



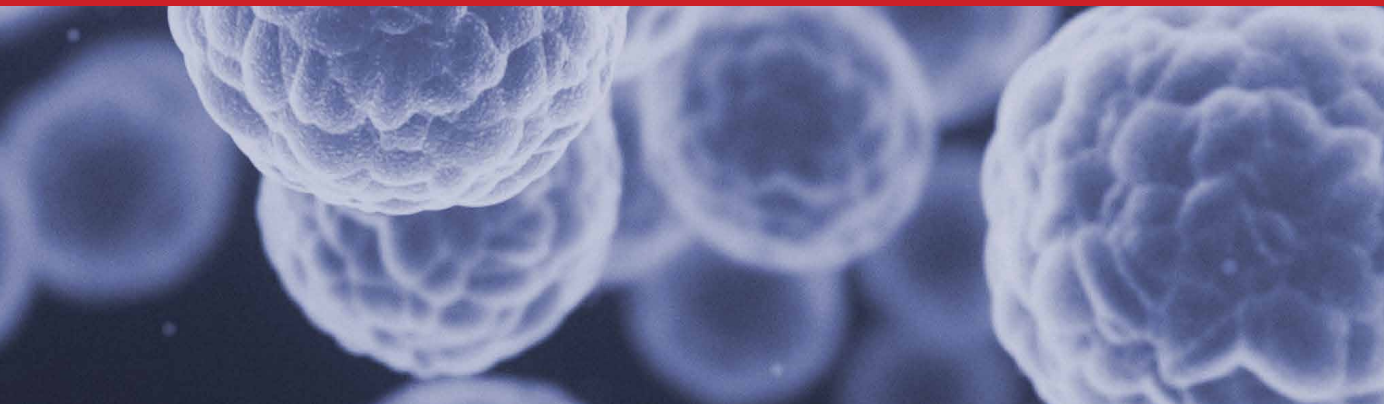
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Modern Meningioma Treatment

Advances in Surgery, Technology,
and Precision Care Medicine

Edited by Roberto Garcia-Navarrete



Modern Meningioma Treatment - Advances in Surgery, Technology, and Precision Care Medicine

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Edited by Roberto Garcia-Navarrete

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Aims and Scope of the Series

The field of oncology has undergone extraordinary change and progress over the past several decades. Today, information is evolving at a rapid rate, with standards of management far different than standards of care applied during the training of most practicing oncologists. Oncology practitioners in all disciplines must remain current to optimize patient care. Basic and translational science remain critical in developing process improvements for patient care. The closer we understand the mechanism, the more we can improve targeted therapies and apply them to patient care. The pace of information is moving faster than at any previous time in history, and all oncology disciplines must remain current to provide excellent service to patients. The modern oncologist must be fluent in using big data and the volume of information generated in clinical trials. As we move closer to personalized patient care based on genomics and molecular biomarkers, the modern oncologist has to be nimble in assessing all available information and how this would be applied to each patient, balanced by the clinical status and medical co-morbidities of each patient. Targeted therapies can bring new and different sequelae, and oncology teams need to remain fluent in managing the consequences of therapy and primary management. In this book series, we will present how modern care has progressed in multiple disease areas and how modern oncology teams need to adapt in order to manage the cancer patients of today successfully. Surgery, radiation therapy, and medical oncology are practiced today with the support of exceptional modern technology, and in this series, we will review how these improvements are applied to each disease site to maintain excellence in patient care.

Meet the Series Editor



Dr. FitzGerald is the professor and chair of the Department of Radiation Oncology at UMass Chan Medical School in the USA. He serves as one of the principal investigators of the Imaging and Radiation Oncology Core (IROC) service for the National Cancer Institute clinical trials program and is directly involved in the quality assurance of clinical trials in the National Clinical Trials Network (NCTN). Dr. Fitzgerald manages NCTN clinical trials with a real-time pre-therapy review of imaging and radiation therapy treatment objects to ensure the care plan complies with study objectives and the patient stage has been assigned to the correct study. His basic science interest is in hematopoietic stem cell biology and cellular adhesion molecules as they pertain to therapeutic resistance and mitigation of injury from therapy.

Meet the Volume Editor



Dr. Roberto García-Navarrete is a distinguished Pediatric Neurosurgeon, trained in Mexico at the Instituto Nacional de Neurología y Neurocirugía and the Instituto Nacional de Pediatría. He directs the Neurosurgery Department and is Director of Technology and Innovation in Neurosurgery at Punta Medica Hospital. Dr. García-Navarrete specializes in the surgical treatment of central nervous system tumors and incorporates advanced technologies into his patients' care, including multimodal neuronavigation, robotic-assisted visualization, mixed and augmented reality, and neurophysiological monitoring. His multidisciplinary approach emphasizes collaboration across medical disciplines, improving surgical outcomes and survival rates, and enhancing the quality of life for patients with brain cancer, making him a leader in modern Mexican neurosurgery.

Contents

Preface	XIII
Chapter 1	1
Innovative Technology Designed to Enhance Neurosurgeons' Skills and Improve Patient Outcomes: The Meningioma Challenge <i>by Roberto Garcia-Navarrete, Ericka León-Álvarez, Javier Terrazo-Lluch, José Luis Pérez-Gómez, Alfonso Marx-Bracho, Juan Antonio Alvaro-Heredia, Ricardo Santiago Villagrana Sánchez, Franea Mendoza-Sánchez, Sebastián Gurtazaca-Guerrero, Gabriel Carrillo-Marhx and Kevin Yiron Frías-Arroyo</i>	
Chapter 2	19
Current Advances and Concepts in the Treatment of Meningioma <i>by Lucas Schiavão, Roberta Schiavão, Gabriel Pokorny and Wellingson Silva Paiva</i>	
Chapter 3	33
Surgical Approach to Parasagittal Meningioma <i>by Noman Ahmed and Hafsa Binte Sohail</i>	
Chapter 4	51
Pediatric Meningioma <i>by Javier Terrazo-Lluch, Jesus Murillo, Roberto Garcia-Navarrete and Alfonso Marx-Bracho</i>	
Chapter 5	75
Management of Intracerebral Meningiomas in the Elderly <i>by Collignon Frederic, Hentati Karim and Perano Francesco</i>	
Chapter 6	91
Current Findings in Embolization of Intracranial Meningiomas: Feasibility, Utility, Classification, and Techniques <i>by José de Jesús Gutiérrez Baños, Carlos Alberto Murillo Ponce, Carlos Castillo Rangel, Mauricio Ivan Rodriguez Pereira and Daniel Oswaldo Davila Rodriguez</i>	

Preface

In the cartoon series that we grew up with during childhood, the possibility that a human being could enhance their physical capabilities was made possible with a special suit that would allow them to increase strength, velocity, and to obtain information from various sources, and facilitate decision-making when performing a specific task, in general terms: to do things in a better and easier way.

Today, we have these resources, which enhance neurosurgeons' skills to perform highly complex surgical procedures safely and confidently.

Neurosurgery is one of the surgical disciplines that has undergone the most changes in recent decades. The increasing integration of neuronavigation systems in the surgical environment has changed the way high-risk procedures are performed. Nowadays, imaging studies no longer help us establish the radiological diagnosis of tumors and other nervous system diseases solely through computed tomography, magnetic resonance imaging, digital angiography, and PET-CT. During the preoperative evaluation of each case, it is possible to identify early risks to life and function associated with each disease, from the structural, functional, and metabolic perspectives of each patient, thereby allowing personalized treatment. In this way, through an exhaustive preoperative evaluation, characteristic information for each pathology can be integrated and reviewed in a mixed reality environment, enabling the anticipation of risk situations during surgery. During surgical procedures, the integration and rational use of these resources have created a new dimension in precision medicine. Augmented reality takes the way we can approach brain tumors to its maximum expression. The surgical microscope is no longer only helpful for magnifying tissues and identifying anatomical structures in detail; in this new technological environment of augmented reality, it has become a precision instrument by establishing strong correlations between imaging findings and anatomical structures, increasing the chances of success of each surgery for the safe and extensive resection of brain tumors. One of the most critical points in the early days of navigation in neurological surgery was the loss of correlation between the navigation system and the patient's anatomy, due to cerebrospinal fluid depletion or during brain tumor resection. It was suggested that intraoperative acquisition of tomographic or magnetic resonance imaging would improve the system's accuracy and maintain the correlation between the patient's anatomical structures and the imaging studies. However, to date, many specialized centers in Latin America lack these resources. A more accessible alternative is a 3D ultrasound that can be easily integrated into navigation platforms to help complete the extensive resection of brain tumors.

Meningiomas are the most common extracranial tumors of the intracranial space, and worldwide, there is extensive experience in their treatment. This work aims to show the technological resources currently available that facilitate the approach to this pathology. We provide a review of the main characteristics and current areas of interest in the treatment of meningiomas, with a special emphasis on the development

of new targeted therapies. A review of surgical techniques for treating meningiomas presents details of parasagittal meningioma surgery, including the most common complications and available management options. Although it is a predominantly adult disease, it is not uncommon to present itself at the extremes of life, both in pediatric patients and in older adulthood. Thanks to the participation of world-renowned authors, we will be able to showcase their experience in treating meningiomas in children and the elderly. In pediatric patients, the specificities of the population treated over the years at the Instituto Nacional de Pediatría, the national reference center for the treatment of brain tumors in children in Mexico, are highlighted. The biological behavior of this disease and the long-term outcomes of this patient cohort are described. Regarding the geriatric population, the specific characteristics of this age group are outlined, and the expert group's recommendations are presented. This book includes a recent review of the molecular fingerprint that characterizes meningiomas, whose importance is fundamental for the development of new targeted therapies.

One of the determining factors of the surgical outcome of meningioma surgery, regardless of the age group, is intraoperative bleeding. Our work builds on the experience of a renowned group of Mexican neurosurgeons who recently proposed a preoperative classification of meningiomas based on the angioarchitecture of each case and the benefits of embolization before resection of these tumors.

Because it is not only essential to do things right, this work highlights the importance of surgical experience, technological resources, and the identification of new target therapies to improve the survival, functional capacity, and quality of life of patients with meningiomas.

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Innovative Technology Designed to Enhance Neurosurgeons' Skills and Improve Patient Outcomes: The Meningioma Challenge

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Abstract

In recent years, neurosurgery has significantly improved the quality of life and functional outcomes for patients with brain tumors. This progress is attributed to increased precision in the surgical field through neuronavigational platforms, which integrate various types of radiological information—structural, functional, and metabolic. Moreover, augmented reality devices increase precision and bring new information to the surgical theater. Furthermore, three-dimensional ultrasound can provide real-time images in the operating room that align with predefined surgical plans, allowing for the maximum safe resection of tumors. These advancements have improved patient outcomes, reduced complications, and enhanced functional prognoses. In this context, meningiomas present notable challenges from a neurosurgical perspective. These challenges stem from their location, which can be in critical brain areas, their size, which can vary significantly, and their proximity to venous sinuses, whether at the convexity or the skull base. Overcoming these challenges requires high precision and control, where innovative technology plays a crucial role. This review will examine the procedures and recent advancements in neuronavigational platforms, the benefits of augmented reality, and intraoperative stains for brain tumors using the robotic-assisted microscope. It will also discuss why these innovations should be viewed as a new dimension in precision brain surgery, as well as the process to enhance neurosurgeons' capabilities and streamline decision-making processes in the operating room, ultimately improving surgical outcomes and functional prognoses.

Keywords: meningioma, neurosurgery, neuronavigation, mixed reality, augmented reality, robotics

1. Introduction

Meningioma is the most common extraxial primary tumor identified within the intracranial space. It typically shows a benign course, and surgery is the primary treatment in most cases. Several genetic and epigenetic findings are related to recurrence and survival in atypical and malignant meningiomas [1–3].

Neurosurgery has undergone significant changes in recent decades. Since its inception, using neuronavigation devices has enhanced the efficacy and mitigated the associated risks of surgical procedures [4–6]. Surgery and, in selected cases, radiotherapy, represent the fundamental approaches. In patients undergoing surgical treatment, increased resections are correlated with improved prognosis and a diminished recurrence rate [7]. Nonetheless, the effect of new technologies on decreasing recurrence rates is still unknown.

In this chapter, we aim to present the existing evidence regarding the advantages of neuronavigational platforms, the possible uses of augmented reality, and the groundbreaking potential of robotic technology as a complement to the surgical microscope, along with their potential uses as enhancing devices to improve human skills.

2. Neuronavigation systems

Neuro-navigation platforms are sophisticated medical instruments specifically designed to facilitate image-guided surgical procedures. These platforms have considerably enhanced surgical outcomes within neurosurgery, providing substantial benefits to numerous patients. The fundamental principle underlying these instruments involves the establishment of a referenced system that amalgamates data from structural imaging studies (such as CT scans and MRI), functional imaging techniques (including Diffusion Tensor Imaging (DTI) tractography and BOLD sequences), or metabolic imaging methods (such as PET/CT or MRI) tailored to each patient.

A fundamental characteristic that these systems must possess is the capability to generate information that facilitates decision-making in the operating room during surgical procedures on patients. One of the most critical phases in navigation is preoperative planning, during which all pertinent information from the patient's imaging studies is collected. The patient's structural, functional, and metabolic data can be integrated into preoperative visualization models. This integration facilitates the early identification of risks associated with the dissection and resection of lesions located in regions deemed to possess high eloquence, such as the language areas, the primary motor cortex, the parietal lobe, the thalamus, or the brainstem, as well as deep within the base of the skull. Today, artificial intelligence tools enable the segmentation of anatomical structures with exceptional precision and, more importantly, algorithms that correct the inadvertent distortion seen between the several image modalities (CT, MRI, and PET), increasing the accuracy of neuronavigation planning (**Figure 1**) [8–10].

Specific systems employing passive marker technology establish an interface between imaging studies and the patient's anatomy with significant precision and reproducibility. Their integration with surgical instruments and visualization systems, such as microscopes and endoscopes, enables the secure identification of anatomical structures during surgical interventions, thereby preventing serious complications that could jeopardize patient safety [11, 12].

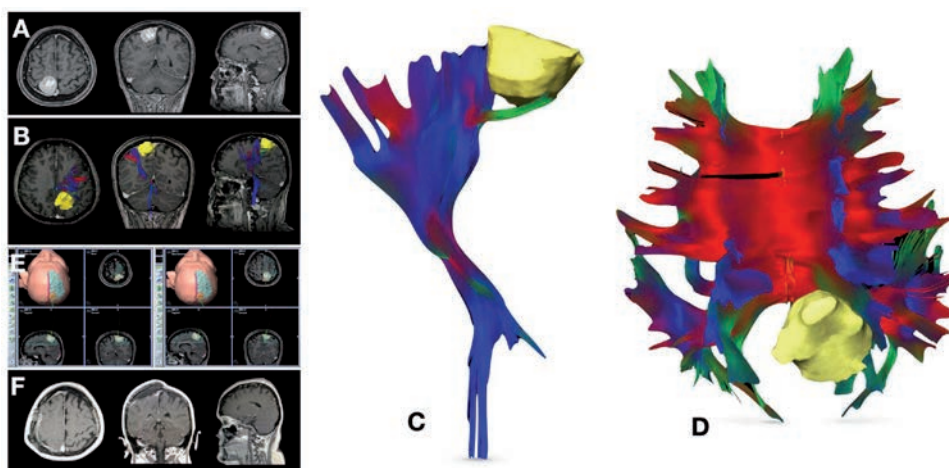


Figure 1.
 The relevance of integrating structural and functional information (DTI) through magnetic resonance imaging in a convexity meningioma is illustrated. A. Structural MRI. B. Fusion of DTI with structural MRI (axial T1-weighted slices with contrast medium). C, D. Reconstruction of the pyramidal tract and the corpus callosum, respectively, showing their relationship with the tumor. E. Intraoperative neuronavigation images. F. Postoperative MRI images showing complete tumor resection (axial T1-weighted slices with contrast medium).

