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Review Article

Approaches to anterior and anterolateral foramen magnum lesions: A critical review

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Abstract

Foramen magnum (FM) lesions represent some of the most complex cases for the modern neurosurgeon because of their location near vital brainstem structures, the vertebral arteries, and lower cranial nerves. In particular, anterior or anterolaterally located FM tumors have traditionally been most difficult to resect with high morbidity and mortality resulting from approaches through the posterior midline or transorally. For many neurosurgeons, the far lateral, extreme lateral approach, and more recently, endoscopic endonasal approaches have become the preferred modern methods for the resection of anterior or anterolateral FM tumors. In this review, we examine both operative and non-operative approaches to FM tumors, including surgical anatomy, surgical technique, and indications for operative intervention in these complex cases. In addition, we compared outcomes from prior series.

Key words: Foramen magnum, meningioma, extreme lateral approach: Cerebrospinal fluid, computed tomography, foramen magnum, karnofsky performance scale, magnetic resonance angiogram, magnetic resonance imaging, stereotactic radiosurgery, vertebral artery

INTRODUCTION

Since the first autopsy description of a foramen magnum (FM) meningioma was presented by Hallopeau[1] in 1872, it has been appreciated that lesions in this region may present many challenges to a surgeon attempting resection. FM tumors are located in an anatomically complex region surrounded by bony elements of the craniocervical junction, the vertebrobasilar system of vessels, the lower cranial nerves, and by delicate brainstem neural elements. Since the first successful FM meningioma resection in 1922 was reported by Frazier and Spiller,[2] a number of surgical refinements have been introduced to aid in the management of these technically demanding lesions. The use of microneurosurgical techniques with modern skull base approaches now allows for definitive surgical management with an acceptable risk profile in most cases. Expanded endoscopic endonasal approaches are also now being performed in attempt to further minimize surgical morbidity in removing these lesions. However, in those cases where definitive surgical management cannot be performed due to age, medical condition, or patient preference, radiosurgery is also a viable option and has been utilized with some success.

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Lesions of the posterior or posterolateral foramen magnum are classically reached via posterior midline or retrosigmoid approaches. The original surgical approaches to anterior or anterolateral FM lesions were also through the posterior midline; however, this approach requires significant brainstem retraction and reports of high morbidity and mortality prevented its widespread acceptance.[3,4] Neurosurgeons then explored alternate anterior approaches such as the transoral route. These cases, however, were plagued by cerebrospinal fluid (CSF) leaks and infections, craniocervical instability, and incomplete resections for tumors extending laterally.[5,6] The main advantage of the transoral approach was its direct route to the FM lesion. Developed along the same line of thought, the endoscopic endonasal approach has recently emerged as a modern approach to midline cranial base lesions, including those in the anterior foramen magnum and offers the possibility of reduced morbidity as compared to open approaches. The typical open approaches currently in use represent a lateral extension of the posterior midline approach and include the far lateral,[7] and extreme lateral approaches.[8] The posterior midline approach has also recently been resurrected as a possibility for these lesions.[9] Here we present a detailed review of the literature on the management of FM lesions, whether approached via one of these surgical approaches or treated with radiosurgery. The epidemiology, clinical presentation and workup, surgical anatomy and approach to resection or radiosurgical treatment, as well as the surgical outcomes and complications are reviewed in detail.

METHODS

In order to find studies examining the diagnosis and treatment of FM lesions, we performed a literature search of all papers (English) published from 1978 to 2009 using Medline. Medline search terms included the following keywords and phrases: foramen magnum, tumor, meningioma, surgical approach, expanded or extended endoscopic endonasal approach, and stereotactic radiosurgery. Because of the rare nature of these lesions, we included in our results any study that presented more than 5 patients with FM lesions. When studies reported cases included in previous reports, we only included the most recent study. For studies reported prior to 1978, we have used Yasargil's report[3] as the definitive summary of such cases.

Epidemiology

Early data demonstrated that tumors of the FM comprise only 1.1–3.8% of all brain and spinal cord tumors.[10-12] Love's study[11] showed that approximately 30% of these tumors were benign and extramedullary, indicating a curative potential for surgical interventions. Of these benign, extramedullary FM tumors, meningiomas are most frequently seen comprising 61–87% of all FM tumors.[4,12-14] Neurofibromas and chordomas are also commonly seen and usually account for most of the remaining tumors seen in the FM. Although FM tumors are the most common surgical pathology encountered in this region, studies have also described approaches to treat vertebral artery aneurysms and rheumatological disease in this region.[11,15-18]

Clinical presentation

The clinical presentation of patients with FM lesions varies greatly and can mimic many other neurological disorders. Indeed, prior to the advent of advanced imaging technologies, patients with FM tumors were frequently misdiagnosed with a variety of disorders including multiple sclerosis, cervical spondylosis, and amyotrophic lateral sclerosis because of the uncommon symptoms caused by the anterior location of the lesion.[19,20] Table 1 shows the clinical characteristics of all major studies reporting patients presenting with lesions in the FM region (n = 1,010). Examining the literature that reports on such patients allows one to identify some obvious trends. Females are more likely to be afflicted with an FM tumor than males by an approximate ratio of 1.8:1, mainly due to the known propensity for meningiomas to occur more frequently in women. Patients were an average 46.3 years of age and ranged from as young as 10 to as old as 85. They experienced symptoms for an average of 26.5 months and most frequently complained of suboccipital headaches and/or neck pain (54.5%), followed by symptoms of motor weakness (47.6%) and gait disturbance (18.3%). In addition, about 1/3 of patients experience sensory deficits such as limb numbness, parasthesias and dysesthesias. Lower cranial nerve deficits are common and produce symptoms such as swallowing difficulty (10.3%). Signs on physical examination follow from the patients' symptoms and most frequently include upper motor neuron signs (26%) such as hyperreflexia and plantar extensor response or objective signs of weakness such as hemiparesis/plegia (10.1%) and quadriparesis/plegia (14.4%). They also may include lower cranial nerve palsies, sensory loss, and less commonly, ataxia or cerebellar signs on exam.

