

Critical Appraisal of Minimally Invasive Keyhole Surgery for Intracranial Meningioma

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Abstract

Purpose

Minimally invasive meningioma removal through transcranial and endoscopic endonasal keyhole routes remain controversial. Herein we detail results of keyhole meningioma removal defined as use of a minimally invasive “retractorless” approach for which a traditional larger approach is often used instead.

Methods

Retrospective analysis from 2008-2021 of consecutive patients undergoing keyhole meningioma removal through one of six approaches: extent of resection, complications, endoscopy use, MRI FLAIR/T2 changes. Surgical goal was maximal safe removal including conservative(subtotal) removal for some invasive locations.

Results

Of 329 patients, keyhole approaches were utilized in 193(59%) patients (mean age 59 ± 13 ; 30(15.5%) prior surgery) who underwent 213 operations; 205(96%) were skull base location. Approaches included: endoscopic endonasal(n=74,35%), supraorbital(n=73,34%), retromastoid(n=38,18%), mini-pterional(n=20,9%), suboccipital(n=4,2%), and contralateral transfalcine(n=4,2%). *Primary outcomes:* Gross total/near total(>90%) resection: 125(59%); (5% for petroclival, cavernous sinus/Meckel’s cave, sphenocavernous locations vs 77% other locations). Complications included: permanent neurological worsening 12(6%); CSF leak 2(1%); meningitis 2(1%); no patients sustained DVT, PE, MI, or 30-day mortality. Median LOS was 3 days with 94% discharged home and 96% with favorable 90-day KPS. *Secondary outcomes:* Small persistent FLAIR/T2 changes: 11(5.2%) patients. Endoscopy use: 87/139(63%) of craniotomies, facilitating additional tumor removal in 55%. Tumor progression was observed in 26(13%) patients(mean follow-up 42 ± 36 months).

Conclusion

This analysis suggests keyhole meningioma removal can be associated with reasonable resection rates, low complication rates, short hospitalizations and high 90-day performance scores. Subtotal removal may be appropriate for invasive/adherent meningiomas to avoid complications. With careful patient selection and requisite experience, these approaches may be considered alternatives to traditional approaches.

Introduction

Meningiomas are the most common primary brain tumor with almost 35,000 patients being diagnosed annually in the US¹, and although 85-90% are benign (WHO Grade 1), they frequently encase or become adherent to arteries, veins and cranial nerves, and have a propensity to invade multiple skull base compartments. While surgery remains first-line treatment for meningiomas, the approach used and aggressiveness of removal is highly location-dependent and influenced by other factors such as tumor invasiveness, prior treatments and surgeons’ philosophy. Innovative skull base surgery approaches developed in the early 1990s generally employed large incisions, extensive bone removal and promoted maximal tumor removal as the primary goal. However, results from multiple series using these approaches indicate that overly aggressive tumor removal can be associated with relatively high rates of permanent cranial nerve deficits and other neurological complications²⁻⁵. Furthermore, stereotactic radiosurgery and radiotherapy (SRS or SRT) have long-term control rates of 90% or higher for most recurrent or progressive WHO grade I meningiomas, and some primarily treated cavernous sinus (CS) meningiomas⁶⁻⁹. Thus, over time, restoring or maintaining neurological function

and quality of life have gained greater priority and the dictum of *maximal safe tumor removal* has gained wider acceptance^{2,10-13}.

Minimally invasive surgical (MIS) techniques have been increasingly applied across multiple surgical subspecialties often with the aid of endoscopy^{14,15}. Although the concept of minimally invasive brain tumor removal has been promoted for decades, it has remained controversial and not widely practiced. The term “keyhole surgery” was introduced 50 years ago by Donald Wilson in his 1971 technical note, “Limited exposure in cerebral surgery”¹⁶. Since the 1990s, the keyhole concept has been refined by application of modern micro-neurosurgical techniques and technology^{17,18}. In the last 20 years, the endoscopic endonasal approach has evolved into an accepted and commonly used minimally invasive route for many midline skull base pathologies, given its ability to facilitate tumor removal without brain retraction¹⁹⁻²³.

