (93)
II	2 (7)
Location	
Anterior	3 (11)
Anterolateral	12 (43)
Lateral	6 (21)
Posterior	2 (7)
Posterolateral	5 (18)
Tumor volume (cm^3)	
Mean (cm^3)	18.4 (0.9–54.4)
Largest tumor dimension (cm)	
Mean (cm, range)	3.0 (1.2–4.7)
Vertebral artery encasement	
Complete	7 (25)
Partial	3 (11)
No encasement	18 (64)
Surgical approach	
Far lateral	22 (79)
Suboccipital	6 (21)
Resection	
Gross total	11 (39)
Subtotal	17 (61)
Recurrence	1 (4)
Adjuvant radiation for subtotal resection	8 (29)
Adjuvant radiation modality	
Fractionated external beam radiotherapy	7 (25)
Stereotactic radiosurgery	1 (4)

Table 3 Complications

	n (%)
Cases	28 (100)
Number of patients with complication	12 (43)
Complications requiring surgery	6 (21)
Surgical	
CSF leak/pseudomeningocele/ hydrocephalus	7 (25)
Required shunt	*5 (18)*
Required wound revision	*1 (4)*
Required lumbar drain	*1 (4)*
Weakness	4 (14)
Numbness	4 (14)
Ambulation difficulty	2 (7)
Nystagmus	1 (4)
Proprioception	1 (4)
Apraxia	1 (4)
Cranial neuropathies	
CN VII	1 (4)
CN IX, X	4 (14)
CN XI	2 (7)
CN XII	5 (18)
Medical	
Pneumonia	1 (4)
Meningitis	1 (4)

Abbreviations: CN, cranial nerve; LD, lumbar drain.

seven patients, one resolved with transient lumbar CSF drainage, one required a wound revision without shunt after failing lumbar drainage, and five required CSF diversion with a shunt. Other significant complications included new postoperative weakness ($n = 4$, 14.3%), numbness ($n = 4$, 14.3%), and ambulation difficulty ($n = 2$, 7.1%). Given the location of FMM, we analyzed postoperative lower cranial neuropathies. The most common new or worsened cranial neuropathy was CN XII ($n = 5$, 17.9%). Other cranial neuropathies included CN IX, X ($n = 4$, 14.3%), CN XI ($n = 2$, 7.1%), and CN VII ($n = 1$, 3.6%). Of the four patients with CN IX and X neuropathies, three required percutaneous gastrostomy tube placement and two required vocal cord medialization. One patient had transient dysphagia that did not require a feeding tube and transient dysphonia, both of which resolved within a year. No patients required tracheostomy.

Risk Factors for Complications and Extent of Resection

To determine what risk factors were associated with postoperative complications and subtotal resection, we performed univariate logistical regression (►**Table 4**). We tested whether gender, age, WHO Grade, vertebral artery encasement, extent of resection, tumor location, and tumor volume were associated with the occurrence of a complication and subtotal resection. Patients with a subtotal resection ($p = 0.0398$) and any vertebral artery encasement (partial or complete, $p = 0.0386$) were significantly more likely to have a complication. When tumor volume was considered as a continuous variable, it was significantly associated with complication occurrence ($p = 0.0062$). We performed recursive partitioning analysis, which split tumor size based on whether or not a complication occurred, and found that when tumor volume was greater than 14cm^{3,} there was an increased risk of complications ($p = 0.0010$). We also found that tumor volume greater than 14cm^3 significantly predicted subtotal resection ($p = 0.0201$). Interestingly, tumor location within the foramen magnum was not associated with the occurrence of an intraoperative complication or with subtotal resection. Finally, we calculated OR (►**Table 5**) for the significantly associated variables.