Diagnostic workup

Computed tomography (CT) and magnetic resonance imaging (MRI) revolutionized the care of patients with FM tumors as it allowed not only for correct diagnosis but also for detailed anatomical mapping of the tumor. Typically, gadolinium-enhanced T1 MRI images are used to identify the tumor location, its dural attachment, and any neural or vascular structures that may be encased within the tumor, although more sophisticated techniques such as three dimensional reconstruction are occasionally used to modify surgical approach if necessary.[21] Magnetic resonance angiography (MRA) can also be used to identify vertebral artery (VA) involvement or displacement, VA dominance, and any collateral blood supply in the region. Pre-operative angiography is generally limited to cases in which the tumor receives its main blood supply from a meningeal VA branch and embolization is considered. Bone windows on CT are used to identify tumor calcifications, and bony erosion from extradural tumor extension.

Surgical anatomy and approaches

Far-lateral approach

The far-lateral approach is essentially a lateral extension of the posterior midline or retrosigmoid approach that was initially used for anterior or anterolateral FM tumors. This approach is intended to facilitate visualization of and access to the anterior portion of the FM. Originally described by Heros[7] for VA aneurysms, it was modified for the removal of anterior FM benign tumors by George *et al.*[22] and has undergone subsequent modifications in the intervening years. The current approach has been discussed in great detail previously,[23,24] but

Table 1: Patient characteristics from major studies of foramen magnum meningioma resection reported in the English literature

Study	Total n	N of FM Meningiomas	Gender	Mean age, years (Range)	Symptomatic period, mths (range)	Commonly presenting symptoms	Commonly presenting signs
Yasargil[3]	114	114	N/A	N/A	N/A	N/A	N/A
Meyer[4]	102	78	*34M, 68F	*49 median, (12-81)	*27, (5-78)	*Neck pain 66% (67), dysesthesia: hand 59% (60) arm 54% (55) leg 27% (27) face 7% (7), gait disturbance 49% (50), arm weakness 40% (41), leg weakness 29% (30), hand clumsiness 27% (27), bladder dysfunction 22% (22), dysphagia 13% (13), headache 11% (11)	*Hyperreflexia 71% (72), motor weakness 68% (69): quadriparesis 15% (15) hemiparesis 14% (14), Babinski sign 58% (59), gait disturbance 47% (47), sensory loss: pain and temperature 37% (39) joint 27% (27) touch 22% (22), incoordination 37% (38), Brown-Sequard 29% (30), nystagmus 25% (25), meningismus 22% (22), XI CN palsy 28% (28)
George[40]	230	106	32M, 74F	53.7, (13-83)	28.5, (0.25-240)	#Posterior headaches 40% (42), motor deficits 13% (14), paresthesias 10% (11)	
Dodge[13]	30	26	*11M, 19F	*(19-69)		*Posterior neck pain/ suboccipital headache 83% (25), paresthesias 87% (26), muscle weakness 87% (26), gait disturbance 40% (12), swallowing difficulty 30% (9), respiratory difficulty 20% (6)	*Motor deficits 90% (27): quadriparesis/plegia 30% (9), hemiparesis/plegia 23% (7), sensory deficits 70% (21), CN deficits 50% (15): CN XI 37% (11), CN X, XII 13% (4)
Yasuoka [14]	57	37	8M, 29F	51 median, (31-73)		*Dysesthesia: upper extremity 95% (54), lower extremity 37% (21), suboccipital/neck pain 75% (43), weakness: upper extremity 49% (28), lower extremity 42% (24), gait disturbance 47% (27), hand clumsiness 42% (24), bladder disturbance 33% (19)	*Hyperreflexia 83% (39), weakness 68% (32): tetraparesis/plegia 26% (12) hemiparesis/plegia 15% (7), sensory loss: pain and temperature 57% (27) joint 38% (18) touch 30% (14) hypalgesia of C-2 region 34% (16), Babinski sign 57% (27), gait disturbance 40% (19), Brown-Sequard 23% (11), CN XI palsy 32% (15)
Guidetti and Spallone [12]	18	11	3M, 8F	44.2 (20-65)	42, (3-156)	*Suboccipital/neck pain 100% (18), motor weakness 88% (16), sensory disturbance 78% (14), sphincter disturbance 39% (7), headche/vomiting/diplopia 28% (5), respiratory difficulty 28% (5), hoarseness 17% (3), swallowing impairment 11% (2)	*Hyperreflexia 100% (18), motor weakness 94% (17), hemiparesis 44% (8), quadraparesis 28% (5), sensory loss 94% (17): hypesthesia 78% (14), joint 61% (11), nuchal rigidity 89% (16), hand atrophy 39% (7), nystagmus 50% (9), CN palsy 56% (11): XI 33% (6) , IX-X 17% (3)
Sen and Sekhar[8]	6	5	N/A	N/A	N/A	HA 40% (2), neck pain 20% (1)	XI, XII palsy 20% (1), Brown-Sequard 20% (1), motor weakness 40% (2): hemiparesis 20% (1) tetraparesis 20% (1)

(Table Contd.)