In recent years, these tools have incorporated many surgical instruments to enhance safety in surgical procedures. Throughout the evolution of navigation systems, sources of error have been identified that could be dangerous when making intraoperative decisions. It is well known that brain shift, whether due to decreased cerebrospinal fluid or the resection of large tumors, affects the accuracy of preoperative planning. To address these situations, high-definition ultrasound equipment capable of generating three-dimensional reconstructions that update the navigation plan has been incorporated. This allows for the recovery of the system's accuracy or, based on intraoperative findings, assessing the possibility of finding residual tumor.

2.1 Integration of technology in neurosurgical treatment of meningioma

Incorporating sophisticated imaging and navigation systems has transformed the neurosurgical treatment of meningiomas, increasing precision, minimizing complications, and enhancing patient outcomes. This review examines the impact of these technologies, highlighting the use of imaging techniques and navigation systems in meningioma surgeries.

2.1.1 Neuroimaging in meningioma surgery

A wide range of neuroimaging techniques is available to enhance our ability to plan and conduct neuronavigation within the surgical setting. Advanced imaging, CT, and PET techniques are essential for the diagnosis, treatment planning, and follow-up of patients with meningioma. The structural information provided by CT scans and MRI is well-validated, offering detailed insights into tumor morphology, vascularity, and surrounding neuroanatomy, all crucial for surgical planning [13, 14]. The significance of CT lies in its ability to depict the anatomical relationships of meningiomas with osseous landmarks on the skull base. In some cases, a hyperostotic reaction is

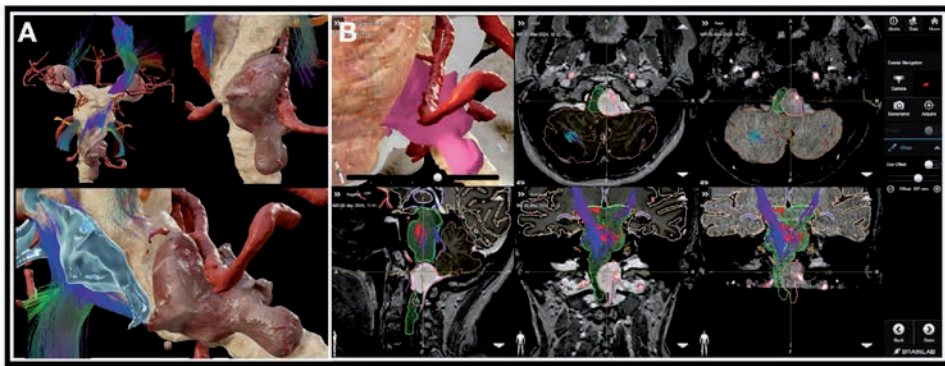


Figure 2.

Despite the anatomical references used to locate structures at risk, it was crucial in this case to identify the course of the vertebral artery. (A) Neuronavigation planning models help to identify the associated risks. (B) During the surgical procedure, the course of the vertebral artery and its relationship with a meningioma of the foramen magnum are easily identified.

often observed in meningiomas located at the convexity or near the skull base; in rare instances, it may show a loss of cortical integrity associated with local osseous invasion in the context of intraosseous meningiomas.

MRI provides a more precise definition of the structure and boundaries of meningiomas, including the anatomical details resulting from brain compression, vascular infiltration, and midline displacement, which are crucial for successful brain surgery. Functional MRI techniques, such as Diffusion Tensor Imaging (DTI), facilitate the visualization of white matter tracts and are essential for planning approaches that reduce the functional risk to critical neural pathways (**Figure 2**) [13–15]. Nuclear medicine plays a significant role in monitoring and evaluating treatment for meningiomas, particularly in radiosurgery [14].

3. Intraoperative imaging

Reports indicate that the intraoperative use of tomography and magnetic resonance imaging equipment is highly advantageous in brain tumor surgery [16, 17]. However, this resource is generally unavailable in many countries with emerging economies. It is asserted that these imaging modalities enhance the visualization of tumors and surrounding tissues in real-time during surgical procedures. Nonetheless, this assertion is not entirely accurate, as acquiring the images necessary to update the navigation plan as surgery progresses involves a time-consuming process and necessitates specialized facilities for proper functioning, particularly for magnetic resonance imaging. To address this issue, intraoperative three-dimensional ultrasound (3D US) has emerged as an invaluable tool in neurosurgery, particularly regarding the resection of meningiomas. This advanced technology provides real-time imaging, compensates for brain displacement, and offers intricate visualization of tumor boundaries and adjacent structures. Integrating 3D US with neuronavigation systems has further augmented its utility, facilitating more precise and safer resections. In a study of 20 patients with anterior and middle skull base meningiomas, the use of intraoperative US was associated with low rates of permanent neurological deficits [18]. This comprehensive analysis investigates the technical advantages and clinical outcomes of intraoperative 3D US in meningioma surgery. Studies have consistently demonstrated

that the use of intraoperative 3D US in meningioma surgery is associated with high rates of gross total resection (GTR). For example, in a series of 15 giant meningiomas, 3D US-guided resection achieved Simpson Grade I or II resection in 80% of cases [19]. Similarly, in a study of falxine meningiomas, the combination of endoscopic and 3D US techniques resulted in complete resection in all patients [20]. The improved surgical precision and reduced complications associated with 3D US-guided resection have been linked to shorter hospital stays. For instance, in a series of giant meningioma resections, the mean hospitalization duration was only 4.9 days [19, 21]. This highlights the potential of 3D US to improve patient outcomes and reduce healthcare costs (**Figure 3**).

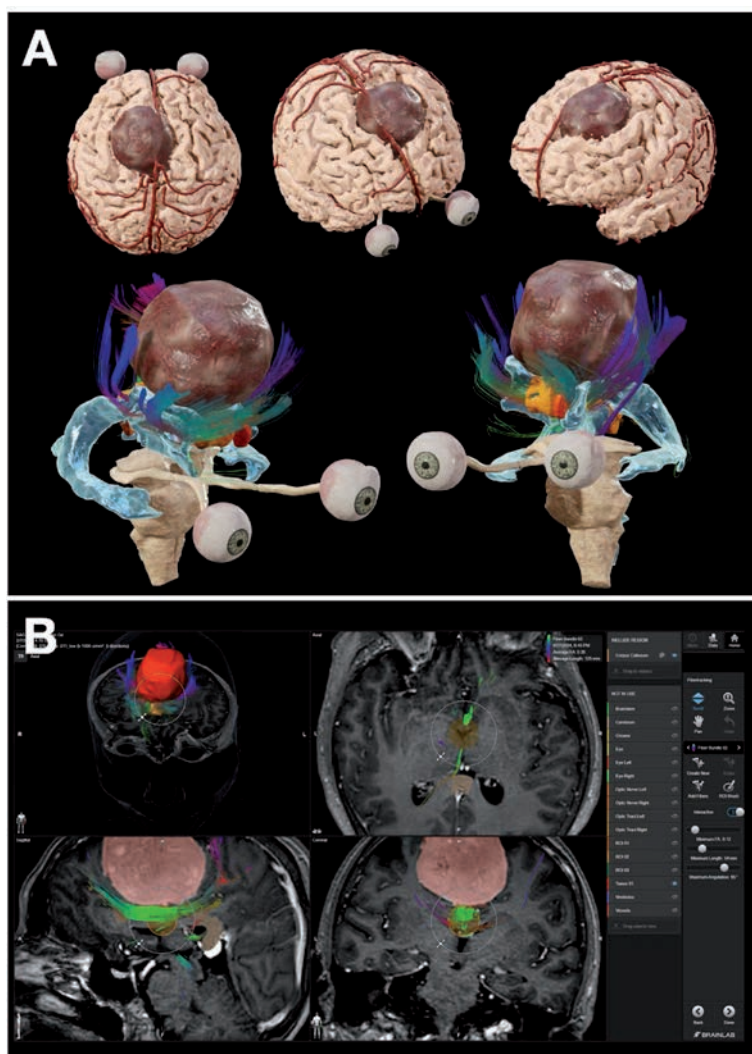


Figure 3.
 The segmentation tools available on some neuronavigation platforms are handy for recognizing the relationship between convexity meningiomas and the superior longitudinal sinus (A). Although the application of artificial intelligence in the segmentation of anatomical structures is highly accurate, a thorough review of the boundaries will always be necessary to ensure the proper use of the system (B).

4. Navigation systems in meningioma surgery

Neuronavigation systems have become indispensable in meningioma surgery, providing intraoperative guidance and improving surgical precision [22, 23]. The utilization of infrared light-based navigation systems, specifically the Brainlab Vectorvision, has exhibited numerous advantages in meningioma surgery. These advantages include minimizing craniotomy size, optimizing operating room duration, and, most critically, reducing postoperative complications, such as venous sinus injuries and hematomas [22]. Furthermore, adopting this technology has been correlated with shortened hospital stays and decreased healthcare expenditures (**Figure 3** and Video 1, <https://bit.ly/3JwauH0>) [24].

5. Mixed and augmented reality in meningioma surgery

Mixed (MR) and augmented reality (AR) are becoming revolutionary technologies in neurosurgery, especially in meningioma resections. Overlaying digital information onto the actual surgical environment boosts accuracy, aids intraoperative decision-making, and reduces complications. This response delves into the technological advancements and clinical uses of AR in meningioma surgery, contrasting it with conventional surgical techniques. From a technological standpoint, AR systems combine all the information generated during the planning of neuronavigation with the information generated intraoperatively in the form of three-dimensional ultrasound, iCT, or iMRI. Brainlab's Curve neuronavigation system allows for reconstructing three-dimensional models of tumors and nearby functional structures, enabling neurosurgeons to perform precise planning and simulations of surgical approaches through mixed reality technology (**Figure 3**).

Within augmented reality platforms, the Dextroscope and VOSTARS workstations integrate the patient's anatomy generated from imaging studies into the surgical field

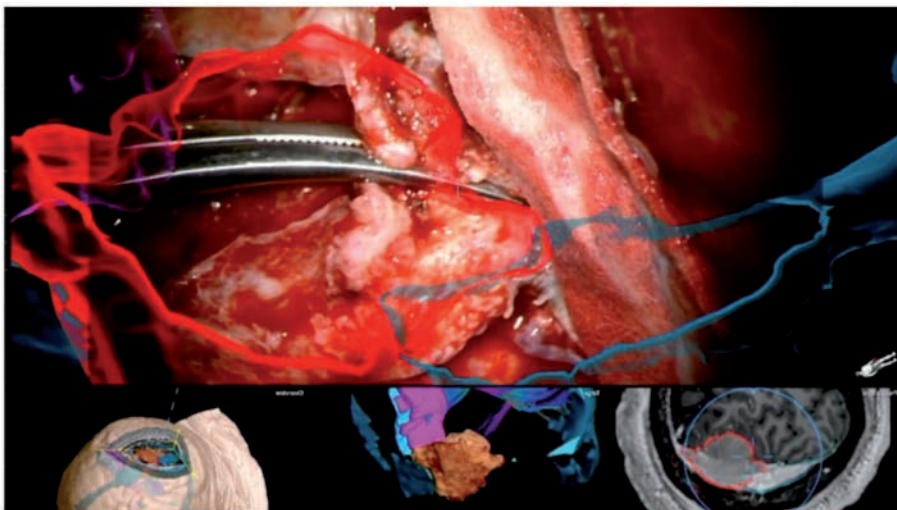


Figure 4.

Integrating augmented reality into the surgical field enables us to more easily identify risk structures. In this image captured from the surgical microscope, the boundaries of the superior longitudinal sinus (blue) and the edges of the tumor (red) are overlaid.

[25, 26]. There are augmented reality systems that use microscopes. In the case of meningioma surgery at the base of the skull, these systems allow for the overlay of the arrangement of blood vessels, such as the internal carotid artery in the cavernous sinus, and accurately establish the boundaries of the tumor, as well as identify the edges of the venous sinuses in situations involving tumor invasion into the superior longitudinal sinus. This integration enhances surgical orientation and precision in the operating field, as demonstrated in a study where 39 patients underwent resection with high registration accuracy and minimal neurovascular injuries [16]. Other benefits of augmented reality systems include a reduction in planning time of up to 39% without compromising the quality and accuracy of the process (**Figure 4** and Video 1, <https://bit.ly/3JwauH0>) [27].

Augmented reality represents a significant advancement in meningioma surgery, offering improved accuracy, efficiency, and patient outcomes compared to traditional methods. AR enhances surgical precision and minimizes complications by integrating preoperative imaging, intraoperative data, and real-time visualization. As this technology continues to evolve, its adoption in routine neurosurgical practice can potentially revolutionize the field.

6. Robotic applications in meningioma surgery

Neurosurgical robots are classified according to the surgeon-robot interaction: autonomous systems, master-slave systems, and shared-control systems. Autonomous systems perform specific operations by reproducing programmed motion or calculating the target trajectory under supervision. The master-slave system allows the surgeon complete control over the robot, as in telesurgeries. Shared-control systems integrate features of the previous types above [28].

Currently, the applications of robotic surgery in neurosurgery are few. The applications are limited to robotic surgical assistants or robotic holders for endoscopes, instruments for vertebral instrumentation surgery, and frameless biopsy needles to assist surgeons during complex procedures.

The main experience with robotics is with the radiosurgery equipment, such as CyberKnife. Studies have shown that robotic-assisted surgeries result in lower postoperative complication rates than traditional methods. For instance, using CyberKnife robotic stereotactic radiosurgery (SRS) in elderly meningioma patients has been associated with minimal adverse effects, with only 13 patients experiencing complications out of 82 treated [29–31].

7. Resource limitations

Resource limitations in low- and middle-income countries significantly impact access to advanced technologies such as intraoperative 3D ultrasound. These limitations can stem from various factors, including inadequate healthcare infrastructure, limited funding for medical equipment, and a shortage of trained personnel to operate sophisticated technologies. As a result, healthcare providers in these regions may struggle to offer high-quality surgical care, which can lead to poorer patient outcomes compared to higher-income countries where such technologies are more readily available. Addressing these disparities is crucial for improving surgical standards and overall healthcare delivery in resource-constrained settings.

The adoption of advanced technologies in neurosurgery, particularly for meningioma treatment, is significantly influenced by several factors, including technical infrastructure, training, and maintenance. Each of these elements plays a crucial role in the successful implementation and utilization of innovative technologies such as neuronavigation systems, augmented reality, robotic applications, and intraoperative imaging tools.

7.1 Equipment

The presence of advanced medical equipment, such as CT and MRI machines, neuronavigation systems, and 3D ultrasound, is essential for effective surgical planning and execution. In low- and middle-income countries, inadequate healthcare infrastructure can limit access to these technologies, resulting in suboptimal surgical care and poorer patient outcomes. The ability to integrate various imaging modalities and surgical tools into a cohesive system is vital for enhancing surgical precision. For example, neuronavigation systems must be compatible with surgical instruments and imaging technologies to provide real-time guidance during procedures. Continuous advancements in technology require healthcare facilities to invest in regular upgrades to their systems. This ensures that neurosurgeons have access to the latest features and capabilities, which can improve surgical outcomes.

7.2 Training

Effective training programs are essential for neurosurgeons to become proficient in using advanced technologies. Surgeons must understand how to interpret the data provided by neuronavigation systems and augmented reality tools to make informed decisions during surgery. Training must also extend to other healthcare professionals, including radiologists and operating room staff, to ensure a comprehensive understanding of the technologies and their applications. This collaboration can enhance communication and efficiency in the surgical setting. Incorporating simulation-based training can help neurosurgeons practice using these technologies in a controlled environment, allowing them to build confidence and refine their skills before performing actual surgeries.

7.3 Maintenance

Advanced technologies require ongoing maintenance to ensure their accuracy and reliability. Regular calibration and servicing are crucial for preventing technical failures that could compromise patient safety during surgery. Access to technical support and troubleshooting services is essential for healthcare facilities to address any issues that arise with the equipment. This support can help minimize downtime and maintain the continuity of care. Healthcare institutions must allocate appropriate budgets for the maintenance of advanced technologies. In resource-limited settings, financial constraints can hinder the ability to perform necessary maintenance, leading to decreased efficacy of the technologies.