For almost 15 years, we have used several minimally invasive approaches for brain tumors, particularly for skull base and parasagittal meningiomas that eliminate the need for fixed brain retraction by relying on gravity assistance and endoscopic visualization²⁴⁻³². Herein we report detailed outcomes and two illustrative videos of our use of these MIS approaches including extent of resection, the value of endoscopy for tumor removal, complications, LOS, and 90-day performance status in a large cohort of patients with meningioma treated over 13 years. By measuring acute post-operative MRI changes, we also demonstrate that these “retractorless” approaches can be performed with minimal brain impact and manipulation. Except for our recent report on elderly meningioma patients and that by Burks et al, to our knowledge, there are no prior studies with over 40 patients treated with a minimally invasive keyhole paradigm for all intracranial meningiomas^{26,33}.

Methods

Patient population & data collection

After institutional review board approval (IRB# JWCI-19-1101), all patients at Saint John’s Health Center, Santa Monica, CA, between January 2008 and January 2021 who underwent surgical removal of an intracranial meningioma were identified. Patient consent was not necessary as data was deidentified. All operations were performed by one of two neurosurgeons (DK, GB) and endonasal operations were performed with otolaryngology collaboration (CG). Data collection included prior treatments, tumor histopathology, size and location on MRI, endoscope usage, extent of resection, complications, length of stay, disposition, readmissions and long-term tumor control.

MIS “keyhole” definition and approach selection: Keyhole approaches are defined as: *the use of a minimally invasive approach for a given tumor in which a traditional larger approach may be used instead*. These six approaches include the endoscopic endonasal, supraorbital, mini-pterional, retromastoid, suboccipital tentorial and transfalcine routes (Figure 1A & 1B, **supplemental GIF, Supplemental Table 1**). Non-keyhole approaches include convexity craniotomies, pterional, and bifrontal craniotomies, orbito-zygomatic and other traditional skull base approaches, and far-lateral approaches. Table 1 describes the strategy for applying these 6 keyhole approaches; two **videos** provide 6 case examples. During the study period, traditional open skull base craniotomies were rarely used.

Table 1
Surgical Decision Making for Keyhole Meningioma Removal

Meningioma Location	Factors for Surgical Decision Making	Approach Selection
Olfactory Groove/ Anterior Planum	Olfaction preservation	Supraorbital
Posterior Planum/ Tuberculum Sella	1. Proportion of tumor above the planum 2. Sellar depth 3. Tuberculum angle 3. Optic canal Invasion 4. Extent of tumor extension lateral to supraclinoid ICA 5. Maximal tumor diameter	Majority of tumor below planum, deep sella, steep (acute) tuberculum angle, minimal lateral extension, small size (under 3 cm): Favor Endonasal Medial optic canal invasion: Favor Endonasal Majority of tumor above planum, shallow sella, broad tuberculum angle, significant lateral extension, lack of medial optic canal invasion, larger size (over 3 cm): Favor Supraorbital
Clinoidal	Extension into middle fossa	Predominantly above the lesser wing: favor Supraorbital Predominantly within the middle fossa: favor Mini-pterional
Sphenoid Wing	Angle of Attack with respect to the Optic Chiasm and Supraclinoid Carotid	Mini-pterional
Spheno-Orbital/ Spheno Cavernous	Angle of attack with respect to the optic chiasm and supraclinoid carotid artery	Mini-pterional ± orbitotomy
Cavernous Sinus/ Meckel's Cave, Spheno-cavernous	Surgical goal of decompression	Endonasal
Petroclival/ CP Angle/ Foramen Magnum	Clival and CP Angle component	If substantial petrous and posterior CP angle component posterolateral to CN VI: Favor Retromastoid If substantial clival component more anterior: Favor Endonasal ± Retromastoid
Tentorial	Proximity to convexity	If away from convexity – Suboccipital sitting gravity-assisted endoscopic-assisted or fully endoscopic
Falx	Abutting primary motor or sensory cortex with overlying ipsilateral cortex	Contralateral gravity-assisted trans-tentorial endoscopic

Surgical goals, preparation and technique: A goal of maximal safe tumor removal was applied across all tumor locations. However, subtotal removal was typically the goal for three meningioma subtypes given their invasive nature and tendency to encase neurovascular structures: petroclival, CS/Meckel's cave, and spheno-cavernous locations, as well as some meningiomas with prior surgery and/or radiotherapy²⁸. Residual meningioma was deliberately left along neurovascular structures if too adherent or left in the skull base bone if deemed too infiltrative. Four patients had planned staged approaches for large meningiomas (maximal diameter >6 cm: endonasal debulking combined with a pterional, mini-pterional or retromastoid approach.