Table 1: (Contd.)

Study	Total n	N of FM Meningiomas	Gender	Mean age, years (Range)	Symptomatic period, mths (range)	Commonly presenting symptoms	Commonly presenting signs
Kratimenos[33]	15	7	1M, 6F	55.6 (39-70)	19, (5-52)		Lower CN palsies, upper cervical cord and medullary compression signs
Babu[18]	22	11	6M, 5F	53.7 (41-70)	N/A	Headache 27% (3), motor weakness 27% (3), sensory loss 9% (1)	Cerebellar signs 45% (5), VIII nerve deficit 18% (2), IX-X palsy 36% (4), XI palsy 9% (1), XII palsy 9% (1), pyramidal signs 18%, hemiparesis 9% (1), quadriparesis 9% (1), monoparesis 9% (1)
Akalan[41]	16	8	4M, 4F	31.1, (18-51)	29.8, (1-216)	Motor weakness 75% (6), sphincter disturbance 75% (6), pain 50% (4)	Quadriparesis 50% (4), hemiparesis 12.5% (1), monoparesis 12.5% (1)
Bertalanffy[50]	19	19	5M, 14F	59	N/A	N/A	N/A
Samii[29]	40	25	*13M, 25F	*49, (17-74)	*22	Motor weakness 52% (13), pain/headache 48% (12), sensory deficit 40% (10), dysesthesias 12% (3)	Gait ataxia 68% (17), CN IX and X palsies 44% (11), CN XII palsy 24% (6), CN XI palsy 28% (7), sphincter disturbance 20% (5), hydrocephalus 16% (4)
George[26]	40	40	11M, 29F	51.6, (14-76)	30.8, (0.3-96)	Motor weakness 50% (20), posterior headache 42.5% (17), sensory deficit 42.5% (17), sphincter disturbance 12.5% (5)	Motor deficit 50% (20): tetraplegia 25% (10) hemiplegia 12.5% (5) paraplegia 12.5% (5), sensory deficit 42.5% (17), CN IX, X palsies 30% (12), CN XI palsy 12.5% (5), CN XII palsy 17.5% (7)
Pirotte[31]	6	6	3M, 3F	53.3, (45-73)	32.7, (0.5-72)	Neck pain 100% (6), gait disturbance 50% (3), motor deficit 16% (1), diplopia 16% (1)	Hemiparesis 50% (3), tetraparesis 33% (2), VI nerve deficit 16% (1)
Salas[16]	69	24	N/A	N/A	N/A	*Gait disturbance 49% (34), headache 40% (29), swallowing difficulty 40% (29), dysarthria 17% (12), sensory loss 11% (8)	CN IX-XI deficit 37% (26), CN VIII deficit 29% (20), CN XII deficit 30% (21), motor deficit 20% (14)
Arnautovic[30]	18	18	5M, 13F	58, (36-77)	45, (1-120)	Occipital pain/headache 72% (15), facial numbness 22% (4), hand numbness 22% (4), swallowing difficulties 33% (6), diplopia 28% (5), shoulder weakness 17% (3)	Ataxia/gait difficulty 33% (6), dysarthria 6% (1), hemiparesis 11% (2), quadriparesis 11% (2), paraparesis 6% (1), hydrocephalus 6% (1)
Roberti[44]	161	21	*33M, 128F	47, (10-81)		*Gait impairment 62% (13), head pain 47% (10), swallowing difficulties 38% (8), sensory impairment 24% (5)	*Hemi/monoparesis 43% (9), hydrocephalus 24% (5), dysmetria 14% (3)

Table 1: (Contd.)

Study	Total n	N of FM Meningiomas	Gender	Mean age, years (Range)	Symptomatic period, mths (range)	Commonly presenting symptoms	Commonly presenting signs
Goel[9]	17	17	6M, 11F	39.2	12.6	Motor weakness 100% (17), neck pain 71% (12), sphincter disturbance 47% (8)	Sensory deficits: touch 47% (8), pain and temperature 47% (8), joint 24% (4), CN IX-XI deficit 29% (5), CN XII deficit 18% (3), hand wasting 18% (3)
Nanda[17]	10	6	0M, 6F	56.2, (46-70)		Headache 50% (3), dizziness 16% (1), dyspnea 16% (1), hand/leg numbness 16% (1)	Quadriparesis 33% (2), quadriplegia 16% (1), hemiparesis 16% (1)
Marin Sanabria[51]	7	7	2M, 5F	53.3, (39-66)	20, (6-51)	Dysesthesia 86% (6), gait disturbance 71% (5), UE weakness 28% (3)	Hyperreflexia/UE wkness 86% (6), quadriparesis 43% (3), paraparesis 14% (1), hemiparesis 14% (1), monoparesis 14% (1), sensory disturbance: hypalgesia 28% (2), cape sensory loss 43% (3), hand atrophy 28% (2), lower CN palsy 28% (2)
Parlato[52]	15	7	*4M, 11F	*52.3, (16-70)	*(1-60)	Gait disturbance 57% (5), headache/occipital pain 29% (2), swallowing difficulty 14% (1), diplopia 14% (1)	
Chandra[53]	30	8	*18M, 12F	*38, (13-75)	N/A	* Suboccipital/neck pain 80% (24), paresthesias 73% (22), sensory hypoesthesia 70% (21), motor weakness 67% (20)	* Hyperreflexia 60% (18), posterior column signs 47% (14), hand atrophy 40% (12), nystagmus 33% (10)
Boulton[54]	10	10	2M, 8F	55, (34-72)	10, (3-24)	occipital pain, hand paresthesias	N/A
Pamir[21]	22	22	4M, 18F	47.2, (18-74)	10, (1-72)	Headache/neck pain 73% (16), nausea/vomiting 55% (12), swallowing difficulties 32% (7)	Monoparesis 23% (5), dysarthria 14% (3), tongue atrophy/fasciculations 14% (3), quadriparesis 9% (2)
Margalit[27]	42	18	*14M, 28F	*47, (14-80)	N/A	* Neck pain 38% (16), headache 26% (11), motor weakness 36% (15), swallowing problems 24% (10)	*Myelopathy and gait difficulty 55% (12), numbness 36% (8), motor weakness 32% (7), CN VI deficit 14% (3), CN VIII deficit 14% (3), CN IX-XI deficit 36% (8), CN XII deficit 9% (2)
Bassiouni[43]	25	25	6M, 19F	59.2, (33-78)	14, (2-48)	Neck pain 72% (18), upper limb paresthesia 32% (8), gait disturbance 32% (8), swallowing difficulties 8% (2)	Ataxia 48% (12), hypesthesia 40% (10), hemihypesthesia and hemiparesis 16% (4), Brown-Sequard 12% (3), IX and X CN palsies 8% (2)
Kandenwein[55]	16	16	4M, 12F	61, (40-85)	48, (4-180)	Dizziness/headache 75% (12), sensory deficits 44% (7), weakness 25% (4)	Ataxia 88% (14), hydrocephalus/ incontinence 19% (3), CN IX palsy 6% (1)