8. Cost-effectiveness of innovative technology in neurosurgery for meningioma treatment

Research on cost-utility analyses comparing augmented reality (AR)-assisted surgeries with traditional techniques in meningioma brain tumor surgery has emerged as a critical

area of inquiry due to its potential to enhance surgical precision, reduce operative risks, and optimize healthcare resource allocation [32, 33]. The evolution of AR in neurosurgery spans from early neuronavigation systems in the late twentieth century to contemporary mixed reality platforms integrating real-time 3D visualization and intraoperative guidance [34, 35]. This technological progression has been driven by the need to improve surgical outcomes in complex brain tumor resections, with meningiomas representing a significant clinical challenge due to their proximity to critical neurovascular structures [16, 36]. The practical significance of this research is underscored by data indicating reduced complication rates and shorter hospital stays with image-guided techniques, suggesting potential cost savings and improved patient quality of life [32, 37].

Despite advances, the specific problem of quantifying the cost-effectiveness and utility of AR-assisted meningioma surgeries remains inadequately addressed [34, 38]. Existing literature reveals a knowledge gap concerning comprehensive economic evaluations that integrate clinical outcomes with financial metrics across diverse AR platforms and surgical settings [39–41]. Controversies persist regarding the balance between the high initial costs of AR technology and its long-term benefits in reducing operative time and complications [33]. Some studies report improved surgical accuracy and reduced cognitive load with AR, while others highlight challenges such as device calibration, learning curves, and variable registration accuracy [37, 42]. The absence of standardized evaluation metrics further complicates the assessment of AR's cost-utility, potentially delaying its widespread adoption [41].

Augmented reality (AR) in neurosurgery has emerged as a transformative technology, particularly in the treatment of meningiomas. By overlaying digital information onto the surgical field, AR enhances surgical precision, reduces complications, and improves patient outcomes. However, evaluating the cost-effectiveness of AR technologies is crucial for their adoption in clinical practice, especially in resource-constrained settings.

8.1 Cost analysis

The implementation of AR systems in meningioma surgery involves several cost components. The initial investment, which includes the purchase and installation of AR systems, including software and hardware, represents a significant upfront cost. This may consist of expenses for specialized equipment, such as the curve, dextroscope, or VOSTARS workstations [25]. Effective utilization of AR technologies requires comprehensive training for neurosurgeons and operating room staff. Investment in training programs is essential to ensure proficiency in using AR systems. Ongoing costs for the maintenance, calibration, and upgrade of AR systems must be considered to ensure their continued efficacy and reliability. While the initial costs of AR technologies may be high, several factors suggest potential long-term savings, a reduced complication rate, because AR systems enhance surgical accuracy, leading to fewer postoperative complications, such as venous sinus injuries and hematomas. This reduction in complications can decrease hospital readmission rates and associated healthcare costs [25, 42].

Studies have shown that the use of AR in meningioma surgeries is linked to shorter hospital stays, which can significantly reduce overall treatment costs. For instance, improved surgical precision may lead to faster recoveries and earlier discharges. The ability to achieve higher rates of gross total resection (GTR) can lead to better long-term patient outcomes, reducing the need for additional treatments, such as radiotherapy or repeat surgeries, which are costly.

8.2 Economic evaluation

A comprehensive economic evaluation should include cost-utility analyses comparing AR-assisted surgeries with traditional techniques. Metrics such as quality-adjusted life years (QALYs) gained, cost per QALY, and overall healthcare expenditures can help assess the value of AR technologies in meningioma treatment. Research on cost-utility analyses comparing augmented reality (AR)-assisted surgeries with traditional techniques in meningioma brain tumor surgery has emerged as a critical area of inquiry due to its potential to enhance surgical precision, reduce operative risks, and optimize healthcare resource allocation [32, 33]. The evolution of AR in neurosurgery spans from early neuronavigation systems in the late twentieth century to contemporary mixed reality platforms integrating real-time 3D visualization and intraoperative guidance [34, 35]. This technological progression has been driven by the need to improve surgical outcomes in complex brain tumor resections, with meningiomas representing a significant clinical challenge due to their proximity to critical neurovascular structures [16, 36]. The practical significance of this research is underscored by data indicating reduced complication rates and shorter hospital stays with image-guided techniques, suggesting potential cost savings and improved patient quality of life [32, 37]. Despite advances, the specific problem of quantifying the cost-effectiveness and utility of AR-assisted meningioma surgeries remains inadequately addressed [34, 38]. Existing literature reveals a knowledge gap concerning comprehensive economic evaluations that integrate clinical outcomes with financial metrics across diverse AR platforms and surgical settings [39–41]. Controversies persist regarding the balance between the high initial costs of AR technology and its long-term benefits in reducing operative time and complications [32]. Some studies report improved surgical accuracy and reduced cognitive load with AR, while others highlight challenges such as device calibration, learning curves, and variable registration accuracy [37, 42]. The absence of standardized evaluation metrics further complicates the assessment of AR's cost-utility, potentially delaying its widespread adoption [41].

8.2.1 Cost-effectiveness

AR-assisted surgeries can reduce overall costs by approximately 20% compared to traditional methods, mainly through reduced complications and shorter hospital stays [32, 36]. Several studies noted potential cost savings in implant fabrication and surgical planning with AR, suggesting economic benefits beyond direct surgical costs [42].

8.2.2 Surgical time efficiency

AR-assisted surgeries reduced operative times or planning durations significantly, with reductions ranging from 10% to nearly 40% in planning or surgical phases [26, 27, 32, 35, 36]. Smartphone and mobile AR applications showed promise for efficient surgical planning, though with variable success rates [43].

8.2.3 Complication and morbidity rates

Some studies reported lower or comparable complication rates with AR-assisted surgeries, including reduced severe complications and intraoperative seizure rates [16, 32, 36, 37]. Several clinical series reported no new neurological deficits

postoperatively with AR use, indicating safety and potential morbidity reduction [44, 45]. Simulation studies suggested AR may reduce inadvertent contact with critical structures, potentially lowering morbidity [37].

8.2.4 Extent of tumor resection

AR-assisted surgeries achieved comparable or improved gross total resection rates compared to traditional methods, with rates ranging from 66% to over 85% [16, 32]. AR facilitated better intraoperative visualization of tumor boundaries and critical neurovascular structures, aiding maximal safe resection [16, 34]. Some studies emphasized AR's role in complex skull base and eloquent area meningiomas, where resection extent is critical [16].

8.2.5 Hospital stay and resource use

A reduced hospital length of stay and intensive care unit time with AR-assisted surgeries is reported, contributing to overall cost savings [16, 32, 36]. AR-assisted procedures were associated with more precise surgical approaches, potentially reducing resource utilization related to complications and prolonged recovery [32, 36].

The current body of literature on cost-utility analyses comparing augmented reality (AR)-assisted surgeries reveals a promising yet still emergent landscape. Collectively, the evidence indicates that AR integration into neurosurgical practice offers enhanced surgical precision, improved intraoperative orientation, and the potential for better clinical outcomes such as higher rates of gross total resection and reduced complication rates. These clinical improvements are often attributed to AR's ability to provide real-time three-dimensional visualization of tumor boundaries and critical neurovascular structures, facilitating safer and more effective resections. Additionally, AR platforms have demonstrated utility in preoperative planning, enabling more accurate craniotomy sizing and incision placement, which may contribute to more targeted and minimally invasive approaches.

From an economic perspective, limited but encouraging data suggest that AR-assisted surgery may lead to cost savings primarily through reductions in severe complications, shorter hospital stays, and decreased intensive care utilization. The potential for cost-effectiveness is further enhanced by the adoption of affordable mobile and wearable AR technologies that lower the barrier to implementation. However, comprehensive cost-utility studies remain sparse, and the heterogeneity of AR platforms, cost structures, and evaluation metrics complicates generalizability. The economic impact of AR is also influenced by factors such as initial investment costs, training requirements, and maintenance, which are inconsistently accounted for across studies.

Methodologically, research in this field is characterized by variability in study design, sample sizes, and outcome measures, with a predominance of case series, pilot studies, and technical validations rather than large-scale randomized controlled trials. Evaluation metrics commonly include registration accuracy, surgical time, user satisfaction, and clinical outcomes, but the lack of standardization impedes direct comparison. Technological challenges such as brain shift, system latency, and calibration accuracy persist, affecting intraoperative reliability. Adoption barriers include the learning curve, cost considerations, and integration into surgical workflows, which may limit widespread clinical uptake despite demonstrated benefits.

9. Future directions and emerging technologies

Artificial intelligence is increasingly integrated into neuroimaging workflows, offering new possibilities for meningioma treatment. AI algorithms can analyze imaging data to predict tumor behavior, identify molecular markers, and optimize treatment plans [13].

Integrating radiomics with clinical and pathological data through machine learning (ML) models significantly improved the prediction of meningioma outcomes. These ML models surpass conventional MRI in predicting meningioma recurrence and aggressiveness, providing crucial insights for personalized treatment and surgical planning [31].

Advances in radiotherapy planning and delivery, such as adaptive fractionated stereotactic radiotherapy (a-gkFSRT), are enhancing the treatment of meningiomas. These techniques utilize integrated imaging modalities, including cone-beam CT, to adapt treatment plans in real-time, ensuring the precise delivery of radiation doses.

10. Conclusion

The integration of these advanced technologies promises to significantly enhance the precision and effectiveness of surgical interventions for meningiomas, ultimately leading to improved patient outcomes. Incorporating advanced imaging and navigation systems has markedly improved the neurosurgical treatment of meningiomas. These technologies enhance preoperative planning, intraoperative precision, and postoperative results while reducing complications and costs. As these tools advance, they are expected to assume an increasingly significant role in managing meningiomas. The progressive integration of artificial intelligence and augmented reality tools in the field of neurosurgery has led to a substantial reduction in the risks associated with high-risk procedures. Furthermore, the implementation of robotic assistance technologies will further enhance the performance of medical staff by providing more precise tools. A strategy design for acquiring neuronavigation devices in middle- and low-income countries is out of the scope of this chapter.

Neuronavigation and augmented reality (AR) platforms have become fundamental in modern neurosurgery, improving surgical accuracy, lowering complication rates, and aiding complex intracranial procedures. Despite these benefits, such technologies are still out of reach for most patients in middle- and low-income countries (MLICs), where neurosurgical conditions—especially brain tumors and epilepsy—remain undertreated due to limited infrastructure, expertise, and funding. Given the rising global burden of neurosurgical diseases and the expanding digital divide, there is an urgent need to develop inclusive strategies that broaden access to neuronavigation and AR-assisted surgery.

Conflict of interest

The authors declare no conflict of interest.

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Current Advances and Concepts in the Treatment of Meningioma

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Abstract

Meningioma is the most common primary intracranial tumor in adults, with an incidence of 9.51 per 100,000. Meningiomas are firmly attached to the inner surface of the dura; however, some high-grade tumors may present variable degrees of brain invasion. These tumors are usually benign but can present as malignant (cancerous), but only a few have these characteristics. In order to enhance the diagnosis and prognosis of these conditions, several techniques involving advanced imaging and molecular targets are being developed aiming to better differentiate meningiomas and to bring more clarity to surgeon in their decision-making process. Moreover, in the same hand of diagnosis and prognosis, the treatment of meningiomas has faced significant improvement in recent years, with the establishment of minimally invasive protocols and the aid of enabling technologies. Additionally, several pharmacological treatments are being implemented using new molecular targets, drug combinations, and gene-editing technology. The present chapter presents the evolving scenario of meningioma treatment, from diagnosis to treatment decision-making.

Keywords: meningioma, benign tumor, advances in neurosurgery, molecular markers, meningioma pharmacological treatment

1. Introduction

Meningiomas accounts for roughly 30% of all central nervous system tumors. They arise from the arachnoidal cap cells of the leptomeninges and are typically slow-growing, benign lesions. However, a subset demonstrates atypical or malignant behavior, characterized by rapid growth, brain invasion, and higher rates of recurrence [1, 2].

Meningiomas occur most frequently along the cerebral convexities (25–30%), parasagittal/falx region (20–25%), and skull base including sphenoid wing, olfactory groove, and tentorial attachments (50%). Spinal meningiomas represent ~12% of all cases, predominantly in the thoracic region⁸. Tumor location not only dictates presenting symptoms—for example, seizures with convexity lesions, visual deficits with tuberculum sellae masses—but also influences choice of surgical approach and risk of

Scheme	Grade I (Benign)	Grade II (Atypical)	Grade III (Anaplastic)
WHO 2021 (CNS5) [5]	Meningothelial, fibrous, transitional, psammomatous, angiomatous, microcystic, secretory, lymphoplasmacyte-rich, metaplastic	Increased mitotic index (≥ 4 MF/10 HPF) or brain invasion; includes chordoid and clear cell subtypes	≥ 20 MF/10 HPF or exhibits frank malignant features
TERT modification proposal [6–8]	Exclusion of TERT-mutant/CDKN2A-deleted; low-risk methylation class	Presence of 4–19 MF/10 HPF, brain invasion, or intermediate methylation class	TERT promoter mutation or CDKN2A/B homozygous deletion; high-risk methylation class

Table 1.
WHO 2021 Classification versus emerging molecular proposals.

complications. Advances in neuroimaging, molecular biology, and surgical technique have collectively reshaped our understanding of meningioma biology and refined the therapeutic armamentarium available to clinicians [3–5].

The World Health Organization (WHO) grading is divided into grade I (benign), grade II (atypical), and grade III (anaplastic) meningiomas. Grade I tumors often warrant a conservative approach when asymptomatic, with serial radiological surveillance serving to detect interval growth³. In contrast, symptomatic or enlarging lesions are generally offered microsurgical resection, aiming for gross-total excision [5]. Recent advances in molecular diagnosis are showing that certain characteristics might influence the outcomes and profile of the meningiomas, therefore some authors proposed to change eventually classify all TERT-mutant/CDKN2A-deleted meningiomas directly as grade III (**Table 1**) [6–8].

2. Prognosis and survival

Benign (WHO grade I) meningiomas generally carry a favorable prognosis, with population-based series reporting 5-year overall survival (OS) rates of approximately 85–90%. By contrast, atypical (grade II) tumors have intermediate outcomes, with 5-year OS around 60–70%, and anaplastic (grade III) lesions show markedly poorer survival—5-year OS near 40–50%—reflecting their aggressive biology and higher recurrence rates. Progression-free survival (PFS) likewise declines with grade, underscoring the need for vigilant follow-up in higher-grade cases [9].

The extent of surgical resection remains a key determinant of long-term control. In NRG Oncology/RTOG 0539, which enrolled “high-risk” patients (recurrent grade II, newly diagnosed grade III, or subtotal resection of grade II), 3-year PFS was 58% and 3-year OS was 78%, demonstrating that even aggressive multimodal therapy yields moderate durability in these populations. Conversely, patients achieving Simpson grade I resection of convexity WHO I meningiomas often exceed 10-year PFS rates of 85–90% in single-institution series [10–13].

2.1 Pediatric meningiomas

Johannes Wach et al. performed the largest individual-patient data meta-analysis of pediatric meningiomas (n = 1010) across 20 studies (2011–2023). They found

that WHO grade-1 tumors in children had a median PFS of 209.8 months versus 137.5 months for grade 2 and 72.1 months for grade 3 ($p < 0.001$). Overall survival did not differ significantly between grade 1 and 2 in the pediatric cohort. Importantly, NF1-associated tumors exhibited a shorter PFS (59.7 months) than NF2-associated (138.4 months) or sporadic cases (180.6 months), highlighting the need for genotype-adapted monitoring and therapy in this age group [14].

3. Impact of molecular biomarkers

Molecular and cytogenetic alterations further refine prognostication. NF2-mutated meningiomas have been linked to worse survival: one large series found low merlin expression associated with significantly shorter OS ($P = 0.014$) and PFS ($P = 0.024$). Similarly, homozygous deletion of CDKN2A/B predicts rapid progression (median time to progression 8 vs. 101 months) and poorer OS, prompting its inclusion in WHO CNS5 as a grade III criterion [7, 15]. Also, copy number alterations also carry prognostic weight, such as loss of chromosome 1p36 or the co-deletion of 1p/14q, with combined losses seen in 7% of benign, 39% of atypical, and 63% of anaplastic cases, indicating a potential role of allelic alteration in affecting tumor characteristics [16, 17].