Total intravenous anesthesia (TIVA) was used to promote rapid emergence from anesthesia³¹. Preoperative tumor embolization was not used. Lumbar drains for CSF diversion were used infrequently and only early in the series. As recently described and highlighted in Video 1, all endonasal cases were performed fully endoscopically using a 0° 4-mm rigid endoscope initially; 30° and 45° endoscopes (Karl Storz-America, El Segundo, CA), are used at various stages of the procedure^{28,32}. A pedicled nasoseptal flap (or middle turbinate flap) is harvested in cases of tuberculum and planum meningiomas but not for all CS/Meckel cave meningiomas, depending upon CSF leak grade^{28,29,32}.

Except for the fully endoscopic sitting suboccipital approach, all transcranial keyhole craniotomies are performed initially with the microscope and then with endoscopy as needed for illuminating areas poorly seen with the microscope, and for endoscopic tumor resection. Endoscopy is typically performed with an assistant driving the endoscope. Patient positioning is critical to optimize gravity-assisted exposure and for endoscopy. Our use of the supraorbital and mini-pterional approaches have been well-described^{30,32,34}. The retromastoid approach is performed with the patient supine or lateral position, utilizing a short linear or curvilinear incision with approximately 2x3cm craniotomy³³. The suboccipital approach is performed in the sitting or lateral position typically using an approximate 2x2cm craniotomy for tentorial meningiomas. As previously described (and highlighted in Video 2), the gravity-assisted transfalcine approach is performed specifically for parafalcine meningiomas that have a ring of edematous overlying eloquent cortex at risk from an ipsilateral approach²⁴. The patient is placed in lateral position with tumor side up and inclined in reverse Trendelenburg position with the vertex at 30-45 degrees²⁴, allowing for gravity-retraction and access from the unaffected contralateral side.

Outcome and statistical analysis: Primary outcomes included extent of tumor resection, complications, hospital LOS, reoperations and readmissions within 90 days, 30-day mortality, KPS, and cranial (CN) outcomes. A favorable KPS at ≥ 90 days follow-up was defined as improved or unchanged from preoperative KPS. As previously published, resection rates were categorized as: gross total resection (GTR), near total resection (NTR $\geq 90\%$ tumor resection), or subtotal resection ($< 90\%$)^{26,32}. Simpson resection classification was not assessed given that most patients had invasive skull base meningiomas in which complete tumor resection and removal of involved bone and dura is typically not feasible^{26,32,35}.

Three secondary outcomes were included: 1) To quantify approach-related trauma of tumor removal, post-operative day #1 or 2 MRIs were independently assessed by a neuroradiologist (JR) for new FLAIR/T2 signal changes in the peritumoral and surgical approach areas³². New FLAIR/T2 change in the axial plane around the resection area or approach trajectory was quantified by maximal diameters. Persistence or resolution was documented on 3-month postoperative MRI. 2) For transcranial operations, as previously published, the utility of endoscopic visualization was determined by if endoscopy facilitated additional tumor removal^{30,32} 3) Tumor progression or recurrence based on sequential MRIs and need for additional treatment (repeat surgery and/or radiotherapy) was assessed for each patient.

The statistical comparison of the mean in the data amongst different groups was performed using ANOVA and independent Student's t-test. Univariate analysis was done using Chi-square or Fisher's exact test when applicable. Binomial multivariate analysis was done using logistic regression analysis and p-values less than 0.05 were considered statistically significant. Tumor control data for testing binomial variables were plotted using Cox Regression and Kaplan-Meier analysis.

Results

Demographics: Of 329 patients, keyhole approaches were used in 193 (66.3%) (74% female, mean age 59 \pm 13, mean follow up 42 \pm 36 months; WHO Grade I: 173/193(89.6%), Grade II: 19/193(9.8%), Grade III: 1/193(0.6%)); 32(9.7%) had prior radiation. The 213 keyhole approaches included 205 (96%) for skull base location and 47(22%) were in patients with prior surgery. Approaches were endonasal (n=74), supraorbital (n=73), retromastoid (n=38), mini-pterional (n=20), sitting

suboccipital (n=4), and contralateral gravity-assisted transfalcine (n=4) (Table 2). Four patients had planned staged approaches for large meningiomas (endonasal combined with a pterional, mini-pterional or retromastoid approach). Lumbar drains were used in 5/74(7%) endonasal cases all prior to 2013, and 1/139 (0.7%) transcranial approach in 2017.