N/A indicates that the authors did not report the figure. * indicates that the characteristic includes all patients in the study, not only those with FM meningiomas. † represents only the initial symptoms of patients in study. ‡ These studies are separated out from Yasargil's review as they represent the largest dataset for which there is clinical data will be summarized below to illustrate both relevant regional anatomy and the approach itself.

Skin incision and muscular dissection

The patient can be positioned in either the sitting, prone, lateral or supine positions. Some authors note the importance of keeping the patient's head in any degree of flexion so as to avoid further narrowing the space between the neuraxis and anterior rim of the FM.[25,26] There are two commonly used variations for skin incision. The first is a C-shaped incision starting 2 finger breaths above the pinna and extending down well below the mastoid. The other is a more traditional "hockey-stick" midline incision extending from approximately the fourth cervical vertebra to the occipital protuberance and then extending laterally towards the mastoid process on the affected side. After detaching the sternocleidomastoid from its mastoid and lateral occipital attachments, the rest of the posterior muscles are divided close to their occipital attachments and reflected laterally. This exposes the occipital bone, C1 lamina and posterior arch, and, if necessary, the C2 lamina.

VA control

The VA courses within a periosteal sheath along a groove in the posterior arch of C1. Within this periosteal sheath exists a surrounding venous plexus. Gaining control of the VA so as to better visualize the anterior FM is essential. Methodological differences exist in the literature on this point. Most authors report coagulation of the venous plexus that surrounds the VA.[23,27] However, George, *et al.* emphasize the importance of exposing the VA and its venous plexus by dissecting in the subperiosteal plane of the posterior arch of C1 from medial to lateral and inferior to superior. In this way, the VA and venous plexus are naturally protected from injury by the periosteal sheath and unnecessary bleeding from the venous plexus is avoided.[24,25] In addition, this obviates the concern that aberrant vessels coming off of this portion of the VA such as an extradural posterior inferior cerebellar artery (PICA) will be coagulated and occluded. After passing along the lateral part of the posterior arch of C1, the VA courses through the lower border of the atlanto-occipital membrane which, in up to 52% of cases,[28] can ossify and transform the groove of the posterior arch into a bony canal. This can make the exposure of the horizontal portion of the VA more difficult. Once exposed, the VA is displaced superiorly to show the lateral mass of the atlas.

Bony opening

Typically, the posterior arch of the atlas is resected towards the transverse process ipsilaterally while the contralateral side undergoes resection about halfway from the midline. Again, controversy still exists as to how much lateral drilling is needed in order to successfully perform these cases. Some maintain that, even for purely anterior tumors, one never needs to resect more than one-fifth to one-third of the occipital condyle and lateral mass of C1.[24,25,29] This is to maintain cranio-cervical stability. Others describe more aggressive approaches such as routine drilling of one-third to one half of the condyle in order to create a better working space, without any reports of cranio-cervical instability or need for occipito-cervical (OC) fusion.[21,27,30,31] It is, however, generally accepted that there is no need for condylar or lateral mass drilling in tumors that are located more laterally.[24,27]

Intradural tumor removal

A vertical dural incision is made lateral to the midline on the tumoral side extending from immediately dorsal to the VA to just behind the sigmoid sinus.[23,24,32] In order to further expand the surgical field anterior to the spinal cord, the first two attachments of the dentate ligament must be sectioned. The most rostral attachment of the dentate ligament is located just ventral to the dural incision above the VA as it enters the dura and behind the spinal accessory nerve while the second attachment of the dentate ligament occurs just below and behind the intradural portion of the VA.[23,33] The first cervical nerve can also be sectioned distal to its connection with the spinal accessory nerve with minimal clinical consequence and provides better surgical access.[22,24]

Care must be taken to protect the lower cranial nerves while removing the tumor. George *et al*. originally described an approach based on the location of the FM meningioma relative to the position of the VA.[26] For example, most tumors are located below the VA, therefore pushing the lower cranial nerves superiorly and can be reliably located when resecting the superior border of the tumor. Tumors located above the VA or above and below the VA, however, displace the lower cranial nerves in an unpredictable manner and the position of the lower cranial nerves cannot be anticipated. In this case, the cranial nerve rootlets must be identified and followed along their course towards the meningioma. As the tumor is progressively debulked using either an ultrasound aspirator or CO_2 laser, the rootlets can be mobilized. Finally, a watertight dural closure is required to prevent a postoperative CSF leakage, although some claim that this is not possible around the VA.[27] If necessary, a dural patch using the suboccipital aponeurosis can achieve closure sufficient to prevent CSF leakage.