Moreover, in a recent study, systematically reviewed 100 IHC-based biomarker studies encompassing 16,745 adult patients. Their meta-analyses identified high Ki-67/MIB-1 index as an adverse prognostic factor for OS (HR 1.03 per 1% increase; 95% CI 1.02–1.05) and PFS (HR 1.02; 95% CI 1.00–1.04). Overexpression of cyclin A and TOP2A conferred nearly fivefold higher risk of recurrence (HR 4.91 and 4.90, respectively), while strong progesterone receptor and p21 staining were protective (HR 0.60 and 0.53 for RFS) (Table 2) [18].

Population/Subgroup	Survival estimate	Prognosis
WHO grade I meningioma	5-year OS ~85–90%	Favorable
WHO grade II (atypical) meningioma	5-year OS ~60–70%	Intermediate
WHO grade III (anaplastic) meningioma	5-year OS ~40–50%	Poor
NRG Oncology/RTOG 0539 “high-risk” cohort (recurrent grade II, new III, or subtotal grade II)	3-year PFS 58%; 3-year OS 78%	Moderate
NF2-mutated meningiomas (low merlin expression)	OS and PFS significantly reduced ($P < 0.05$)	Worse
CDKN2A/B homozygous deletion	Median TTP 8 vs. 101 months	Marks WHO III behavior
1p36 deletion	Associated with shorter OS (log-rank $P < 0.001$)	Poor
Pediatric sporadic meningiomas	Median PFS 180.6 months	Favorable
Pediatric NF1-associated meningiomas	Median PFS 59.7 months	Poor
Pediatric NF2-associated meningiomas	Median PFS 138.4 months	Intermediate

Table 2.
Subgroups' survival estimates.

4. Imaging diagnosis

Meningiomas are most often present insidiously, with symptoms arising from mass effect on adjacent neural structures. Headache is the most common complaint, followed by seizures in up to 30% of patients when lesions involve cortical surfaces or irritate the cortex. Focal neurological deficits—such as cranial nerve palsies with skull-base tumors, motor weakness with parasagittal masses, or visual field cuts with tuberculum sellae lesions—reflect both tumor location and growth rate. Cognitive or behavioral changes may occur with frontal convexity meningiomas, and hydrocephalus can develop when lesions obstruct cerebrospinal fluid pathways [5, 19].

Magnetic resonance imaging (MRI) remains the cornerstone of radiological diagnosis. On T1-weighted sequences, meningiomas typically appear isointense or slightly hypointense relative to cortex, with homogeneous contrast enhancement and a classic “dural tail” sign on gadolinium-enhanced imaging. Computed tomography (CT) complements MRI by revealing hyperostosis or calcification of adjacent bone. More recently, somatostatin receptor PET tracers—such as ^{68}Ga -DOTATOC and ^{68}Ga -DOTATATE—have demonstrated superior sensitivity for detecting small or transosseous meningiomas compared with MRI alone. In one intraindividual comparison, ^{68}Ga -DOTATOC PET/CT identified tumor extension beyond contrast MRI in several cases, facilitating more accurate delineation for radiotherapy planning [20–22].

Somatostatin receptor scintigraphy using ^{111}In -octreotide also remains a valuable adjunct in equivocal cases. Its high affinity for SSTR2—overexpressed in most meningiomas—yields sensitivity approaching 100% for receptor-positive lesions and can distinguish recurrent tumor from postoperative scar or radionecrosis. Although PET tracers offer improved spatial resolution, SRS scintigraphy continues to inform management in centers without PET availability, particularly for skull-base tumors where bone invasion may be subtle on anatomical imaging [21, 22].

Definitive diagnosis relies on histopathological examination of tumor tissue obtained by biopsy or resection. The 2021 WHO CNS5 now integrates key molecular alterations—such as TERT promoter mutations, CDKN2A/B deletions, NF2 inactivation, and SMO/AKT1/TRAF7/KLF4 mutations—to refine grading and prognostication. Immunohistochemistry for progesterone receptor, Ki-67 labeling, and epigenetic markers like H3K27me3 further stratify risk. Together, clinical presentation, multi-modal imaging, and integrated histomolecular analysis establish the framework for personalized treatment planning in meningioma patients (Table 3) [19].

Technique	Advantages	Pitfalls
Magnetic resonance imaging (MRI)	• Superior soft-tissue contrast; delineates tumor extent and dural tail • Multiplanar capability for surgical planning	• May underestimate transosseous or skull-base extension • Cannot distinguish scar/reaction from small residual tumor without adjunct imaging
Computed tomography (CT)	• Excellent at detecting hyperostosis, calcifications, and bone invasion • Widely available, rapid acquisition	• Poor soft-tissue contrast compared with MRI • Radiation exposure; limited in distinguishing tumor from adjacent brain edema

Technique	Advantages	Pitfalls
⁶⁸ Ga-DOTATOC/DOTATATE PET (PET/CT or PET/MRI)	• High sensitivity for SSTR2-expressing tumors, including small or transosseous lesions • Improves target delineation for radiotherapy planning	• Limited availability; higher cost • False negatives in low-SSTR2 tumors; potential overlap with other SSTR-expressing lesions
Somatostatin receptor scintigraphy (¹¹¹ In-octreotide SRS)	• Near-100% sensitivity for receptor-positive meningiomas • Distinguishes recurrence from scar or radionecrosis	• Lower spatial resolution than PET; longer imaging times • Limited anatomic detail without fusion imaging
^{99m} Tc-HYNIC-octreotide SPECT/CT	• Better resolution than planar SRS; useful where PET not available	• Still inferior to PET in lesion detection; tracer uptake may be variable
Histopathology ± immunohistochemistry	• Gold standard for definitive diagnosis and WHO grading; IHC (e.g., PR, Ki-67, and SSTR2A) adds prognostic value	• Invasive (biopsy/resection) required • Sampling error in heterogeneous tumors; processing artifacts can obscure mitotic figures

Table 3.
Imaging techniques.

5. Molecular diagnosis and its impact on the treatment of meningioma

Molecular profiling has revolutionized the classification and management of meningiomas, complementing traditional histopathology with genetic and epigenetic insights. Next-generation sequencing studies have identified key driver alterations—including TERT promoter mutations, NF2 inactivation, and activating mutations in AKT1, SMO, TRAF7, and KLF4—that stratify tumors into molecular subgroups with distinct clinical behaviors and therapeutic vulnerabilities. Integrating these markers into routine diagnostics enables more accurate prognostication and paves the way for targeted therapies in high-risk patients (**Table 4**) [23–25].

Although the use of molecular diagnosis seems promising, the European Association of Neuro-Oncology guideline systematically reviewed the predictive value of a broad spectrum of molecular alterations in meningiomas—including NF2, AKT1, SMO, SMARCE1, PIK3CA, CDKN2A/B, CDK4/6, TERT, TRAF7, BAP1, KLF4, ARID1/2, SUFU, PD-L1, SSTR2A, PR/ER, mTOR, VEGF(R), PDGFR, as well as homologous recombination deficiency, copy number variations, methylation classes, and gene expression profiles—and assessed their clinical actionability using the ESMO ESCAT criteria. No molecular target achieved an ESCAT I (“ready for clinical use”) classification, indicating a current lack of validated biomarkers for routine targeted therapy in meningioma. Only mTOR pathway activation and NF2 alterations reached ESCAT II (“investigational”) status, highlighting these as the most promising candidates for inclusion in future clinical trials and targeted treatment strategies. Thus, the implementation of molecular diagnosis and molecular-based decision-making for treatment should be employed with caution and in very specific cases [26].

Marker/test	Method	Frequency	Prognostic impact	Pitfalls
TERT promoter (C228T/C250T)	NGS or Sanger sequencing	6–11%	Shorter PFS and OS across WHO grades; aggressive behavior	Rare; may require high-depth sequencing
NF2 (Merlin) inactivation	NGS; FISH for deletions	40–50%	Correlates with higher WHO grade and recurrence	Mosaic cases can be missed; complex structural variants
AKT1 (E17K)	NGS hotspot panel	~10%	Intermediate recurrence risk; skull-base enrichment	Limited therapeutic options outside trial settings
SMO (L412F)	NGS hotspot panel	3–5%	Predominant in anterior skull-base; prognostic role under investigation	Low frequency; clinical impact still under study
H3K27me3 loss	IHC	~20% in grade 1–2	Increased recurrence risk; independent of grade	Requires validated antibody and expert interpretation
DNA methylation profiling	Array or sequencing classifier	—	Divides tumors into epigenetic subgroups with distinct PFS	High cost; requires bioinformatics support
CDKN2A/B homozygous deletion	NGS; FISH	1–3%	Marker of WHO III; severe prognosis; mandates adjuvant therapy	Rare; FISH probes may not cover all deletion breakpoints

Table 4.
Molecular diagnosis of meningiomas.

6. Surgical treatment of meningioma

Recent years have witnessed a paradigm shift in meningioma surgery, driven by the convergence of minimally invasive techniques, refined microsurgical strategies, and molecular-guided decision-making [27–29]. Surgical resection remains the cornerstone of meningioma management, with the extent of tumor removal—as classified by the Simpson grading system—being the strongest predictor of long-term local control and recurrence. Modern surgical strategies emphasize maximal safe resection while preserving neurological function, often employing advanced intraoperative tools such as neuronavigation, fluorescence-guided imaging, intraoperative ultrasound, and endoscopic assistance to improve visualization—especially in challenging skull-base locations. Minimally invasive approaches have evolved to reduce brain retraction and morbidity, and tailored craniotomies or keyhole techniques are increasingly used for convexity, falcine, and parasagittal tumors [30, 31].

Despite aggressive resection strategies, recurrence—particularly in higher-grade (WHO II/III) lesions—remains a concern, and reoperation may be indicated for symptomatic regrowth or residual disease. Multidisciplinary preoperative planning incorporating anatomical, molecular, and radiographic data helps optimize approach selection, balancing maximal tumor removal with preservation of neurological function. Emerging evidence suggests that integrating molecular profiles (e.g., methylation classes and driver mutations) may further refine surgical decision-making and prognostication, although standardized protocols are still under investigation [30–32].

Stereotactic radiosurgery (SRS) has become a mainstay adjunct or alternative to surgery for small, surgically inaccessible, or residual meningiomas, delivering a high dose of radiation in one or a few fractions with submillimeter precision. Clinical outcomes demonstrate durable tumor control rates exceeding 90% for appropriately selected WHO grade I meningiomas, with low rates of radiation-induced toxicity when critical structures are respected. SRS is also frequently employed for recurrent disease following subtotal resection or in patients unfit for further surgery, offering a noninvasive salvage option with rapid outpatient recovery [31].

Technological adjuncts have further expanded the surgeon's armamentarium. Intraoperative neuronavigation integrated with diffusion tensor imaging enables real-time mapping of white-matter tracts, minimizing functional deficits during parasagittal or motor-strip adjacent resections. Fluorescence-guided surgery using 5-ALA or fluorescein has shown promise in delineating tumor margins, particularly in atypical meningiomas where microscopic invasion can be occult. Moreover, patient-specific 3D-printed guides and tubular retractor systems facilitate keyhole craniotomies—such as supraorbital and retrosigmoid mini-craniotomies—reducing muscle disruption and accelerating recovery [27].

7. Pharmaceutical treatment

Systemic (medicamentous) therapy for meningioma remains largely investigational, with no phase III randomized trials definitively establishing a standard regimen. Recurrent and high-grade meningiomas often demonstrate resistance to surgery and radiotherapy, prompting exploration of cytotoxic agents, hormonal modulators, somatostatin analogs, anti-angiogenic drugs, and pathway-targeted inhibitors. Six-month progression-free survival (PFS-6) rates in recurrent cohorts vary widely—from as low as 6% to as high as 100%—reflecting heterogeneity in trial design and patient selection [33].

7.1 Cytotoxic chemotherapy

Hydroxyurea has been the most extensively studied cytotoxic agent. As a ribonucleotide reductase inhibitor, it induces S-phase arrest and apoptosis. Early phase II studies reported partial radiographic responses in a minority of patients, with PFS-6 rates around 26–43%, but subsequent trials failed to reproduce meaningful benefit, and toxicity—particularly myelosuppression and mucocutaneous effects—limits its utility. Temozolomide and irinotecan have been assessed in small cohorts without convincing activity; thus, no cytotoxic agent is routinely recommended outside clinical trials [33].

7.2 Somatostatin analogs and hormonal therapy

Meningiomas frequently overexpress somatostatin receptor 2 (SSTR2), providing the rationale for octreotide and pasireotide. In the phase II CEVOREM study, combination everolimus–octreotide (targeting mTOR and SSTR pathways) achieved a PFS-6 of 55%, with 14% partial responses, and was generally well. Monotherapy with octreotide yielded lower PFS-6 (~30%) and few objective responses. Antiprogesterone agents (e.g., mifepristone) have shown minimal activity in small non-randomized series and are not recommended outside trials [33, 34].

7.3 Anti-angiogenic and mTOR-targeted therapies

Bevacizumab, a VEGF-A antibody, has demonstrated disease stabilization in refractory meningioma, with retrospective PFS-6 rates of 43–86% and occasional tumor shrinkage. A multi-institutional phase II trial reported bevacizumab PFS-6 of ~60% and acceptable safety. mTOR inhibitors (everolimus, temsirolimus) disrupt PI3K–AKT–mTOR signaling; in combination with octreotide, everolimus achieved meaningful disease control rates and warrants further evaluation in randomized settings [34, 35].

7.4 Molecularly targeted agents

Genomic profiling has enabled small trials of AKT1 inhibitors (capiwasertib), SMO antagonists (vismodegib), and FAK inhibitors (GSK2256098) in genotype-selected cohorts (Alliance A071401 umbrella trial). Early phase II data suggest pathway-specific activity—for example, vismodegib in SMO-mutant meningiomas—but full results and randomized comparisons are pending. CDK4/6 inhibitors (abemaciclib) and immune-checkpoint inhibitors (anti-PD-1) are also under investigation in small proof-of-concept studies [26, 36]. However, the true effect of this approach is yet to be determined with more robust studies (Table 5).

Drug group	Example agents	Advantages	Pitfalls
Cytotoxic chemotherapy	Hydroxyurea	Oral; well-characterized toxicity profile	Low response rates; myelosuppression; mucocutaneous toxicity
Somatostatin analogs	Octreotide, pasireotide	Targets SSTR2-positive tumors; favorable safety	Modest single-agent activity; requires combination with mTOR inhibitors for better efficacy
Anti-angiogenic agents	Bevacizumab	Disease stabilization; occasional tumor shrinkage; manageable toxicity	Risk of hypertension, proteinuria; no phase III data
mTOR inhibitors	Everolimus, temsirolimus	Synergistic with somatostatin analogs; PFS-6 benefit in phase II trials	Metabolic adverse effects; non-randomized data only
Genotype-directed targeted therapy	Vismodegib (SMO), capiwasertib (AKT1), GSK2256098 (FAK)	Biomarker-driven; potential for higher efficacy in selected subgroups	Early-phase studies; pending RCTs; off-label use; pathway resistance mechanisms
Hormonal modulators	Mifepristone	Oral; theoretical benefit in PR-positive tumors	Minimal clinical activity; side effects; no supporting RCTs
Immune-checkpoint inhibitors	Pembrolizumab, nivolumab	Case reports of durable responses; favorable safety in other tumors	Lack of robust efficacy data; potential for immune-related adverse events

Table 5.
Major pharmacotherapy treatment options for meningioma.