Table 2
Meningioma Characteristics, Resection Rates & Surgical Parameters for 213 Keyhole Operations

	Endonasal (n=74)	Supraorbital (n=73)	Mini- pterional (n=20)	Retromastoid (n=38)	Suboccipital (n=4)	Transfalcine (n=4)	Total (n=213)
GTR	17 (23%)	34 (46.6%)	10 (50%)	19 (50%)	2 (50%)	3 (75%)	85 (40%)
GTR/NTR	22 (29.7%)	54 (74%)	14 (70%)	28 (73.7%)	3 (75%)	4 (100%)	125 (58.7%)
Redo Surgery	24 (32.4%)	16 (21.9%)	3 (15%)	3 (7.9%)	1 (25%)	0	47 (22.1%)
Invasion to CS/MC/Orbit /ITF	40 (54%)	15 (21%)	10 (50%)	9 (24%)	0	0	74 (35%)
Median Skull Base Compartments Occupied	2	2	2	2	1	1	2
Mean Max Tumor Diameter (mm)	29.1 ± 13.2	28.5 ± 13.0	29.7 ± 14.1	32.1 ± 13.5	26.5 ± 12.5	40.0 ± 21.2	29.7 ± 13.4
Use of Endoscopy	74 (100%)	54/73 (74%)	5/20 (25%)	21/38 (55%)	3/4 (75%)	4/4 (100%)	161/213 (76%)
New/Worsened FLAIR/T2 Changes (mean diam, mm)	2/74 2.7% (2.5mm)	11/73 15.1% (6.9 mm)	4/20 20.0% (9.5 mm)	18/48 37.5% (8.1 mm)	1/4 25% (11 mm)	0/4 0 (NA)	36/213 (16.9%) (7.67 mm)
Persistent FLAIR Changes at 3 months or more postop	1/74 (1.4%)	2/73 (2.7%)	2/20 (10%)	6/48 (12.5%)	0	0	11/213 (5.2%)
Median LOS	3	3	2	2	3	2	3

PRIMARY OUTCOMES:

Resection rates by approach and tumor location: As shown in Tables 2 and 3, GTR was achieved in 85(40%) operations while GTR/NTR (>90% resection) was achieved in 125(59%) operations. By meningioma location, GTR/NTR rates were highest for frontal fossa, parafalcine tentorial, olfactory groove and planum meningiomas (N=158, range 84-100%), and lowest for sphenocavernous, CS/Meckel's cave, petroclival (N=55, range 5-6%) (Table 3). Excluding petroclival, CS/MC and sphenocavernous location, GTR/NTR was achieved in 114/136 (84%) in first-time operations. Dense adherence to neurovascular structures was associated with 36% GTR/NTR versus 100%, without dense adhesions. (p<0.001). (**Supplemental Table 2**). All patients with STR/NTR had at least one risk factor (prior surgery, radiotherapy, invasion cavernous sinus/Meckel's cave/infratemporal fossa/orbit).

Table 3
Resection Rates in 213 Keyhole Approaches by Meningioma Location, Invasiveness & Use of Endoscopy