Extreme lateral approach

While six types of the extreme lateral approach have been described,[16] this approach mainly differs from the far-lateral approach in the extent of bony removal. Extreme lateral approaches to the foramen magnum generally necessitate more aggressive removal of bone laterally. Most variations of the extreme lateral approach entail removing the posterior arch of C1 as well as some of the lateral mass. In addition, all variations except for the retrocondylar approach involve at least partial occipital condyle drilling and removal, while this is frequently not part of the far lateral approach.[26]

Endoscopic endonasal approach

Because of the potential to minimize surgical morbidity, endoscopic approaches to the anterior foramen magnum have been described. Although case series using this approach are generally limited to the upper to middle clivus and suprasellar regions, the foramen magnum can also be reached. This approach represents a potential new avenue for reducing the surgical morbidity of lesions in this region and has been previously described in detail.[34,35]

Although endoscopic approaches have traditionally been adopted because of their minimally invasive nature, this approach involves significant drilling and bony removal in the sphenoid sinus and could be considered similarly "invasive" as open approaches to this region. The main theoretical benefit to this approach, then, could be more appropriately viewed as avoiding the brain retraction used in open approaches, as has been noted in reviews of this technique.[36] On the other hand, the major complication associated with an endoscopic approach is CSF leakage, a problem which can be avoided with scrupulous attention to reconstructive technique. Regardless, this approach will undoubtedly undergo further sophistication and represents a significant improvement in approaches to the FM.

Stereotactic radiosurgery

Sterotactic radiosurgery (SRS) has become a viable alternative for arresting growth of FM tumors.[37-39] In general, the treatment isodose and fractionation schedule are based on the size, location and projected risk to surrounding structures. Mean isodoses have been prescribed in the range of 10-20 Gy with maximal doses ranging from 20-35 Gy for lesions 0.1-18.5 ccs in volume.[37,39] In particular, frameless LINAC-based systems offer both the tangible benefit of the ability to treat lesions below C1 and the theoretical benefit to nearby structures of the ability to fractionate dosing.

Surgical outcomes

Surgical morbidity and mortality using the far lateral, extreme lateral and posterior midline approaches

Table 2 demonstrates the results seen in all studies reporting use of the far lateral approach for FM lesions. One hundred and fifty-three cases using the far lateral approach have been reported since 1993. Surgical morbidity and mortality is often quite good in these series with, on average, 5.2% of cases resulting in death (8 in total), ranging from 0–13%. Permanent morbidities were seen in 7.8% of all cases (12 total) and ranged from 0–31%. These included lower cranial nerve deficits, paralysis, and infarcts resulting from VA injury. As would be expected, temporary morbidities are seen more frequently (24.8%) with typical complications including transient lower CN palsies, transient hemiparesis, and CSF leaks.

The primary alternative approach currently in use is the extreme lateral approach. Salas *et al*. have published the largest series to date using this approach and advocate variations of its use depending on the type of lesion present.[16] In total, 161 cases of a version of the extreme lateral approach to treat an FM lesion have been reported since Sen and Sekhar's original report in 1990 [Table 3]. Mortality in these cases was 5.6%, comparable to the 5.3% seen using the far lateral approach. Morbidity is reported in 151 of these cases resulting in 41.7% temporary morbidity and a 14.6% permanent morbidity rate. This compares to a 21.8% temporary morbidity and 7.5% permanent morbidity rate seen using the far lateral approach. Given the small number of cases, no conclusions can be drawn regarding the morbidity and mortality rates of these approaches.

Three major studies comprise much of the literature on FM tumor resection prior to the introduction of laterally extended approaches. Yasargil published a review of 114 cases reported prior to 1976,[3] Meyer reported 102 total FM tumors seen at the Mayo Clinic from 1924 to 1982,[4] and George reported 230 FM tumors in 1993[40] for a total of 446 cases. Smaller case series occurring after these studies include Guidetti and Spallone's report of their experience with 18 cases of FM lesions,[12] Akalan's experience with 16 FM tumors,[41] and Goel's more modern report of 17 FM lesions.[9] Strictly posterior approaches were used in all of these studies. It has been reported many times that the posterior midline approach used in these studies resulted in higher morbidity and mortality because of lateral brainstem displacement when removing anteriorly located tumors.[18,22,42] Thus, lateral approaches were developed in order to provide an easier and more natural working space for the surgeon to remove lesions, potentially resulting in better patient outcomes. The data from these studies show this to be the case [Tables 2 and 4]. Total mortality is decreased when comparing the far lateral or extreme lateral approaches to earlier, posterior approaches. In these studies, posterior approaches yielded a mortality of 10.5% as compared to 5.2 or 5.3% using the far lateral or extreme lateral approaches, respectively. Because these earlier studies tended to focus on clinical rather than surgical data, morbidities were rarely reported. Therefore, it is difficult to compare approaches in this regard. Given that much of the data on this approach comes from studies performed as early as the 1920s, we cannot exclude the possibility that much of this improvement in mortality may be due to any of a myriad of factors related to modern medicine including improved microneurosurgical techniques, anesthesia and perioperative care.