8. Recent literature on pharmaceutical treatments

8.1 Everolimus + octreotide (CEVOREM, phase II)

The open-label, multicenter CEVOREM trial enrolled 20 adults with recurrent meningioma (2 WHO I, 10 WHO II, 8 WHO III; 4 with NF2 germline mutations) to receive everolimus 10 mg/day plus octreotide LAR 30 mg monthly. The primary endpoint—6-month progression-free survival (PFS-6)—was 55% (95% CI 31.3%–73.5%). Median overall survival at 12 months was 75% (95% CI 50.0%–88.7%), and 78% of tumors demonstrated a > 50% reduction in growth rate at 3 months ($P < 0.0002$). Toxicity was manageable: the most common adverse event was stomatitis (55%, grade 3 in 15%), with fatigue and hypercholesterolemia in ~45 [34].

8.2 Bevacizumab (VEGF-A antibody, phase II)

A multi-institutional phase II study assessed bevacizumab (10 mg/kg every 2 weeks) in 31 patients with recurrent meningioma (grades I–III). The overall PFS-6 was 60%, with a median PFS of 8.4 months and median OS of 16.8 months. Grade 3–4 toxicities occurred in 19% (hypertension, proteinuria). A subsequent systematic literature review (11 studies, 92 patients) reported a pooled PFS-6 of 73% (range 44–93%) and median PFS of 16.8 months, reinforcing bevacizumab's role in disease control, albeit pending randomized validation [35, 37].

8.3 RANO group systematic review and meta-analysis (2024)

The RANO Meningioma Working Group conducted a meta-analysis of 34 completed and 27 ongoing trials (cumulative $n \approx 600$), establishing PFS-6 benchmarks for recurrent meningioma therapies. Pooled PFS-6 was 45% (95% CI 38–52%) across all systemic approaches, with anti-angiogenic and mTOR + SSTR combinations outperforming cytotoxics (PFS-6 55% vs. 27%, $p < 0.01$). Heterogeneity was high ($I^2 = 68\%$), underscoring variable trial designs and patient selection. The authors propose a “rate of probable interest” PFS-6 of $\geq 35\%$ to justify phase III testing [38].

8.4 Emerging genotype-directed trials

The Alliance A071401 umbrella trial assigns patients by tumor genotype: SMO-mutant to vismodegib, NF2-altered to FAK inhibitor GSK2256098, AKT1/PIK3CA to capivasertib, and CDK pathway dysregulation to abemaciclib. Interim results in the NF2 arm ($n = 37$) show PFS-6 of 83% in WHO I and 33% in WHO II/III, with manageable toxicity, demonstrating feasibility of precision oncology in meningioma [32, 33, 39, 40].

9. Conclusion

Meningiomas are a complex class of tumors that present themselves in a variety of locations and aggressiveness profiles, which makes the diagnosis and surgical management very complex.

Recent advances in molecular analysis of the meningiomas might present a paradigm shift in the treatment of those complex pathologies, given that with these specific profiles the surgeon will be able to better understand the best line of action to treat the patient while minimizing the risk of complications. Although this scenario seems prosperous, more robust studies on the real effect of molecular/genetic-specific treatments for meningiomas are warranted.

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Surgical Approach to Parasagittal Meningioma

Noman Ahmed and Hafsa Binte Sohail

Abstract

Parasagittal meningiomas are among the most frequently encountered primary central nervous system tumors, accounting for a substantial proportion of intracranial meningiomas. Their unique anatomical relationship with the superior sagittal sinus poses both diagnostic and surgical challenges. This chapter provides a comprehensive overview of the epidemiology, anatomical classification, clinical presentation, radiological features, and surgical management of parasagittal meningiomas. Magnetic resonance imaging remains the gold standard for diagnosis and preoperative planning, with adjunctive imaging modalities, such as CT and MR venography, aiding in the assessment of sinus involvement. Detailed surgical techniques are described, including patient positioning, incision planning, craniotomy, tumor dissection, and closure, with special attention to preserving venous anatomy and achieving maximal safe resection. The chapter also discusses intraoperative considerations, potential complications, and postoperative outcomes.

Keywords: parasagittal meningioma, superior sagittal sinus, magnetic resonance imaging, surgical management, venous preservation

1. Introduction

Meningiomas are the most common primary tumors of the central nervous system (CNS), accounting for approximately 36.6% and 54.5% of all nonmalignant tumors [1]. Among these, parasagittal meningiomas are more common, accounting for 18–25% of all meningioma cases, in line with the convexity meningiomas (19–34%) [2]. Other locations described include, sphenoid wing, the anterior cranial fossa, the posterior cranial fossa, the cerebellar convexity, and the clivus.

These tumors occupy the parasagittal angle, being attached to the dura and forming the outer layer of the superior sagittal sinus (SSS), without any brain tissue in between. This causes displacement of the brain tissue, with its compression resulting in symptoms and signs. Olivecrona classified these tumors according to their location along the superior sagittal sinus, dividing them into three categories [3]. The anterior third of these tumors is located from the glabella to the coronal suture, accounting for 15–42% of the cases. Middle-third tumors are more common, situated from the coronal suture to the bregma, accounting for 37–70% and posterior-third tumors, located from the bregma to the torcula, are the least common (9–16%) [4].

It is critically important to differentiate between parasagittal meningiomas from parafalcine and convexity meningiomas because of the different surgical implications. The parafalcine tumors are attached to the dura of the falx, and the convexity tumors approaching the SSS have an intervening brain tissue with no attachment to the dura of the outer layer of the sinus. These features help distinguish and guide the management of parasagittal meningiomas.

2. Clinical presentation

Usually, patients with meningiomas are asymptomatic. However, individuals with parasagittal meningioma can present with variable symptoms earlier in the course of the disease. Typically, seizures are reported first, leading to the diagnosis of these tumors. A retrospective analysis of 192 cases from Huashan Hospital reported seizures in almost one-fourth of the patients [5]. **Table 1** represents other clinical features that were seen.

Patients can present with a Jacksonian seizure, a focal seizure of the simple partial variety, characterized by a predictable progression of abnormal movement or sensation on one side of the body in an awake individual. These are more commonly seen with lesions localized to the middle third of the superior sagittal sinus, due to its proximity to the central sulcus. Additionally, middle-third tumors can present with progressive hemiparesis or hemisensory loss because of their relationship to the motor and sensory cortex.

Tumors related to the anterior third of the superior sagittal sinus commonly present with headaches. However, compression of the frontal lobe can result in personality and behavioral changes. These individuals can manifest variable symptoms, including agitation, aggression, irritability, depression, apathy, and a lack of empathy. Patients can have cognitive dysfunction, with difficulty in planning, solving problems, and abstract thinking. These signs may be subtle and require a high index of suspicion for diagnosis. Additionally, seizures can be the first presenting symptom in some patients with a tumor located anteriorly.

Clinical features	Frequency (%)
Seizure	22.4
Headache	19.8
Hemiparesis	14.6
Monoparesis	13.5
Vertigo	12.0
Asymptomatic	9.4
Calvarial deformity	2.6
Visual symptoms	2.6
Cognitive decline	1.6
Speech disturbance	1.6

Table 1.
Clinical features of parasagittal meningioma from a retrospective cohort.

Parasagittal meningiomas, located posteriorly, are less commonly seen. Clinical features may vary, including episodes of headache or seizures. Due to compression over the occipital lobe, sometimes people present with visual field defects, particularly contralateral homonymous hemianopia.

Clinical signs may include pyramidal tract signs arising from the motor cortex. Individuals can present with unilateral spasticity, motor weakness, brisk reflexes, and a positive Babinski sign. Signs of sensory dysfunction include loss of pain, touch, and temperature sensations. Additionally, lesions found later in the course can also present with bony changes, including bossing of the calvaria.

3. Imaging

MRI is the diagnostic modality of choice for this tumor. It typically appears as a dural-based homogeneously enhancing, well-circumscribed lesion lying adjacent or attached to the superior sagittal sinus without intervening brain parenchyma (**Figure 1**). These are extra-axial lesions with a cerebrospinal fluid (CSF) cleft, better recognized on T2-weighted sequences (**Figure 2a**). Typically, they appear hypo to isointense on T1-weighted sequence and hyperintense on T2-weighted sequence. Peritumoral edema appears hyperintense on T2 and fluid attenuated inversion recovery (FLAIR) sequences (**Figure 2b**), which may also highlight the aggressive nature of the tumor [6, 7].

A CT scan with contrast can be used alternatively in patients who have contraindications to MRI. These may include patients who are claustrophobic or have metallic implants in place. Characteristically, a CT scan may show tumor calcification, bony changes with skull remodeling (**Figure 3a and b**), and a beaten brass appearance [8]. A PET scan with 68-Gallium-labeled somatostatin analog can help in diagnosing a recurrence when a surgical biopsy is not feasible [9]. MRS is another imaging modality that can be used for diagnostic purposes. There are elevated choline and alanine peaks with decreased N-acetyl aspartate and creatine peaks when compared to the normal brain tissue [10].

MR venogram plays an essential role in managing cases of parasagittal meningioma. It helps in identifying the status of occlusion superior sagittal sinus, which may change the surgical plan (**Figure 4A and B**). Additionally, magnetic resonance venograph (MRV) helps identify the location of the peritumoral veins, which need

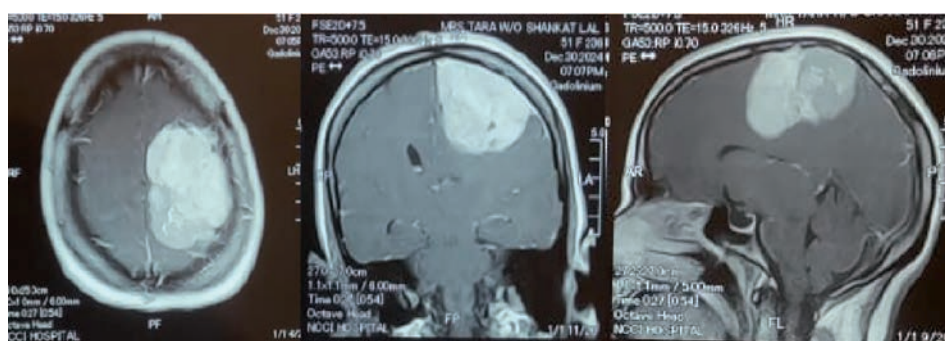


Figure 1.
 MRI brain with contrast showing axial, coronal, and sagittal views of a parasagittal meningioma with underlying brain parenchymal compression.

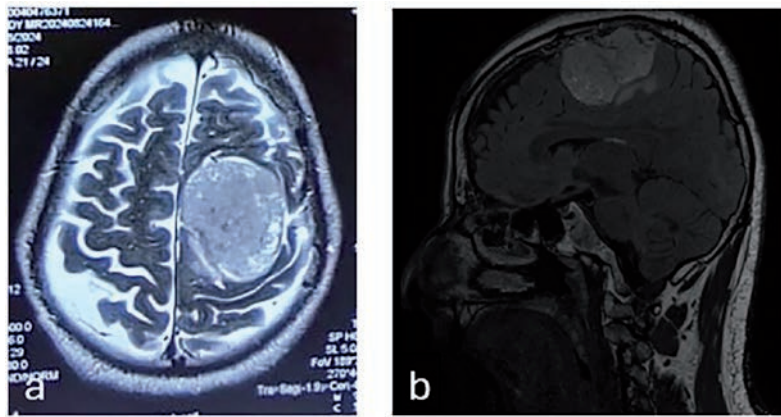


Figure 2.
a. MRI brain axial section T2-weighted image showing a hyperintense lesion with surrounding CSF cleft. b. Shows a FLAIR image, sagittal view of a hyperintense lesion with some peritumoral edema.

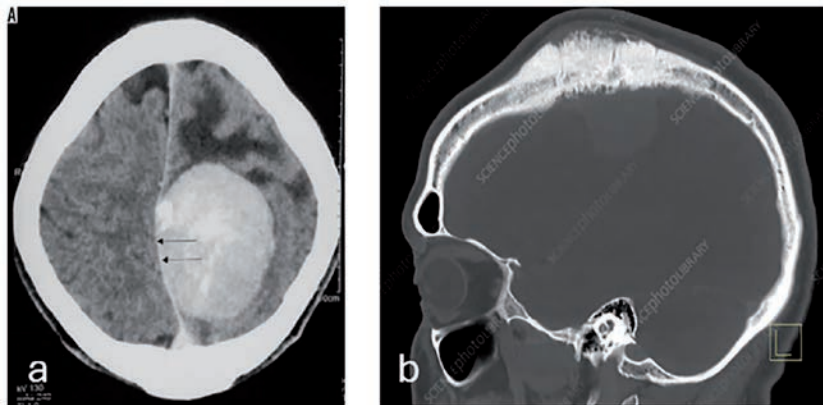


Figure 3.
a. CT head axial section showing a hyperdense midline dural-based lesion. b. Represent a case of parasagittal meningioma with hyperostosis.

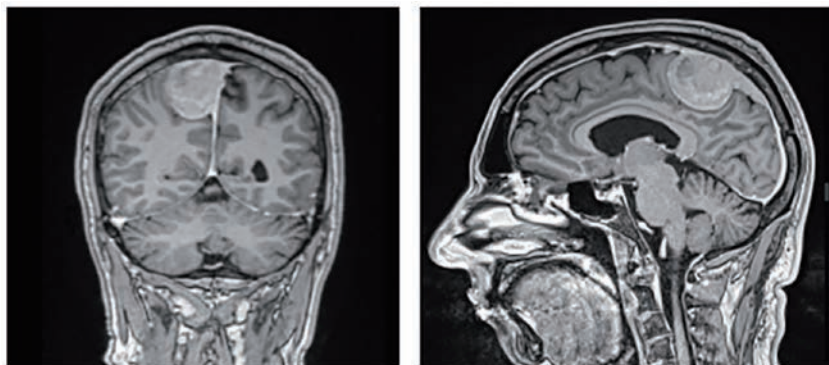


Figure 4.
MRI brain with contrast, coronal and sagittal sections showing tumor invading the middle-third of the sinus, causing total obstruction.



Figure 5.
 Three types of diagrams of peritumoral vein and tumor: (A) type A (surround), the vein surrounds the tumor; (B) type B (ventral), the vein is located on the ventral side of the tumor; (C) type C (dorsal), the vein is located on the dorsal side of the tumor.

to be preserved during the dissection of the tumor to prevent postoperative venous infarcts secondary to congestion. In a study by Cai et al., in China, 57 patients with meningiomas were analyzed, among which 35 patients had parasagittal meningioma [11]. Peritumoral veins were classified into three categories: Type A—Surrounding the tumor; Type B—Ventral side of tumor; Type C—Dorsal side of tumor (**Figure 5A–C**). Most commonly, these peritumoral veins are located near the middle third of the SSS (72%), followed by the anterior third (21.1%) and the posterior third (7.0%).

4. Classification

The parasagittal meningiomas are classified according to various grading systems. The most common classification is the Sindou classification [12], which highlights these tumors' involvement of the superior sagittal sinus. This helps in devising a preoperative plan, considering total or partial excision depending on tumor involvement. The classification is represented in **Figure 6**.

Another simple classification divides the tumor into three categories based on preoperative imaging. Type 1 tumors are attached to the dura, forming the external wall of the sinus. Type 2 tumors invade the sinus and narrow the lumen; however, no complete occlusion is seen. Last, type 3 tumors cause partial occlusion of the tumor (**Figure 7**). The sinus involvement needs to be reviewed during preoperative imaging as it helps in counseling and guides the surgical plan, preventing unwanted complications.