Table 4 Univariate analysis of risk factors for complications and extent of resection

Risk factor	Complication		*p* Value	Risk factor	Extent of resection		*p* Value
	Yes	No			GTR	STR	
Sex				**Sex**			
Female	10 (36)	10 (36)	0.2184	Female	9 (32)	11 (39)	0.2957
Male	6 (21)	2 (7)		Male	2 (7)	6 (21)	
Age				**Age**			
30 s	2 (7)	1 (4)	0.2230	30 s	1 (4)	2 (7)	0.9235
40 s	0 (0)	2 (7)		40 s	1 (4)	1 (4)	
50 s	7 (25)	4 (14)		50 s	4 (14)	7 (25)	
60 s	2 (7)	6 (21)		60 s	4 (14)	4 (14)	
70 s	1 (4)	3 (11)		70 s	1 (4)	3 (11)	
WHO Grade				**WHO Grade**			
I	12 (43)	14 (50)	0.3175	I	10 (36)	16 (57)	0.6402
II	0 (0)	2 (7)		II	1 (4)	1 (4)	
VA encasement				**VA encasement**			
Complete/partial	7 (25)	3 (11)	**0.0386**	Complete/partial	5 (18)	5 (18)	0.3205
None	5 (18)	13 (46)		None	6 (21)	12 (43)	
Extent of resection				**Tumor location**			
Gross total	2 (7)	9 (32)	**0.0398**	Anterior	1 (4)	2 (7)	
Subtotal	10 (36)	7 (25)		Anterolateral	5 (18)	7 (25)	0.9923
				Lateral	2 (7)	4 (14)	
Tumor location				Posterior	1 (4)	1 (4)	
Anterior	2 (7)	1 (4)	0.3167	Posterolateral	2 (7)	3 (11)	
Anterolateral	6 (21)	6 (21)					
Lateral	1 (4)	5 (18)		**Postoperative complications**			
Posterior	0 (0)	2 (7)		Yes	2 (7)	10 (36)	0.0398
Posterolateral	3 (11)	2 (7)		No	9 (32)	7 (25)	
Tumor volume				**Tumor volume**			
$< 14 cm^3$	2 (7)	13 (46)	**0.0010**	< 14 cm^3	9 (32)	6 (21)	0.0201
$> 14 cm^3$	10 (36)	3 (11)		> 14 cm^3	2 (7)	11 (39)	

Abbreviations: GTR, gross-total resection; STR, subtotal resection; VA, vertebral artery; WHO, World Health Organization.
p-value: Fisher's exact test (two variables) or Pearson chi-squared (more than two variables).

Table 5 OR of univariate analysis of risk factors for any complication and subtotal resection

	OR Any complication	95% CI	*p* Value	OR STR	95% CI	*p* Value
Tumor volume > 14 cm^3	21.7	3.02–155.36	0.0010	8.25	1.33–51.26	0.0201
VA encasement	6.07	1.11–33.24	0.0386	–	–	–
Subtotal resection	6.43	1.05–39.33	0.0398	–	–	–
Postoperative complication	–	–	–	6.43	1.05–39.33	0.0398

Abbreviations: CI, confidence interval; OR, odds ratio; STR, subtotal resection; VA, vertebral artery.

Discussion

Key Results

The objective of this study was to analyze and report our surgical outcomes after resection of FMM. We found that tumor volume was significantly associated with both subtotal resection and postoperative complications and that any vertebral artery encasement was associated with an increased risk of complications.

Interpretation

Due to their proximity to the brain stem, FMM typically present with unilateral upper extremity sensory and motor deficits, which can progress to involve the ipsilateral, and subsequently, contralateral lower extremity, followed by contralateral upper extremity weakness.[6,7] Consistent with this, we found that the majority of our patients presented with extremity numbness, followed by headache and gait impairment/weakness. We classified tumor location based on location within the foramen magnum (►**Figs. 1** and **2**), similar to the classification of Bruneau and George.[4] The majority of patients in our cohort had anterior or anterolateral tumors. This location is particularly challenging given that the surgeon must work between the lower CN to reach the lesion, making surgical manipulation and visualization of the tumor difficult.[3,13] Consistent with other groups, we used a far lateral approach to reach the majority of these tumors.[7,14] More recently, Khattar et al described their experience with five patients using an endoscopic approach to anterior/ventral FMM.[15] They had excellent outcomes for purely ventral FMM, but limited the use of the endonasal approach to tumors that do not extend lateral to the vertebral arteries. In experienced hands, this approach is particularly valuable for small ventral tumors that have not caused significant mass effect on the brain. In contrast, large tumors shift the brain stem, which creates a passageway for resection.[14,15] Surgical approach should be determined both by tumor location and as surgeon comfort. In our experience, we have greater ability to dissect adherent tumors from the anterior brain stem using microsurgical techniques through the far lateral approach, consistent with other experienced surgeons in a large contemporary series.[16] Future studies will be needed to compare the far lateral approach with the endoscopic endonasal approach for ventral FMM. Finally, it should always be remembered that due to the insidious onset of symptoms and generally benign nature of these tumors,[6] many small tumors can be managed by observation alone, sparring the patient any risk of surgery or radiation.