Tumor Location (N)	Overall GTR/NTR (n=213)	First-time Surgery GTR/NTR (n=166)	Overall GTR (n=213)	First-time Surgery GTR (n=166)	Use of Endoscopy (n=213)
Frontal Fossa (8)	8 (100%)	8/8 (100%)	8 (100%)	8/8 (100%)	7 (88%)
Parafalcine (4)	4 (100%)	4/4 (100%)	3 (75%)	3/4 (75%)	4 (100%)
Tentorial (18)	17 (94%)	17/17 (100%)	13 (72%)	13/17 (77%)	12 (67%)
Olfactory Groove (14)	12 (86%)	11/12 (92%)	9 (64%)	8/12 (67%)	14 (100%)
Planum Sphenoidale (12)	10 (84%)	8/10 (80%)	4 (33%)	3/10 (30%)	9 (75%)
Clinoidal (19)	14 (74%)	13/15 (87%)	8 (42%)	8/15 (53%)	12 (63%)
Tuberculum Sellae (39)	28 (72%)	26/31 (84%)	22 (56%)	22/31 (71%)	33 (85%)
Cerebellopontine Angle (23)	16 (70%)	14/21 (67%)	9 (39%)	8/21 (38%)	14 (61%)
Sphenoid Wing (16)	10 (62.5%)	10/15 (67%)	7 (44%)	7/15 (47%)	7 (44%)
Spheno-orbital (5)	3 (60%)	3/3 (100%)	1 (20%)	1/3 (33%)	1 (20%)
Total	122/158 = 77%	114/136 = 84%	84/158 =53%	81/136=60%	
Petroclival (17)*	1 (6%)	1/9 (11%)	0 (0%)	0/9 (0%)	14 (82%)
CS/MC (19)*	1 (5%)	0/10 (0%)	0 (0%)	0/10 (0%)	18 (95%)
Spheno-cavernous (19)*	1 (5%)	1/11 (10%)	1 (5%)	1/11 (10%)	16 (84%)
Total	3/55=5%	2/30=7%	1/55=2%	1/30=3%	
TOTAL	125 (59%)	116 (70%)	85 (40%)	82 (49%)	161 (76%)
Dense adherence to critical neurovascular structures					
Yes (N=138)	50 (36%)		20 (15%)		
No (N=75)	75 (100%)		65 (87%)		
p-value	p<0.001		p<0.001		
Abbreviations: GTR: gross total resection, NTR: near total resection, CS: cavernous Sinus, MC: Meckel's cave.					
*These 3 locations represent a subset of 55 invasive skull base meningiomas in which conservative (subtotal) removal was the surgical goal. Of these 55 cases; 7 patients had tumor progression treated with repeat surgery and/or SRS/SRT.					
Of 17 operations for petroclival meningioma (in 13 patients), 14 were approached via the endonasal route for conservative debulking and 3 via the retromastoid route; 13/17 (76%) operations and 9/13 (69%) patients had meningiomas that extended into multiple compartments including CS, Meckel's cave, and/or sellar/suprasellar areas, 8/13 (61%) had prior surgery and 7 (54%) had prior radiation.					

Clinical outcomes and complications

Major complications occurred in 23/193 (11.9%) patients (Table 4). Permanent neurological worsening occurred in 12(6%) patients including 4 with strokes and 8 with cranial nerve injuries (**Supplemental Table 3**). Reoperations were needed in 10(5%) patients, (two for CSF leaks); 2(1%) patients had meningitis No patients developed perioperative DVT, PE or MI. Three patients all with multiple prior surgeries, died of disease progression at 80, 229, and 3508 days after their last operation.

Table 4

Major and Minor Complications, Readmissions, Reoperations and Discharge Status in 193 Patients Undergoing 213 Keyhole Operations for Meningioma

Major Surgical Complications (n=23 patients)	25
Permanent Neurological Worsening	12 (6%)
- Stroke	4 (2%)
- New or Worsening Cranial Nerve Dysfunction	8 (4%)
Transient Neurological Worsening	1 (0.5%)
- Persistent seizures with transient hemiparesis	1
Reoperations	10 (5%)
- Delayed hematoma evacuation	2
- Reoperation for residual tumor (same admission)	2
- Reoperation for residual tumor (readmission)	1
- CSF leak repair	2
- Revision of sellar reconstruction (no CSF leak)	2
- Epistaxis needing surgical intervention	1
Meningitis	2 (1%)
Total Major Complications by Operation (p=0.45)	
- Redo-operation	7/47 (15%)
- First-time operation	18/166 (11%)
Minor Complications	
- Sinusitis	3
- Mucocele	1
- Forehead numbness	11
- Frontalis paresis	7
- Frontalis palsy	2
- Delayed wound dehiscence	1
- Hardware malposition	1
Systemic Complications	2 (1%)
- Aspiration Pneumonia	1
- UTI	1
- DVT/PE/ MI	0
Delayed Radiation Induced Optic Neuropathy	1

* One patient had both CSF leak and meningitis; one patient who had stroke had a multiply recurrent meningioma with prior surgery and RT and was the only mortality in the series

Major Surgical Complications (n=23 patients)	25
Discharge to Home	201/213 (94%)
Readmissions Requiring Surgical Intervention (n=4/213)	2%
- Residual tumor needing more surgery	1
- Delayed hematoma needing surgery	1
- CSF leak repair	1
- Epistaxis	1
Readmissions Managed Medically (n=2/213)	1%
- UTI, Atrial fibrillation	1
- Hyponatremia	1
* One patient had both CSF leak and meningitis; one patient who had stroke had a multiply recurrent meningioma with prior surgery and RT and was the only mortality in the series	

Discharge to home, functional outcomes and readmissions:

Of 213 operations, 201(94%) patients were discharged to home; 12(6%) went to skilled nursing facility or rehabilitation (Table 5). Median LOS was higher for patients discharged to rehabilitation or skilled nursing facility versus home (5 vs 2, $p=0.012$). Over 11 years, median LOS decreased: 3 days (first 71 cases), 3 days (middle 71 cases) and 2 days (last 71 cases), $p=0.013$. Longer LOS ($LOS \geq 4$) was associated with major complications (22% vs 7%, $p=0.005$), discharge to rehabilitation or nursing facility (67% vs. 28%, $p=0.008$). Ninety-day readmissions occurred in 6 (2.8%) cases, including 4 who required surgery.