5. Surgical management

5.1 Preoperative checklist

A thorough history and examination are mandatory before moving on to further investigations. It is important to assess the patient for any comorbidities that may increase the risks of surgery and elevate the chances of complications. A preoperative anesthesia assessment, followed by optimization, should be done before the surgery. Preoperative baseline blood tests include complete blood count, blood grouping and crossmatch, coagulation profile (prothrombin time (PT) and partial thromboplastin

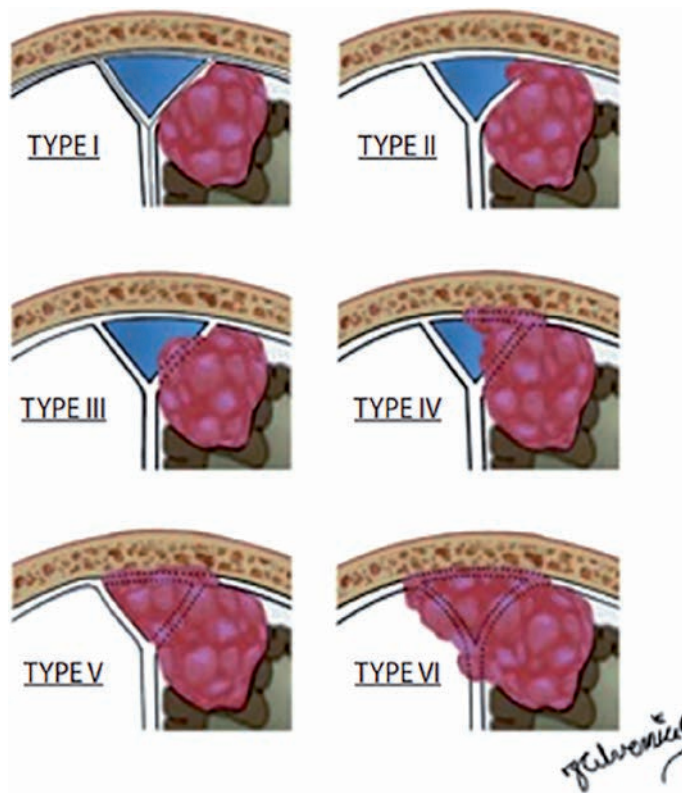


Figure 6.

Sindou grading system for meningioma invasion of the superior sagittal sinus. Type I = Attachment to the lateral wall of the sinus. Type II = Invasion of the lateral recess. Type III = Invasion of the lateral wall. Type IV = Invasion of the lateral wall and roof. Type V = Total sinus occlusion, contralateral wall spared. Type VI = Total sinus occlusion, invasion of all walls.

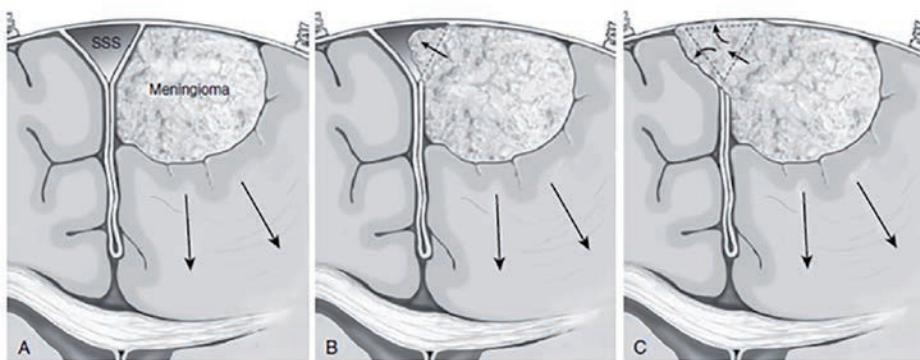


Figure 7.

A. Tumor attached to the lateral wall. B. Tumor invading the sinus with partial occlusion. C. Tumor completely occluding the sinus. (Courtesy: Schmidek and Sweet Operative Neurosurgical Techniques).

time (APTT)), serum electrolytes, creatinine, and blood urea nitrogen (BUN). Other lab tests may be determined as per the patient's condition. A preoperative navigation MRI for surgical planning is done beforehand.

Important preoperative considerations include the involvement of the superior sagittal sinus as described above. Additionally, the bony changes need to be determined to achieve a complete resection to prevent recurrence. A CT scan is a helpful adjunct, as it helps to determine the level of hyperostosis that may require a high-speed drill intraoperatively to remove excessive bone. The MRI image, particularly a T2-weighted sequence, helps to identify the CSF cleft between the tumor and normal brain tissue. The absence of this cleft, along with peritumoral edema, is suggestive of brain parenchymal involvement and makes extrapial resection difficult. In these circumstances, a surgeon needs to understand that leaving the tumor behind is not an undervalued option, preventing postoperative deficits [13].

Additionally, it is important to understand the presence of contralateral extension of the tumor, as it may change the planned position of the patient [14].

5.2 Intraoperative checklist

5.2.1 Prepositioning

The important considerations at this stage include:

- a. Wide bore cannulas (16 or 18G)
- b. Arterial catheter (Managing fluctuating BP)
- c. Central venous catheter (Very important due to risk of air embolism in case of injury to the SSS or major venous tributary)
- d. Foley catheter
- e. Warmer device
- f. Prophylactic IV antibiotic 30 mins before the incision (Commonly 1 g of Cefazolin)
- g. Antiseizure medication prophylaxis
- h. Shaving after planning the incision
- i. Setting up the navigation machine
- j. Reinforced endotracheal tube (In case of surgery in the prone position to prevent kinking of the tube during positioning)
- k. TED stockings/intermittent pneumatic compression devices
- l. 40 g of Mannitol to prevent brain herniation during dural opening.

5.2.2 Positioning

There are different positions available for planning surgery on patients with parasagittal lesions. Tumors located along the anterior third of the sinus are operated

on with the patient in a supine position, the neck in a neutral position, and the head slightly flexed, maintaining a two-finger breadth between the chin and the manubrium sterni. Those tumors situated along the posterior third of the sinus are approached from a prone or concorde position, with the head flexed and a two-finger breadth distance from the manubrium (**Figure 8A-C**).

Tumors near the middle-third of the sinus can be approached either in the supine or prone position, based on the surgeon's preference. A supine position is preferred because it requires less setup time before surgery. In the prone position, all pressure points should be well-padded to avoid pressure-related injuries to soft tissues. In both of these positions, the head is fixed in the Mayfield clamp in the neutral position to maintain stability during the use of neuronavigation. In case of the absence of navigation monitoring, the surgery can be performed with the head placed on the horseshoe stand.

5.2.3 Incision

The incision is planned according to the tumor location. It is important to keep the vascular supply of the scalp in mind to prevent any ischemic insult to the scalp, particularly in redo surgeries. The important blood vessels supplying the scalp include the superficial temporal artery, the supraorbital artery, and the occipital artery. No

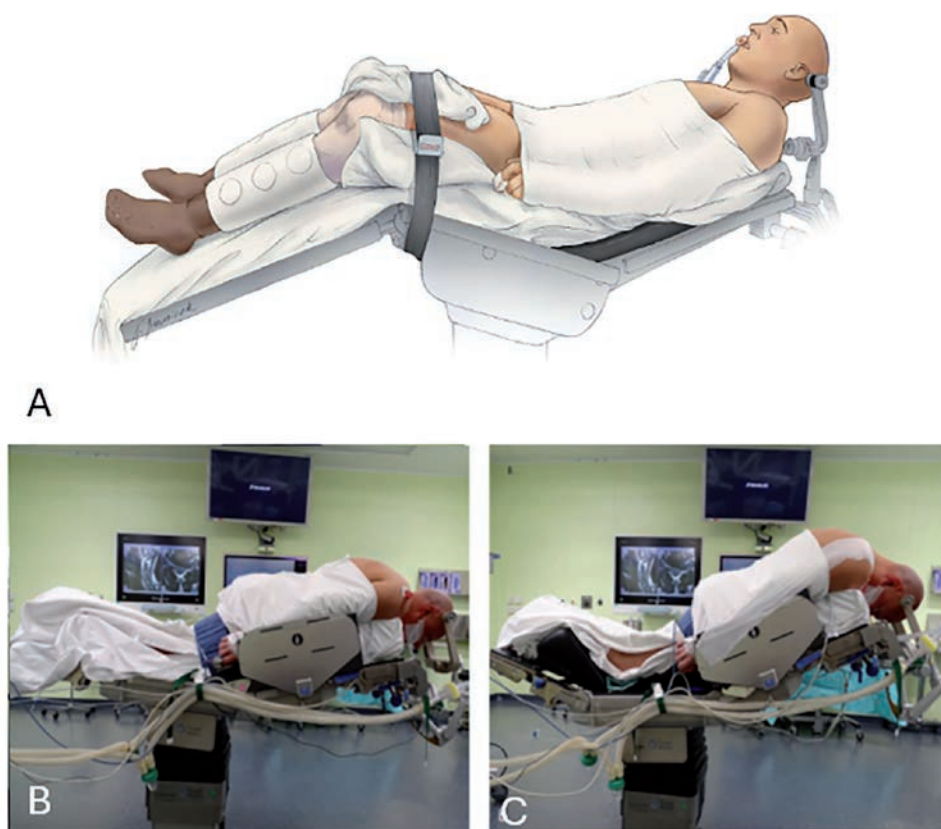


Figure 8.
A. Supine position with pin placement in neutral position. B. Prone position with pins in neutral position. C. Concorde position with neutral pins.

two blood vessel territories must be compromised at one point to preserve the scalp from necrosis.

Commonly, a U-shaped incision is used for midline large parasagittal tumors to provide wide exposure for craniotomy. It is important to cross the midline to ensure that a craniotomy can be performed across the midline to expose the uninvolved sinus, preventing any complication. A U-shaped flap should have a broad base, 1.5 times the length of the flap, to ensure adequate perfusion. Alternatively, a long linear incision can be employed for smaller tumors located anteriorly or posteriorly. Similarly, a bicoronal incision can be used for tumors that are located anteriorly, with the center of the incision based on the widest antero-posterior (AP) diameter of the lesion (**Figure 9A-C**).

A crucial thing to consider while giving an incision is not to use the scalpel very deeply. The purpose is to carefully dissect the subgaleal space to preserve the pericranium, which can be used in dural reconstruction. The pericranial flap can be left vascularized, or it can be detached (kept in a saline-soaked gauze) for later usage.

5.2.4 Craniotomy

After stripping the pericranium from the underlying bone using a pericranial elevator, punctate bleeding can be visualized. This usually provides an idea about the location of the underlying tumor, although a navigation device is used for confirmation. Once confirmed, with the help of navigation, craniotomy margins should be marked.

The edge of the craniotomy must be at least 2 cm away from the junction of the tumor and dural tail and at least 1 cm within the scalp edge. The number of burr holes

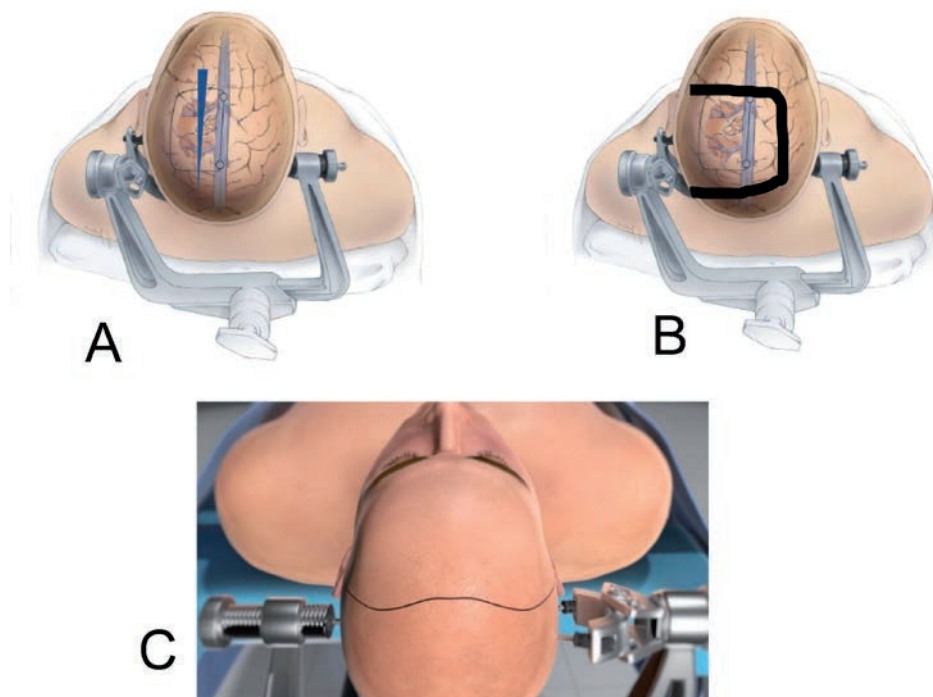


Figure 9.
Demonstrates different incisions used for parasagittal meningioma surgeries. A. Linear incision. B. U-shaped incision. C. Bicoronal incision.

in the midline can be increased according to the patient's age. The more the number of burr holes, the easier it is to separate the bone from the underlying dura, particularly in elderly patients and those with bony involvement in imaging. In midline, at least two burr holes should be made, and one burr hole on the convexity. Using a Penfield or McDonald dissector, separate the bone from the underlying dura. After this, a cutter with a guard loaded on a high-speed drill is used for craniotomy. It is important to note that the cutter should always be running in a direction away from the sinus (**Figure 10**).

The bone flap is elevated carefully, separating the bone from the adherent dura to prevent perforation. The dura can be highly vascular; thus, bleeding may be encountered post-craniotomy. It is important to control bleeding to prevent major blood loss. Different hemostatic agents are available for hemostasis, including sponge stones/gelfoam or surgical, which can result in spontaneous resolution considering venous oozing. In case of arterial bleeding, bipolar cautery can be used for hemostasis. The bone involved can be drilled using a high-speed drill.

5.2.5 Durotomy

Once craniotomy is done securely, tenting sutures can be taken in the periphery between the craniotomy edges and the edge of the dura to prevent bleeding from the epidural space. The dura is incised meticulously, and hemostasis should be considered at every step. Bleeding edges can be secured either using a Cushing clamp or bipolar cautery. The dural incision is typically made over the tumor using a number 11 blade and continued in a C-shaped fashion based on the SSS (**Figure 11A**).

During the dural opening, it is important to visualize the cortical veins connecting to the sinus. Iatrogenic injury to the veins can result in congestion and secondary

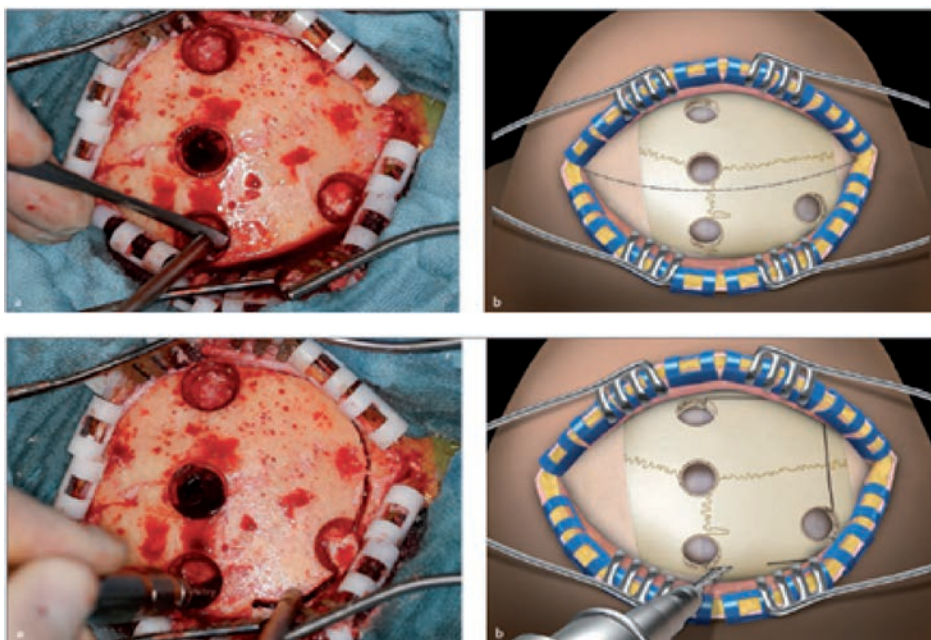


Figure 10.
The picture depicts the placement of burr holes in a parasagittal craniotomy and the direction of cutter usage (Courtesy: The Craniotomy Atlas).