The overall morbidity in our series was 43%, consistent with other contemporary series.[16–18] The most common complications reported are CN dysfunction and CSF leak/pseudomeningocele/hydrocephalus. In a series of 64 patients, Talacchi et al described postoperative worsening or new onset of neuropathies in the following CN: CN IX-X in 36% and 11%, CN XI in 27% and 6%, and CN XII in 46% and 14%, resepectively.[17] Our rates were lower with the most common new or worsened postoperative cranial neuropathies being CN XII and CN IX, X at 17.9 and 14.3%, respectively. Similar to our findings, Sekhar et al found larger tumor size to be an important factor for postoperative neurological dysfunction in their series of petroclival and FMM.[19] Taken together, large tumor size and vertebral artery encasement, which often lead to subtotal resection, are associated with increased risk of complications. Importantly, none of the patients with CN deficits required tracheostomy, which is much lower than a recent large series that reported 29.2% rate of tracheostomy, with 13.0% requiring mechanical ventilation.[16] Three patients (10.7%) required percutaneous feeding tube placement, which is lower than the 29% reported in another series.[17] Our surgical philosophy is to perform a maximal safe resection and minimize CN dysfunction. While this approach may result in a slightly lower rate of gross total resection, the majority of FMM are low grade, and small residuals can be treated effectively with adjuvant radiotherapy. Thus, we make every effort to perform surgery in a way that maximizes the extent of resection and the patient's postoperative functioning.

The senior author has developed several surgical techniques that may be useful to others over the years. First, when elevating and dissecting the soft tissue during exposure for a far lateral flap, we no longer use the monopolar cautery because of an inadvertent injury to an anomalous loop of the vertebral artery during exposure of a petrous face meningioma. Second, we always open over the cervical dura first, to establish a normal dissection plane, and to release CSF prior to approaching the tumor. This allows location of the vertebral artery as proximally as possible, which can be followed toward the tumor and avoid arterial injury. Third, we have found that cutting the dentate ligament greatly facilitates dissection, particularly when approaching anterior and anterolateral tumors. Fourth, we have found the CO_2 laser to be very effective for coagulation and as a small cutting/vaporizing tool for debulking and releasing the tumor when working in the deep and narrow corridors often encountered during the resection of anterior and anterolateral FMM. Fifth, we have found that dripping 1% lidocaine without epinephrine on the cervical portion of the spinal accessory nerve with a 30-gauge needle is very effective at stopping contractions of the trapezius and sternocleidomastoid muscles, which can limit surgical progress and potentially compromise the safety of the patient whose head is secured in pins. Sixth, we always augment our dural closure with fibrin glue and pay great attention to performing a watertight closure to make every possible effort to prevent CSF leaks, which are the most frequent morbidity associated with resection. If the dura is dehiscent, an autologous pericranial graft can be used quite effectively to achieve watertight closure. Finally, the most important nuance is the surgical decision of when to leave a small residual and stop the resection to avoid injury. In our experience, we stop the resection if a small shell of the tumor is adherent to the brain stem, perforating arteries, or the vertebral artery.

The median follow-up time in our series was 5.9 years, and the recurrence rate was low, with only one patient recurring 12 years after subtotal resection and radiotherapy. Given that our study contained mostly Grade I meningiomas, our median follow-up time may be too short to detect additional late recurrences, and the low incidence of recurrence precluded analysis of predictive factors for recurrence. Indeed, Pettersson-Segerlind et al found a recurrence rate as high as 47% if patients with parasagittal meningiomas were followed for 25 years, emphasizing the need for long-term follow-up after meningioma resection.[20] However, Bruneau and George reported gross total resection in 86% of their 107 patient case series and had only one (0.9%) tumor recurrence among their cohort, suggesting that the recurrence rate may be lower for FMM.[4] Another recent large series that had a gross total resection rate of 83.2% reported a recurrence rate of 7.2%, with a mean time to recurrence of 74.8 months. This study also found that large invasive tumors involving the vertebral artery and extending extradural (Type C2) as well as subtotal resection and mitosis greater than one per high power field were significant risk factors for recurrence.[16]