Of 184/193 (95%) patients with available follow-up, favorable 90-day KPS was noted in 176(96%): improved in 126/176(72%) and stable in 50/176 (28%). Mean KPS for the entire cohort improved postoperatively from 72.3 to 82.4 ($p<0.001$).

SECONDARY OUTCOMES:

Acute MRI changes in region of approach: Of 213 operations, POD 1 or 2 MRIs showed regional increase in FLAIR/T2 signal in 36(16.9%), highest in the retromastoid cohort (37.5%) (Table 2). FLAIR/T2 averaged 8 ± 5 mm in maximal diameter and completely resolved in all but 11(5.2%) cases on follow-up MRI. No patients with increased FLAIR had attributable neurological deficits to their FLAIR changes.

Utility of endoscopy

Endoscopy was used in 161(76%) keyhole operations, including all 74 endonasal cases and 87/139(63%) transcranial cases (Table 2). Of 87 endoscope-assisted transcranial cases, in 48(55%) it facilitated additional tumor removal.

Long-term tumor progression or recurrence

Mean follow-up for the 193 patients was 41 ± 36 months. Recurrence after GTR was seen in 1(1.2%) patient, while progression of residual tumor occurred in 26(24.1%) patients, for an overall recurrence/progression rate of 13.9% (27/193). As per Kaplan-Meier analysis, mean time to recurrence or progression was 23.7 ± 27.3 months (range 3-94

months). Of these 27 patients, 4 had repeat surgery only, 11 SRT only, 2 SRS followed by another surgery and 10 were observed or medically managed.

Discussion

Minimally invasive philosophy applied to meningiomas

MIS techniques aim to minimize collateral damage to normal tissues, maintain or improve quality of life, while achieving maximal tumor resection^{16-18, 26,33,36}. Striking that balance while being cost-effective is the ultimate “sweet spot” of any surgical procedure. We propose that the present series and prior series for intracranial meningioma are a step forward for neurosurgery and endoscopic skull base surgery, demonstrating the potential effectiveness of this paradigm^{17,18,23,26,31,33,37}. This evolution is in part a result of cross-specialty collaboration. The adoption of the endoscope into transsphenoidal surgery that began in the 1990s with our colleagues in otorhinolaryngology, has transformed not only pituitary surgery but also the entire field of skull base surgery³⁸. Most pituitary adenomas are now removed through an endoscopic endonasal approach, and as we show here, many midline skull base meningiomas can be removed via the endonasal route^{32,39,40}.

Keyhole meningioma surgery aims to limit brain exposure and manipulation, accessing tumors through smaller strategically placed craniotomies without static brain retractors, facilitated by gravity-assistance, low profile instrumentation and endoscopy^{17,18,33,41,42}. Despite the benefits of visualization, there is ample evidence that fixed brain retractors can cause acute and lasting brain injury^{41,43}. Recent reports highlight the potential for retraction injury and associated complications with traditional craniotomies for tuberculum and planum meningiomas⁴⁴⁻⁴⁶. A major benefit of keyhole retractorless and gravity-assisted endoscopic approaches may be in less brain exposure and parenchymal manipulation^{17,18,32,36,41,42,46}. This advantage was evidenced by the absence of early postoperative FLAIR/T2 changes along the surgical corridor in 82% of patients in this series including 100% of endonasal approaches; for 36 patients with FLAIR/T2 increases, these were small and resolved in all but 5% of patients.

For a neoplasm as diverse in location and invasiveness as meningioma, the surgical team should be facile working through multiple surgical corridors with both microscope and endoscope (see Table 1). Using TIVA anesthesia, smaller scalp and muscle incisions, minimal monopolar cautery, and focused craniotomies to minimize brain exposure, appears to promote rapid healing, less post-operative pain and a greater willingness and ability for patients to mobilize and leave the hospital^{30,31}. Adoption of MIS techniques have been a key component of success in enhanced recovery protocols in other surgical subspecialties which we are adopting as well in all of our brain tumor patients³¹. Having reliable skull base closure techniques especially for endonasal, supraorbital and retromastoid routes where bony sinus and mastoid air cell entry frequently occurs is also essential to avoid CSF leaks and meningitis. This preventative strategy includes liberal use of abdominal fat grafts to obliterate sinus or air cell entry after craniotomy and a graded repair approach for skull base reconstruction including fat grafts and nasoseptal flaps in endonasal surgery without lumbar CSF drainage^{29,34,47}.