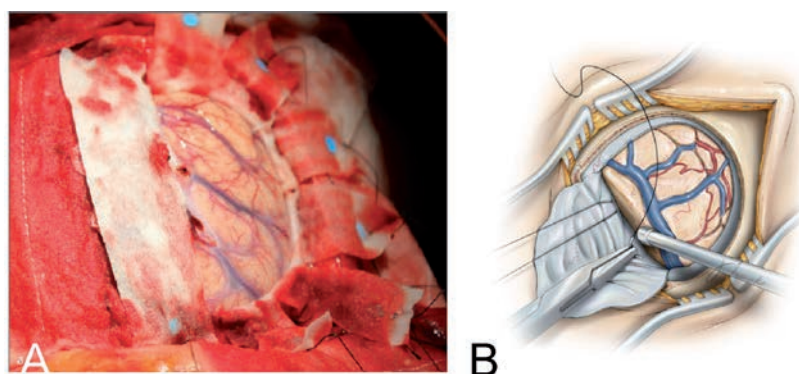


Figure 11. A. C-shaped dural opening with base over the superior sagittal sinus. B. Schematic diagram representing retraction sutures on the falx below the sinus.

venous infarction. The course of durotomy needs to be altered in case one encounters a draining cortical vein to prevent injuring it [14, 15].

Once durotomy is completed, tenting sutures can be taken from lateral to the sinus, or in the falx, inferior to the sinus, can be used to gently retract the falx and sinus contralaterally, allowing better access to the interhemispheric fissure (**Figure 11B**).

5.2.6 Tumor dissection and removal

After durotomy, the tumor can be visualized and differentiated from the normal cortex on inspection. The four Ds of meningioma surgery are employed that is, Devascularization, Dissection, Debulking, and Detachment.

The first step is to separate the tumor from the underlying cortex using the arachnoid plane. Small cottonoid patties are inserted one after the other to separate the tumor from the normal brain parenchyma. During this process, it is essential to coagulate the vessels coursing to the tumor. It is important that during dissection, excessive traction on the brain is avoided to prevent avulsion injury. This can be achieved by tumor debulking, starting from the central core of the tumor. Different instruments can be used for serving this purpose. Conventionally, tumor forceps and suction, alternating with bipolar cautery, can be used once biopsy samples have been taken. In a modern setup, ultrasonic aspirator devices are available for tumor debulking. Secondly, a loop cautery device is used to debulk hard calcified tumors.

The tumor is gradually debulked, making sure there is no extracapsular breach during the procedure. Multiple silk 0 sutures can be taken through the tumor mass, acting as a lever to manipulate the tumor while extracapsular dissection is being done. This surgical technique helps in the dissection, improving the overall surgical time. Once the tumor is maximally debulked, after dissection and devascularization, detachment is finally performed, with removal of the involved dura resulting in Simpson 1 resection.

Parasagittal meningiomas with partial involvement of the sinus (Sindou II-IV) and complete involvement (V and VI) are approached similarly, except for the terminal resection. A Simpson grade 1 resection cannot be done for individuals with partial sinus involvement. In these patients, the tumor is debulked from the sinus wall; however, it cannot be separated without breaching its lumen. Thus, the residual tumor

is cauterized only, while the tumor inside the lumen is left untouched, resulting in Simpson grade 3 resection.

Individuals with a complete obstruction of the sinus lumen are managed differently. The contralateral dura is opened adjacent to the planned sinus resection. A silk 2.0 suture is used to tie the proximal and distal ends of the sinus, followed by En bloc resection of the involved sinus, achieving a Simpson grade 1 resection. It is important to preserve the cortical veins entering the sinus proximal and distal to the obstruction, as they serve as vital collateral pathways for the venous drainage system.

Different surgical opinions exist regarding the management of tumors partially occluding the sinus. Some studies have suggested radical resection (Simpson grades 1 and 2) for tumors partially occluding the sinus walls, as it has improved the overall outcomes by decreasing the risk of recurrence [16]. This can be approached through the lateral sinus wall, after opening it, and resecting the intrasinus tumor using an ultrasonic aspirator, until bleeding is encountered, which can be controlled using a running suture.

Apart from the conventional microsurgical technique, endoscopic surgery can be used for the resection of parasagittal meningiomas [17]. This technique can be employed in redo surgeries when scalp healing is problematic, particularly in cases of postradiation recurrences. As the literature describes, a small incision is made over the normal forehead skin, followed by a small craniotomy. The dura mater is opened, followed by CSF drainage to expose the space between the frontal lobe and falx. A navigation MRI is used to determine the trajectory that the assistant uses to guide the endoscope while the primary surgeon dissects the tumor and debulks it, while visualizing on the monitor (**Figure 12a** and **b**). Once CSF is drained adequately, the instruments can be manipulated in and out of the field easily, without causing significant traction injury. The rest of the surgical process remains the same.

5.2.7 Closure

The closure after parasagittal meningioma surgery can be technically difficult. It is due to the need to reconstruct the dural defect caused by the removal of the involved

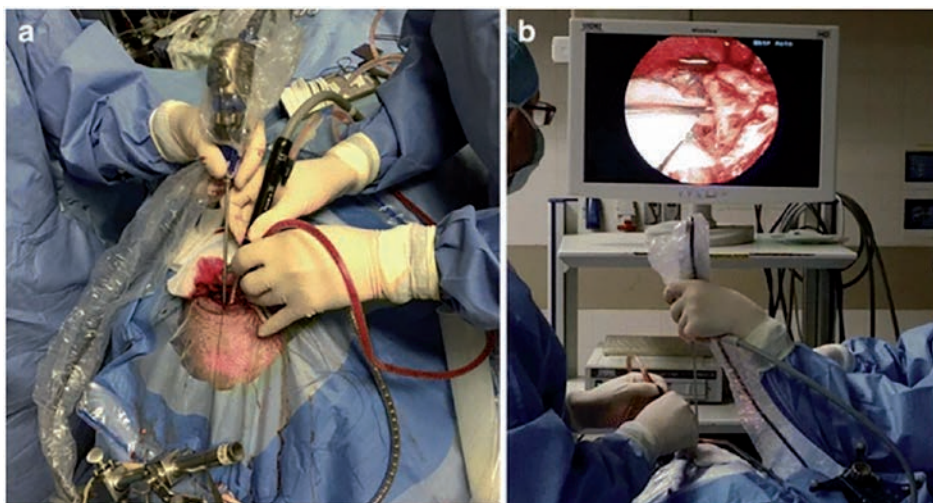


Figure 12. Intraoperative pictures during the fully endoscopic surgery. *a.* The endoscope is navigated by one surgeon, while the second surgeon works with two surgical tools. *b.* Both surgeons visualize the field on the monitor (Courtesy: [17]).

dura or its shrinkage from cautery. The pericranium harvested before the craniotomy can be used for dural reconstruction. It can be sewn using a Vicryl 4.0 suture to the remaining dura in a continuous fashion to cover the defect. Ultimately, dural tack-up sutures are taken, if not already, to prevent extradural hematoma formation.

The bone flap can be reapplied and secured in its place using titanium plates and screws. In setups where titanium implants are not available, the bone can be reapproximated using silk 0 or 1.0 after drilling holes in the bone. This is followed by closure of the scalp in two layers, approximating the galea and skin.

6. Complications

Individuals can suffer from different surgical complications (**Table 2**), considering the extensive nature of the surgery. Surgical resection of parasagittal meningiomas carries specific risks due to their close relationship with the superior sagittal sinus and eloquent cortex. The most frequent complications include seizures (20–40%), motor deficits (10–30%), and venous infarction (~10–12%), often related to venous sacrifice or sinus

Complication	Incidence	Cause	Prevention/Management
Postoperative hemorrhage	~5–10%	Vessel injury, inadequate hemostasis	Meticulous hemostasis, watertight dural closure, early postop CT, urgent evacuation if symptomatic
Seizures	~20–40%	Cortical irritation, venous infarct, edema	Perioperative anti-epileptic drugs (AEDs) in high-risk cases, control edema, and treat infarcts promptly
Motor deficits	~10–30%	Cortical injury, venous infarct, edema	Careful dissection near the motor cortex, preserve veins, minimal retraction, use neuro-navigation
Venous infarction	~ 10–12%	Sacrifice/injury of cortical veins or SSS	Preop MRV for venous anatomy, preserve draining veins, ICP management, ICU monitoring
Venous sinus thrombosis	~10–15%	SSS manipulation, coagulation changes	Limit sinus manipulation, anticoagulation if safe, monitor ICP
CSF leak	<5%	Dural closure issues	Watertight dural repair, lumbar drain if needed
Infection	~3–8%	Wound breakdown, CSF leak, contamination	Aseptic technique, antibiotics, and prompt wound care
Delayed hydrocephalus	~2–5%	Impaired CSF absorption post-surgery	Early detection, CSF diversion (shunt/ETV)
Recurrence	Depends on Simpson grade: ~9–13% at 10 yrs. for Grade I/II, ~40–60% for Grade IV/V	Residual tumor or incomplete resection, especially with SSS invasion	Aim for maximum safe resection. Manage with serial MRI surveillance. Treat recurrent/residual growth with stereotactic radiosurgery (SRS) or redo surgery if feasible
Medical complications	~2–5%	Pulmonary embolism, DVT, electrolyte imbalances, pneumonia, UTI	Early mobilization, pneumatic compression devices, anticoagulation prophylaxis where safe, strict fluid/electrolyte monitoring, antibiotics where needed

Table 2.
Complications of parasagittal meningioma surgery.

involvement. Less common but clinically important issues include hemorrhage (5–10%), sinus thrombosis (10–15%), CSF leak (<5%), and delayed hydrocephalus (2–5%) [18].

Prevention depends on microsurgical technique, preservation of venous drainage, watertight dural closure, and early recognition of complications. The use of MR venography for preoperative planning, perioperative seizure prophylaxis in high-risk patients, and close postoperative monitoring in the ICU are recommended strategies to reduce morbidity.

Recurrence is also seen, which is defined as a new enhanced mass in gross total resection (GTR) cases or a significant increase in the residual mass in subtotal resection (STR) cases six months after surgery. Therefore, regardless of the degree of resection, conventional radiotherapy at the site of surgery, especially in the case of Grade II/III meningioma, must be done along with close follow-ups with MRI/MRV imaging and stereotactic radiosurgery if needed.

7. Prognosis

The predictors of outcomes are variable and depend on different factors. These include the WHO grade of the tumor, the extent of resection, sinus involvement, and the size of the tumor [19, 20]. A WHO grade 1 tumor is associated with a lower risk of recurrence compared to grade 2 and 3 tumors, even if complete resection is not possible. Additionally, radical resection (Simpson grade 1 or 2) is associated with a lesser chance of recurrence in comparison to grade 3 or 4 resections.

Although the involvement of the sinus can negate a complete resection, increasing the chance of recurrence, the authors employ this conservative approach to prevent the high morbidity and mortality associated with its injury [21]. The residual tumor can be followed or be radiated to decrease the chances of recurrence, increasing the overall prognosis.

8. Conclusion

Parasagittal meningiomas constitute a significant subset of intracranial tumors, with distinct anatomical, clinical, radiological, and surgical considerations. Their location along the superior sagittal sinus presents unique diagnostic and therapeutic challenges that necessitate a nuanced and multidisciplinary approach. Detailed preoperative imaging, careful planning, and precise intraoperative technique—especially with respect to sinus involvement and peritumoral venous anatomy—are paramount to achieving optimal outcomes while minimizing complications.

The surgical objective should balance maximal safe resection with functional preservation, particularly in cases with partial or complete sinus invasion. While gross total resection remains the goal, conservative management of sinus-invading tumors, followed by vigilant monitoring or adjuvant therapy, may offer favorable long-term outcomes with reduced morbidity. As imaging modalities, surgical tools, and intraoperative adjuncts continue to advance, so too will our ability to treat these tumors more safely and effectively. Ultimately, a patient-centered, individualized strategy remains the cornerstone of successful management of parasagittal meningiomas.

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Chapter 4

Pediatric Meningioma

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and Alfonso Marx-Bracho*

Abstract

Pediatric meningiomas are rare neoplasms that exhibit unique biological behavior, distinct from their adult counterparts in terms of histology, location, and molecular features. This chapter provides an in-depth review of the current understanding of pediatric meningiomas, integrating classical clinical, radiological, and pathological perspectives with contemporary advances in molecular profiling and surgical innovation. These tumors in children are frequently associated with higher World Health Organization (WHO) grades, atypical anatomical sites, and genetic syndromes such as neurofibromatosis type 2. Management demands tailored strategies that balance oncological control with preservation of neurodevelopmental integrity. Gross total resection remains the cornerstone of treatment, often facilitated by modern neurosurgical tools including intra-operative imaging and electrophysiological monitoring. In cases with subtotal resection or high-grade histology, adjuvant therapies such as proton-beam radiotherapy and immune checkpoint inhibitors may enhance outcomes. The incorporation of DNA methylation profiling and emerging genetic biomarkers is refining diagnostic classification and risk stratification, laying the groundwork for precision medicine in this population. Despite these advances, long-term follow-up reveals a significant burden of neurological, endocrine, and cognitive sequelae, underscoring the need for multidisciplinary care and robust survivorship planning. Drawing from international literature and institutional experience, this chapter highlights the imperative of pediatric-specific treatment models and calls for collaborative research to close persistent gaps in knowledge. Ultimately, improving prognosis in children with meningiomas requires not only effective disease control but also a commitment to preserving the child's potential for a full and meaningful life.

Keywords: pediatric meningioma, neurofibromatosis type 2 (NF2), WHO grade II/III, pediatric neurosurgery, gross total resection, skull base tumors, pediatric brain tumors, pediatric neuro-oncology, intraventricular tumors

1. Introduction

Pediatric meningiomas are rare but clinically and biologically distinct from their adult counterparts, necessitating specialized diagnostic and therapeutic approaches [1, 2]. This chapter presents a comprehensive synthesis of current evidence by integrating classical clinical and imaging features with emerging molecular insights [3, 4]. Unlike adult meningiomas, pediatric cases exhibit a higher incidence of WHO grade II/III histologies, atypical locations, and frequent NF2 mutations accompanied by

chromosome 22 loss [2, 5]. Advanced imaging remains critical for surgical planning; however, molecular profiling—particularly DNA methylation analysis and the absence of adult-type mutations (e.g., SMO and AKT1)—offers new tools for diagnosis and risk stratification [4, 6]. Surgical resection remains the cornerstone of treatment, with gross total resection significantly improving outcomes [7]. Adjuvant therapies, including radiation and emerging immunotherapies, are tailored according to histological grade and molecular profile [8, 9]. Recent international guidelines emphasize the integration of molecular markers into classification and treatment decisions [5]. This chapter *underscores* the need for pediatric-specific strategies, long-term multidisciplinary care, and ongoing research into molecularly targeted therapies [9, 10].

2. Epidemiology and risk factors

Meningiomas are tumors arising from the meninges, the protective layers covering the brain and spinal cord. In the pediatric population, they are rare, accounting for approximately 1–4% of all intracranial tumors in children [3]. This contrasts markedly with the adult population, where meningiomas represent 13–27% of primary brain tumors [3]. Unlike adults—in whom a clear female predominance is observed—pediatric meningiomas show no significant sex difference. The average age at diagnosis is approximately 13 years, although cases have been reported even in infants younger than 1 year of age (**Table 1**) [3].

2.1 Risk factors

Several risk factors have been identified for the development of meningiomas in children:

- *Previous cranial radiotherapy*: Exposure to ionizing radiation, particularly during early life, is a well-established risk factor. Children who have undergone

Characteristic	Pediatric	Adult
Frequency	<5% of intracranial tumors	~30% of intracranial tumors
Sex predominance	None	Female predominance
Genetic association	High (NF2, SMARCE1, BAP1)	Lower association
Most common histology	Atypical / Anaplastic	WHO grade I (meningothelial)
Typical location	Intraventricular, posterior fossa, spine	Convexity, skull base
Clinical behavior	Aggressive, rapid growth	Typically, indolent
Relative incidence	1–4% of intracranial tumors	13–27% of primary brain tumors
Mean age at diagnosis	13 years	60–70 years
NF2 association	Strong	Less frequent
History of cranial irradiation	Common	Present, but less frequent
Need for adjuvant therapy	Common	Less frequent

Table 1.
Comparative analysis of pediatric and adult meningioma characteristics.

radiation treatment for other neoplasms or medical conditions are at increased risk of developing meningiomas later in life [3, 11].