Resection rates using the far lateral, extreme lateral, and posterior midline approaches

Resection rates using the far lateral approach are quite good, although authors have used varying definitions for degree of resection. Some authors report resection rate using the Simpson grading scale, while others merely report "total" or "subtotal" resections. Most authors define "total" resections as Simpson grades 1 and 2, "subtotal" resections as Simpsons grade 3, and "partial" resections as grade 4. Using this definition for all studies that report FM tumor resection rates (n = 149), we see that the far lateral approach achieved gross total resection in 93.2% of all cases, subtotal resection in 5.4%, and partial resection in 1.3% of all cases. For the extreme lateral approach, we found that gross total resection rates were 74.7%, and subtotal resection rates were 25.3%. While resection rates were rarely reported for

Table 2: Surgical results of the posterior midline approach to FM meningioma resection

Study	N	Temporary morbidity, permanent morbidity, mortality(%)	Resection rate, % (n)	Factors leading to subtotal resection	Recurrence rates	Recovery, % (n) or other measure of recovery	Complications, % (n)	Mean follow-up time, months (range)
Yasargil[3]	114	N/A, N/A, 12.8	N/A	N/A	N/A	69.3 good (79), 7.9 fair (9), 22.8 poor (26)	N/A	N/A
Meyer[4]	102	*N/A, N/A, 10	N/A	N/A	N/A	*75 improved (77), 12 mildly impaired (12), 13 markedly impaired (13)	N/A	12-480
George[40]	106	24.2/6.7/7.7	77.7 (80) total, 15.5% (16) subtotal, 6.8 (7) partial	Tumor located on both sides of VA, anteriorly, or with an extradural component	N/A	71 improved (75), 6.6 unchanged (7), 14 worsened (15) Yasargil grading: Pre-op mean: 2.39 Post-op mean: 1.52	#Transient lower CN palsies 41.7 (43), permanent lower CN palsies 35.9 (37), motor deficits 25.2 (26), sensory deficits 6.8 (7)	22.8 (3-120)
Guidetti and Spallone[12]	18	N/A, 0, 11	N/A	N/A	N/A	89% improved (16), 11 worsened (2)	Hallucinatory state 11 (2)	24-312
Akalan[41]	16	N/A, N/A, 0	N/A	N/A	N/A	94 improved (15), 6 unchanged (1)	N/A	51.6 (6-84)
Goel[9]	17	0, 5.88, 0	*82.35 (14) total, 17.64 (3) subtotal	Tumor adherent to VA or branches (n = 2)	N/A	94.11 improved (16), 5.88 (1) worsened	CN palsies 5.88 (1),	43

N/A indicates that the authors did not report the figure. *indicates that the characteristic includes all patients in the study, not only those with FM meningiomas. †30% (n = 31) of patients had lower CN palsies pre-operatively.

Table 3: Surgical results for the extreme lateral approach to foramen magnum meningioma resection

Article	n	Temporary morbidity, Permanent morbidity, mortality (%)	Resection rate, % (n)	Factors leading to subtotal resection	Recurrence rates	Recovery, % (n) or mean KPS	Complications	Mean Follow-up time, months (range)
Sen and Sekhar[8]	6	33, 33,17	67 (4) total, 33 (2) subtotal	Previous surgery (n = 2), scarring between cord/BS and tumor (n = 1)	N/A	67 improved (4), 17 stable (1), 17 worsened (1)	CSF leak 33 (2), LE weakness 17 (1), CN XI palsy 17 (1), respiratory dysfunction/phrenic paralysis 17 (1)	N/A
Babu[18]	18	22.2, 50, 18.2	72.2 (13) total, 27.8 (5) subtotal	N/A	N/A	63.6 improved (14), 22.7 stable (5), 12.5 worsened (3) KPS: Preop: 79.5 Postop: 87.3	CN IX palsy/paresis 37.5 (3), CN X palsy/paresis 37.5 (3), CN XI paresis 25 (2), CN XII palsy/paresis 50 (4), meningitis 25 (2), VA injury 25 (2), transient hemiparesis 12.5 (1), permanent hemiparesis 12.5 (1), quadriparesis 12.5 (1), CSF leak 12.5 (1), hydrocephalus 12.5 (1)	10 (7-19)
Salas[16]	51	46.3, 2.9, 1.4	69 (35) total, 31 (16) subtotal	N/A	N/A	KPS*: Preop: 74.7 Postop: 76.4	*Hydrocephalus 13 (9), CN worsening 10 (7), CSF leak 10 (7), CNS infection 7 (5), hematoma 3 (2)	
Arnautovic[30]	18	55.6, 5.6, 0	67 (12) total, 11.1 (2) near total, 22.2 (4) subtotal	Tumor adherent to VA only (n=2), or to BS, VA and branches (n=2)	5.6%	KPS: Preop: 70 Postop: 85.6	CN IX, X deficits 55.6 (10), CSF leaks 22 (4)	40 (0-80)
Roberti[44]	21	21.5, 21.5, 9.5	76 (16) total, 24 (5) subtotal/partial	Size, BS invasion	13.7% for all posterior fossa meningiomas	KPS: Preop: 77 Postop: 83	New CN deficits or worsening of preop deficits, CSF leaks, but this was not specific to meningiomas	12
Sarat Chandra [53]	10	N/A, N/A, 10	90 (9) total, 10 (1) subtotal	VA encasement (n = 1)	N/A	*80 improved (24), 7.5 lost to F/U (4)	*Lower CN palsy, CSF leak, pseudomeningocele, laryngeal edema, transient worsening of neurological deficits	*42 (4-72)
Parlato[52]	15	60, 13.3, 0	73.3 (11) total, 26.7 (4) subtotal	Tumor adherent to BS, VA and branches (n=1)	None in cases of gross total removal	KPS* median: Preop: 50 Postop: 80	Dysphagia 47 (7), CSF leak 20 (3), Hydrocephalus 13 (2)	*24 (7-55)