To be valid, the MIS keyhole concept should yield low rates of new neurological deficits, CSF leaks and high rates of functional outcomes. Our results in terms of infrequent complications, short LOS and improved post-operative KPS scores support this approach. New cranial neuropathy was observed in only 4% of patients. Lumbar drains were used in only 3% of operations, while post-operative CSF leak rate and meningitis rates were only 1%. There were no cases of perioperative DVT, PE, MI or 30-day mortality. The absence of thromboembolic events is likely due in part to our high patient functionality with few neurovascular complication, early ambulation and limited perioperative narcotic use, and compares favorably to the 2.7-4.1% incidence of PE/DVT recently published⁴⁸.

Prior studies and our experience demonstrate that complications impact quality of life, lengthen hospital stay, increase costs and often require reoperations and readmissions^{29,36,38-40}. Compared to our outcomes of 3-day median LOS, 94% discharged to home, and 7% 90-day readmission rate, and no 30-day mortality, recent reports encompassing all intracranial meningiomas have documented LOS for skull base and other meningioma patients ranging from 4-11 days, discharge to home ranging from 70-83.4%, 90-day readmission rates of 9.2-17.9%, and 30-day mortality ranging from 0-5.4%⁴⁹⁻⁵³. This comparison is notable, given our series is comprised predominantly (96%) of skull base meningiomas (which are generally considered to be of higher complexity and risk profile than convexity meningiomas), while these 5 series include all intracranial meningiomas. A rapid complication-free recovery also benefits those patients who may have more aggressive (WHO Graded 2 or 3) or previously-treated meningiomas who may need to begin adjuvant therapy shortly after surgery³⁵.

Balancing goals of maximal tumor removal and complication avoidance

Perhaps the most serious critique of keyhole meningioma surgery is that ultimately the patient is not well-served because overly conservative tumor removal leads to the eventual need for repeat surgery, radiosurgery, or possibly both. However, our overall meningioma resection rates for all locations except petroclival meningiomas are comparable to prior reports^{10,13,44-46,51}, and our progression/recurrence rate of 14% is similar to prior reports (almost all in patients who underwent NTR or STR), although this rate will undoubtedly increase with longer follow-up^{9,10,54-57}. A growing collective experience places functional preservation as a higher priority than GTR resection, as highlighted by recent reports^{2,10,13,35}. The beneficial impact of this approach for a given patient is a greater likelihood of no new postoperative neurological deficits and preserved or improved QOL while acknowledging that for many patients their meningioma becomes a chronic illness that warrants long-term monitoring with a higher likelihood of tumor progression and need for additional surgery, SRS/SRT or possible medical therapies in the years after non-GTR resection^{8-11,13,54-59}.

Considering petroclival meningiomas, we did not achieve GTR in any of 17 operations and had one new CN deficit (6%). In multiple series of petroclival meningiomas approached through traditional skull base approaches including the retromastoid approach, the GTR rate ranged from 21%-76% but permanent CN and other neurovascular complications ranged from 22%-54%^{2-5,60-63}. Collectively, these reports indicate that overly aggressive attempts at GTR, will likely be associated with a relatively high rate of permanent neurovascular morbidity and lower quality of life for many patients; thus, we prefer a more conservative surgical approach for such invasive skull base meningiomas, as other groups have also recommended^{10,11,13,37,54-59}.

Study limitations and bias

The major limitation of this study is its retrospective nature, and our selection bias for using these 6 keyhole approaches without a comparison cohort of patients treated with traditional skull base approaches, or other relatively new minimally invasive approaches such as the endoscopic transorbital route^{64,65}. Also, the follow-up in our patients averaged 44 months which is relatively short. Longer follow-up is necessary to assess the efficacy of this approach more fully and determine how many patients who underwent NTR or STR ultimately need radiotherapy or additional surgery.

Conclusions

A minimally invasive keyhole paradigm applied to skull base and other select meningiomas can yield comparable tumor resection rates with low rates of neurovascular and systemic complications, short LOS and high rates of functional outcomes. While traditional skull base approaches remain valid and effective, we suggest that with increasing experience, transcranial and endonasal keyhole approaches can be considered part of the surgical armamentarium for many intracranial meningiomas.