The key question for clinicians and patients is what is the optimal management strategy for these FMM? This is especially imperative given that subtotal resection is a risk factor for recurrence, and subtotal resection often occurs when performing maximal safe resection of tumors that are large and invasive. We have proposed the following management strategy based on our experience and the literature (►**Fig. 4**). For asymptomatic, incidentally discovered small tumors, we typically begin with observation.[21] If the tumor grows, then the patient should be evaluated by radiation oncology to determine if they are a candidate for radiotherapy, which has a control rate of 97% for small, presumed grade 1 meningiomas.[22] The case is then discussed in our multidisciplinary tumor board. Whether to perform microsurgical resection or radiotherapy for asymptomatic tumors is a nuanced decision based on patient and surgeon preference. Given that larger tumors are more challenging to resect, and that there is quite good long-term survival after radical resection,[3,16] removing a small, growing, asymptomatic tumor in a good surgical candidate is a reasonable choice for the patient to make. However, for older patients or poor surgical candidates, primary radiotherapy is often the best choice. The choice of fractionated radiotherapy or stereotactic radiosurgery should be made based on each individual tumor and patient. For symptomatic tumors, maximal safe resection should be performed. For subtotal resection or high-grade tumors, adjuvant radiotherapy should be considered after review by a multidisciplinary tumor board. Even after gross total resection, adjuvant radiation therapy should be considered for tumors with an MIB-1 $>$ 7%, where it has shown to provide a survival benefit in our experience.[23] Otherwise, for low grade, low MIB index patients, adjuvant radiation should be reserved for recurrence. We typically follow our patients with surveillance scans every 6 months for 2 years, and then lengthen to annual surveillance.

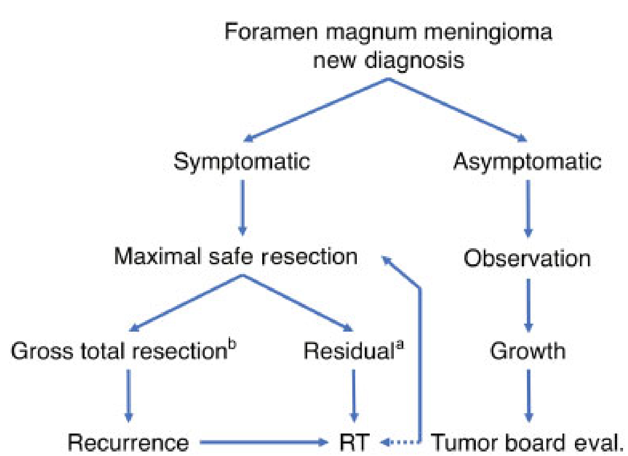

Fig. 4 Proposed flowchart with management strategies for foramen magnum meningiomas. [a]For patients with residual disease, we recommend evaluation for radiotherapy (RT) by a multidisciplinary team including neurosurgeons and radiation oncologists. [b]Even after gross total resection, adjuvant radiation should be considered for patients with an MIB1 index greater than 7%.[23]

Limitations

This study is limited by its retrospective design and the documentation of pre- and postoperative examinations and available imaging. It is limited by its relatively small size, which prevented multivariate analysis and predictive modeling. The study is also limited by our using the volume of a sphere as an estimate of tumor volume, which could introduce error given the complex shapes these tumors can form. Finally, we did not perform endoscopic resection of ventral FMM, which limits our ability to compare results between anterior endonasal and posterolateral approaches, which is becoming increasingly relevant with increased use of the expanded endonasal approach.

Generalizability

These results are those of specialized skull base neurosurgeons working with a team of anesthesia and specialists focused on complex skull base cases, and thus, may not be generalizable to all surgeons or institutions. Nevertheless, the principles and techniques used to approach FMM should be generalizable to other similarly experienced neurosurgeons.

Conclusions

While rare, FMM pose significant challenges in terms of surgical approach and resection goals. We found that tumor volume greater than 14 cm^3, subtotal resection, and vertebral artery encasement are strong predictors of postoperative complications. Despite the morbidity, long-term recurrence-free survival is achievable with maximal safe resection. Gross total resection achieves durable long-term results that are matched by subtotal resection and adjuvant radiation. Finally, we propose an algorithm to serve as a starting point to guide individual clinicians and patients as they determine the best management for each individual FMM.

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