N/A indicates that the authors did not report the figure. * indicates that the characteristic includes all patients in the study, not only those with FM meningiomas

Table 4: Surgical results of the far-lateral approach to foramen magnum meningioma resection

Study	n	Temporary morbidity, permanent morbidity, mortality (%)	Resection rate, % (n)	Factors leading to subtotal resection	Recurrence rates	Recovery, % (n) or other measure of recovery	Complications, % (n)	Mean follow-Up time, months (range)
Kratimenos[19]	15	43, 0, 13.3	85.7 (6) total, 14.3 (1) subtotal	Bone destruction of lateral mass, atlas facets (n=1)	N/A	67 (10) improved, 20 (3) stable, 13.3 (2) worsened	Sepsis 6.7 (1), respiratory failure 6.7 (1), ARDS 6.7 (1), Transient neurological deficits: R hemiparesis 6.7 (1), L facial palsy 6.7 (1), Brown-Sequard syndrome 6.7 (1)	N/A
Bertalanffy[37]	19	0, 0, 0	100 (19) total	N/A	N/A	89.5 (17) improved	None	60
George[9]	31	0, 0, 9.7	96.8 (30) total, 3.2 (1) partial	Size (n=1)	0	87.1 (27) improved, 3.2 (1) stable, 9.7 (3) worsened Yasargil index of severity Pre-op mean: 2.84 Post-op mean: 1.12	Air embolism 3.2 (1), pulmonary embolism 3.2 (1)	57.6 (12-120)
Pirotte[26]	6	33, 16, 16	100 (6) total	N/A	N/A	83.3 (5) completely recovered, 16.7 (1) worsened	Respiratory failure 16.7 (1)	N/A
Gupta[21]	12	50, 25, 0	75 (9) total, 8.3 (1) near total, 8.3 (1) partial	N/A	N/A	83.3 (10) improved, 16.6 (2) worsened	CSF leak 16.6 (2), post-op swan neck deformity 8.3 (1), posterior fusion 8.3 (1)	24.3, (6-84)
Nanda[38]	10	0, 0, 0	100 (7) total	N/A	N/A	100 (10) improved, 80 (8) neurologically intact, 20 (2) improved, but residual paresis	None	N/A

Table 4: (Contd...)

Study	n	Temporary morbidity, permanent morbidity, mortality (%)	Resection rate, % (n)	Factors leading to subtotal resection	Recurrence rates (%)	Recovery, % (n) or other measure of recovery	Complications, % (n)	Mean follow-Up time, months (range)
Pamir[17]	19	42, 4.5, 0	94.7 (18) total, 5.3 (1) ubtotal	Firm consistency (n = 1)	0	KPS: Pre-op mean: 73 Post-op mean: 94 Yasargil index of severity: Pre-op mean: 2 Post-op mean: 0.77	CSF fistula 18 (4), transient CN palsies 9 (2), hydrocephalus 4.5 (1), VA injury 4.5 (1)	40 median, (2-120)
Bassiouni[33]	25	40, 8, 4	96% (24) Grade 2, 4% (1) Grade 3	Prior radiation therapy (n=1)	0	84 (21) improved, 8 (2) worsened KPS: Pre-op mean: 79 (50-90) Post-op mean: 89 (30-100)	CSF leak 16 (4), air embolism 4 (1), postop EDH 4 (1), wound infection 4 (1) Transient neurological deficits: CN XI 8 (2), hemiparesis 4 (1), Permanent neurological deficits: tetraplegia 4% (1), CN XII 4 (1)	73.2, (12-168)
Kandenwein[42]	16	50, 31, 6	87.5% (14) Grade 1/2, 12.5% (2) Grade 3	Adhesion to VA dural entry point (n = 1), BS vessels (n = 1)	0	50 (8) improved, 31.3 (5) stable, 12.5 (2) worsened McCormick score: Pre-op: 2.18 Post-op: 1.63	CSF fistula 19 (3), meningitis 6 (1) Transient neurological deficits: CN IX 6 (1), CN XII 12.5 (2), Permanent neurological deficits: CN IX 6 (1), CN X 12.5 (2), CN XI 6 (1), CN XII 19 (3)	43.5

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most of the older studies using the posterior midline approach, the French Cooperative Study (n = 103) did report their results, showing 77.7% total, 15.5% subtotal and 6.8% partial resection rates (as defined above).[40] Factors leading to subtotal removal were similar for all approaches with firm consistency, neovascularity, adherence to surrounding structures, large overall size, and prior radiation therapy being the most common causes of subtotal removal. Given the high degree of variability and paucity of data, it is difficult to draw conclusions regarding resection rates. There may be, however, a theoretical benefit to greater exposure to overcome the inherent surgical limitations related to individual tumor characteristics leading to subtotal removal such as those mentioned above.