Declarations

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COMPLIANCE WITH ETHICAL STANDARDS

Funding: The authors did not receive support from any organization for the submitted work.

Conflict of Interest: DFK receives royalties from Mizuho Inc. GB is a consultant for Vascular Technologies Inc. and Cerevasc Inc. WS is a consultant for Stryker Corporation. JDT declares that he has no conflict of interest. RJM declares that he has no conflict of interest. AC declares that he has no conflict of interest. SY declares that she has no conflict of interest. AE declares that she has no conflict of interest. JR declares that he has no conflict of interest. HK declares that he has no conflict of interest. NM declares that he has no conflict of interest. CG declares that he has no conflict of interest.

Ethical approval: 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.

Informed consent: Informed consent was waived due to the retrospective nature of the study. For the patients discussed in the surgical videos, informed consent was obtained.

Data Availability: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions: Study conception and design was performed by DFK, GB, JDT, and RJM. Material preparation, data collection and analysis were performed by JDT, RJM, AC, SY, AE, and JR. The first draft of the manuscript was written by JDT, DFK, and RJM and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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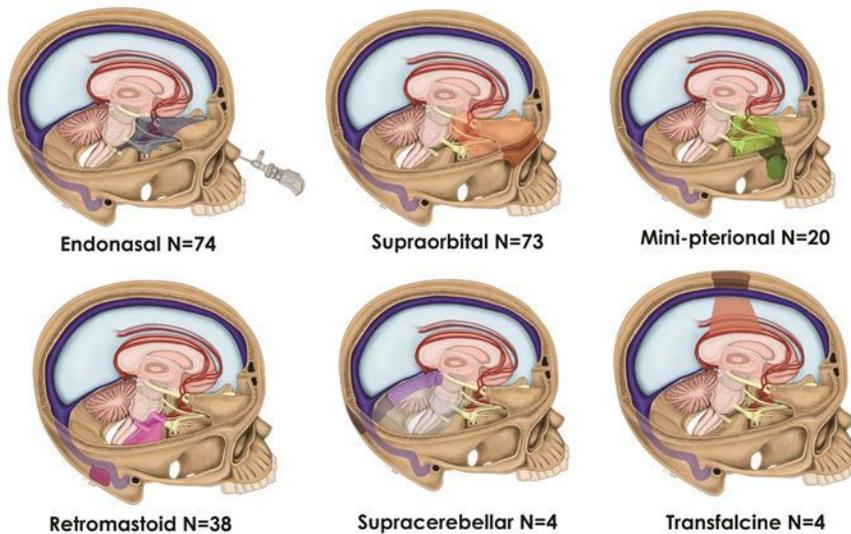
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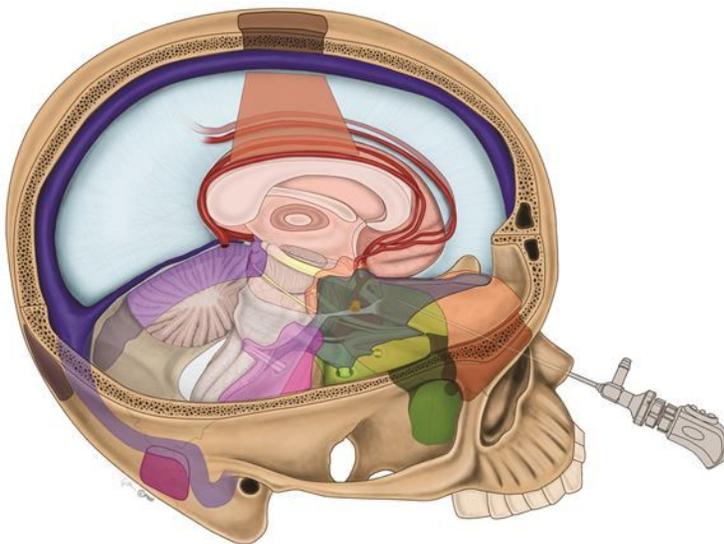
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Figures



A



B

Figure 1

(1A,1B): Drawing and GIF animation (Supplemental File) depicting 6 keyhole approaches for meningioma removal: 1) endonasal, 2) supraorbital, 3) minipterional, 4) retromastoid, 5) suboccipital sitting gravity-assisted and 6) transfalcine gravity-assisted.

Supplementary Files

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