Postoperative recovery using the far lateral, extreme lateral, and posterior midline approaches

Comparing postoperative recovery is equally difficult given the many different definitions of clinical recovery used. For far lateral approach studies that report individual patient data, (n = 134), we see that 80.6% of patients improved, 6.7% of patients remained stable, and 9% of patients worsened with 3.7% of patients unaccounted for. Authors using the extreme lateral approach have tended to report their cases using Karnofsky performance scores (KPS) rather than reporting individual data. Comparing mean KPS for the reported cases of each approach allows us to compare 44 patients using the far lateral approach[21,43] and 47 patients using the extreme lateral approach.[18,30,44] Mean pre-operative KPS in the far lateral cases was 76.4 and improved to 91.2, while KPS improved from 75.3 to 84.5 in cases using the extreme lateral approach, showing that both approaches lead to an improvement in postoperative performance status. Given the small number of patients and the inherent bias in including only those studies that reported KPS, any difference in outcome between the two methods should probably be ignored. Finally, for posterior midline approaches in all studies that reported data for FM lesions (n = 246), 72% of patients improved or had good results, 6.9% of patients were unchanged or had fair results, and 17.5% worsened or had poor results compared to 80.6%, 6.7% and 9%, respectively in the far lateral group. Again, it seems likely that the more modern approaches offer significant benefit in terms of postoperative recovery but comparison is difficult given the different measures of recovery and the improvements in peri-operative care mentioned earlier would certainly impact postoperative recovery status as well.

Recurrence rates using the far lateral, extreme lateral, and posterior midline approaches

FM tumor recurrence rates have been variably reported throughout the history of these studies. Of the far lateral approach studies that do mention tumor recurrence (n = 91), none have been reported. Alternatively, recurrence rates have been reported in various ways in the extreme lateral approach literature [Table 3] with rates of 5.6% for FM meningiomas, 13.7% for all posterior fossa meningiomas, and 0% for only gross total removal of FM meningiomas all being reported. Using the posterior midline approach, Meyer reported that 5% of patients operated on for a FM tumor died due to recurrence in the following three years.[4] The data on recurrence rates is too sporadic to be useful. Because tumor recurrence highly depends on the extent of tumor removal, however, it is worthwhile to note that common reasons for subtotal tumor removal in studies using lateral approaches were never related to lack of exposure, but rather adherence to surrounding structures, size of tumor, and prior radiation therapy or surgery. Without individual data from studies using the posterior midline approach, we cannot know whether a lack of exposure contributed to subtotal removal and tumor recurrence.

Results using the endoscopic endonasal approach

While there are many anatomical studies detailing the possibility of using this approach to remove anterior FM tumors, we did not find any study specifically addressing this issue. Most authors advocate this approach for small to medium-sized midline lesions without significant neurovascular involvement and have used it to remove suprasellar craniopharyngiomas, anterior cranial base meningiomas, or clival chordomas, among other types of lesions.[36,45-49] This approach is exciting because it allows for direct access to anterior FM lesions without brainstem manipulation, however, future studies specifically examining the approach to FM lesions will determine whether this approach will be plagued by the same problems as its transoral and transcervical predecessors.

Results using stereotactic radiosurgery

Stereotactic radiosurgery for FM tumors has mainly been limited to cases in which age or medical conditions prevent operative management or as adjunct therapy when surgery results in subtotal resection. Data detailing the use of stereotactic radiosurgery in the region of the FM is sorely lacking though one large retrospective has been recently published.[37] In this study, 19/23 (83%) patients showed radiographic evidence of either tumor regression or stability. In addition, 18/24 (75%) reported an improvement or stability in their symptoms or signs, with symptomatic improvement taking an average of 8.9 months to occur. Total mortality in this series was 31% (11/35) with 23% (8/35) being related to progression of disease. Morbidity due to radiosurgical treatment was seen in only 11% of patients (4/35), limited to two cases of radiation necrosis, one case of cystic enlargement and one case of temporary emesis. Smaller reports have also been published[39] reporting arrest of FM tumor growth and clinical stability after radiosurgery with minimal side effects or complications during a follow-up period ranging from 1 to 5 years. One major study of SRS for posterior cranial fossa meningiomas showed stable or reduced tumor burden in 95% of patients and progression in only 5%.[38]

Comparison with surgical treatment is difficult given the lack of data, but morbidity directly resulting from radiosurgery is at least comparable, if not better than that resulting from surgery. Both symptomatic improvement after treatment and mortality are probably inferior to that seen with definitive surgical management, an unsurprising result given that radiosurgery is not intended to cure patients of their disease. Thus overall, SRS seems to have minimal morbidity associated with treatment and presents a good, noninvasive alternative to surgical treatment for patients in whom operative management is inappropriate or who refuse surgical resection.

CONCLUSION

As technological improvements continue to reduce surgical morbidity and mortality rates for FM lesions, the modern skull-base neurosurgeon will continue to accumulate tools with which to approach the foramen magnum. Laterally extended open surgical approaches currently represent the gold standard for treatment of FM lesions because of their proven results in terms of morbidity, mortality, resection rates and improved postoperative outcomes. In the future, however, extended endoscopic approaches may challenge this conventional wisdom. Regardless of the approach used, advances in microsurgical techniques have rendered similar patient outcomes for the resection of FM lesions and neurosurgeon preference remains the current standard for determining which approach is taken.

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