- *Neurofibromatosis type 2 (NF2)*: This genetic disorder significantly increases the risk of multiple meningiomas in pediatric patients. NF2 is characterized by tumors in the nervous system, including vestibular schwannomas and meningiomas [3].
- *Cranial trauma*: Although evidence is less conclusive, some studies have suggested a possible association between head trauma and subsequent meningioma development [11].
- *Obesity*: Elevated body mass index (BMI) has been linked to an increased risk of various cancers, including meningiomas. Large cohort studies have shown higher meningioma incidence among obese individuals [11].
- *Hormonal factors*: While hormonal influence is more evident in adults, some research has explored the role of hormones in pediatric meningioma development, although further investigation is needed [11].

3. Pathophysiology

Meningiomas arise from the arachnoid cap cells of the meninges, the membranes covering the brain and spinal cord. While they share general characteristics with adult meningiomas, pediatric meningiomas exhibit distinct features in both their molecular biology and clinical behavior (**Figure 1**) [2].

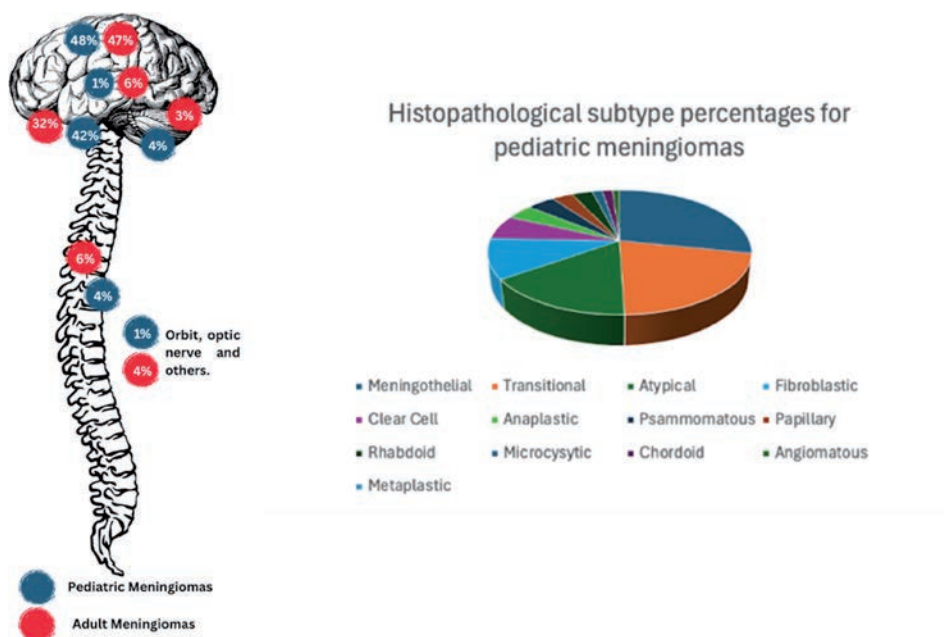


Figure 1.
Location of meningiomas in both adults and children.

3.1 Cellular origin and histological features

Histologically, pediatric meningiomas can display various patterns, including subtypes such as clear cell and papillary meningiomas, both of which are associated with more aggressive behavior and higher recurrence rates compared to the more common subtypes seen in adults [12].

3.2 Genetic and molecular alterations

Meningiomas are associated with key genetic alterations, including mutations in NF2, AKT1, TRAF7, KLF4, SMO, POLR2A, PIK3CA, and the TERT promoter, along with chromosomal losses on 1p, 14q, and 22q, all of which influence prognosis and tumor location. An integrative molecular classification enhances risk assessment beyond standard histology [5]. Pediatric meningiomas are biologically and genetically distinct from those in adults, typically presenting as more aggressive tumors with higher WHO grades (II/III) and increased proliferation rates. NF2 alterations are common, often accompanied by chromosome 22 loss. DNA methylation profiling has identified three epigenetic subgroups, with two (groups 1 and 2A) linked to NF2-related tumors, and the third (group 2B) comprising rhabdoid variants that lack NF2 features. This differentiation suggests distinct oncogenic drivers and has important clinical implications for diagnosis and genetic counseling in NF2 surveillance [2]. The tumor microenvironment also plays a critical role in meningioma progression, shaped by immune cell infiltration, macrophage polarization, and immune checkpoint expression. Overall, pediatric meningiomas tend to exhibit more aggressive behavior than their adult counterparts, with a greater propensity for brain invasion and postoperative recurrence, underscoring the need for vigilant management and long-term follow-up [2].

4. Classification and histopathological aspects

4.1 WHO 2021 classification

The World Health Organization (WHO), in its 5th edition of the Classification of Tumors of the Central Nervous System (2021), defines meningioma as a single tumor type encompassing a broad morphological spectrum, represented by 15 histological subtypes. Notably, the criteria for diagnosing atypical (grade 2) or anaplastic (grade 3) meningiomas apply irrespective of the underlying histological subtype [5].

4.2 Histological grades and subtypes

Grade I (Benign): This category accounts for approximately 80% of meningiomas and is considered to carry a low risk of recurrence. The most common subtypes within this grade include meningotheelial meningioma, fibrous (fibroblastic) meningioma, and transitional (mixed) meningioma. These subtypes are typically characterized by slow growth and a low recurrence rate following complete surgical resection (**Figure 2**) [5].

Grade II (atypical): This grade represents approximately 15–18% of meningioma cases and is associated with a higher risk of recurrence and more rapid growth. Subtypes include atypical meningioma, clear cell meningioma, and chordoid meningioma. These tumors exhibit histological features such as increased mitotic activity, higher cellularity, and, in some cases, brain invasion [5, 12].

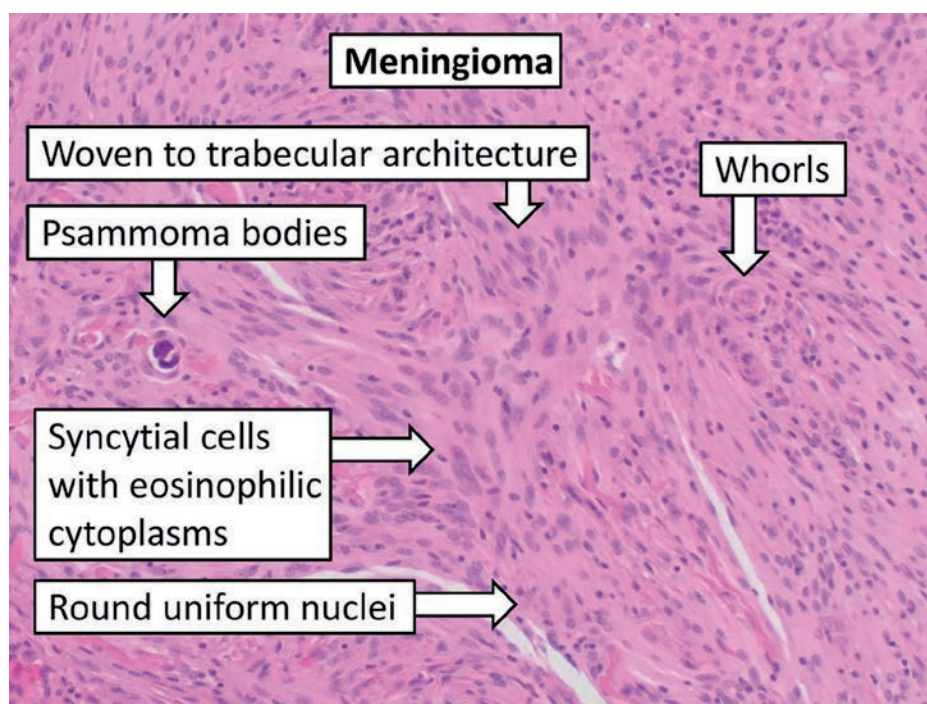


Figure 2.
 Photomicrographs illustrating the histological criteria for classic meningioma.

Grade III (anaplastic or malignant): This is the least common grade, accounting for approximately 1–3% of meningiomas, yet it is the most aggressive, with a high recurrence rate and potential for extracranial metastasis. Subtypes include anaplastic meningioma, papillary meningioma, and rhabdoid meningioma. These tumors are characterized by high mitotic activity, marked cellular atypia, and invasive growth patterns [5, 12].

4.3 Particularities in the pediatric population

In pediatric patients, meningiomas exhibit significant differences compared to those in adults:

- *Higher incidence of aggressive subtypes*: A greater proportion of grade II and III meningiomas is observed in children, indicating more aggressive behavior and a higher risk of recurrence (Table 2) [2, 12].

Grade	Pediatric population (%)	Adult population
Grado I	~80	~80–90%
Grado II	~17	<20%
Grado III	~3	~1

Table 2.
 Distribution comparison of meningioma grades between pediatric and adult populations.

- *Atypical locations:* In pediatric patients, meningiomas are more frequently found in uncommon sites such as the ventricular system and posterior fossa, in contrast to the typical parasagittal, convexity, or sphenoid ridge locations seen in adults [3].
- *Association with genetic syndromes:* There is a stronger correlation with neurofibromatosis type 2 (NF2) and other genetic alterations in the pediatric population, contributing to earlier onset and multifocal tumor presentation [2, 3].

5. Clinical presentation and characteristics

Pediatric meningiomas are rare, and their clinical presentation can vary widely depending on factors such as tumor location, size, and growth rate (see **Table 3**). Unlike adults, in whom meningiomas are often slow-growing and asymptomatic for prolonged periods, pediatric cases tend to present more aggressively, often with overt symptoms [2, 7]. Common clinical manifestations include:

- *Headache:* The most frequent symptom, present in up to 70% of pediatric cases, typically resulting from intracranial hypertension secondary to the tumor’s mass effect [13].
- *Seizures:* Frequently observed, particularly in tumors located on the cortical surface or convexity [13].
- *Focal neurological deficits:* Presentation varies by tumor location and may include motor weakness, sensory disturbances, or speech impairment [13].
- *Visual disturbances:* Tumors compressing the optic pathway or situated near the sellar region can lead to visual field defects or reduced acuity [13].
- *Signs of increased intracranial pressure:* Nausea, vomiting, and papilledema may signal elevated intracranial pressure [13].
- *Macrocephaly:* In infants and very young children, an increased head circumference may be an early indicator of an expanding intracranial mass [13].
- *Developmental delay:* In some cases, delayed milestones or regression may occur due to chronic neurological impairment [13].

Location	Common symptoms
Cerebral convexity	Headache, seizures
Skull base	Diplopia, hearing loss, dysphagia
Intraventricular region	Nausea, vomiting, lethargy
Posterior fossa	Ataxia, nystagmus, vertigo

Table 3.
Common symptoms of pediatric meningiomas according to location.

- *Endocrine disturbances:* Meningiomas affecting the hypothalamus or sella turcica may lead to hormonal dysregulation [13].
- *Personality or behavioral changes:* Involvement of the frontal lobes may result in altered behavior, personality shifts, or academic decline [13].

6. Imaging diagnosis

Imaging plays a central role in the initial assessment, characterization, and surgical planning of pediatric meningiomas. While clinical symptoms may raise suspicion, imaging modalities provide precise evaluation of tumor location, extent, vascular supply, relationship to critical neurovascular structures, and radiological features suggestive of histological grade [1].

6.1 Computed tomography (CT)

CT is useful for initial evaluation, particularly in emergency settings or when calcifications, hemorrhage, or bone involvement are suspected (**Figure 3**). Pediatric meningiomas on CT may present as:

- Hyperdense extra-axial lesions with homogeneous contrast enhancement
- Internal calcifications, which are more frequent in WHO grade I tumors
- Adjacent hyperostosis or bone erosion [2]

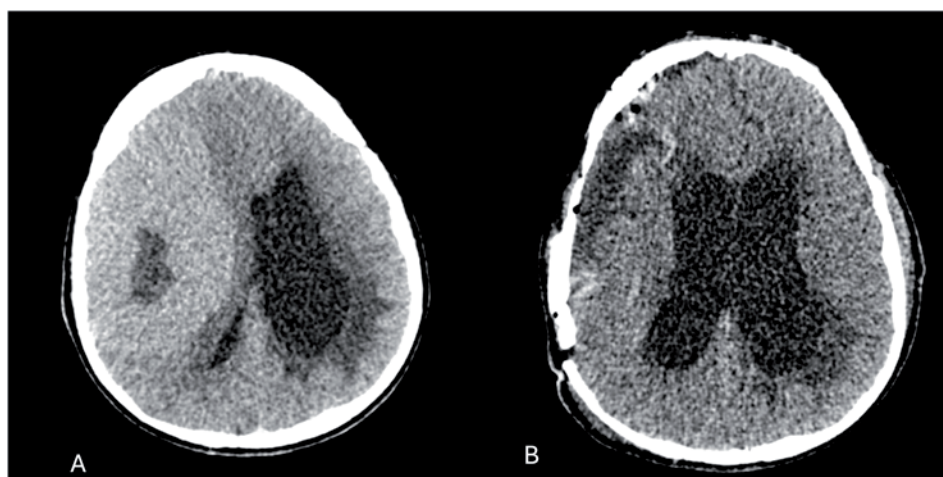


Figure 3.

A. CT scan of a 15-year-old male patient with a history of headache and left-sided hemiparesis for 3 months, who presented to the emergency department. A simple CT scan was performed, revealing an extra-axial hyperdense lesion with midline structure displacement and hydrocephalus. B. Post-surgical CT scan showing complete tumor resection.

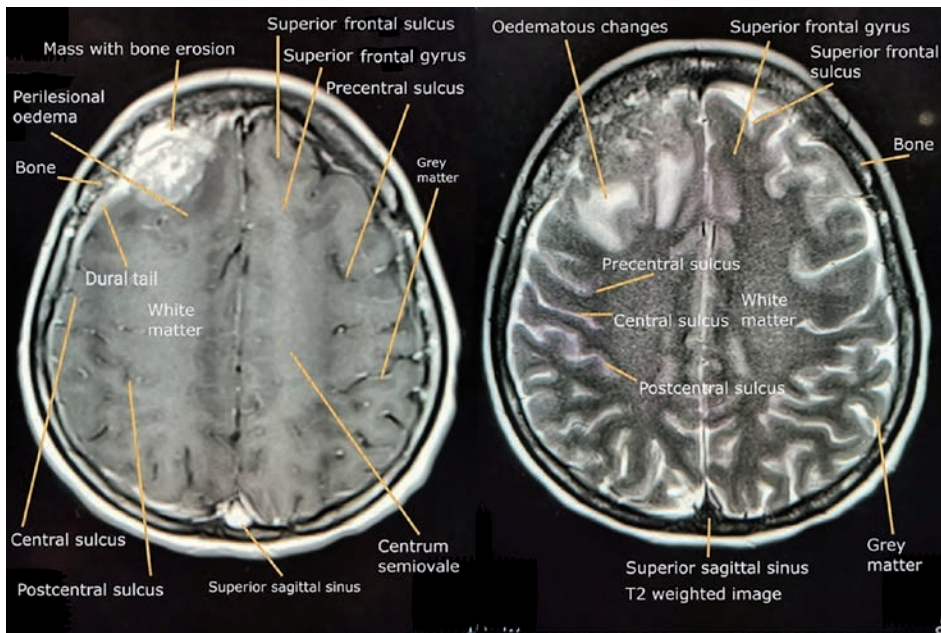


Figure 4.
Key features of meningiomas observed in MRI scans.

6.2 Magnetic resonance imaging (MRI)

MRI is the modality of choice for characterizing pediatric meningiomas, offering greater sensitivity for tumor detection and superior assessment of adjacent structure involvement (see **Figure 4**). Typical MRI features include:

- Isointensity or mild hypointensity on T1-weighted images
- Iso- to hyperintensity on T2-weighted images, depending on tumor cellularity and associated peritumoral edema
- Homogeneous post-contrast enhancement, often accompanied by the classic “dural tail” sign, in approximately 60–70% of cases
- Vasogenic edema surrounding the lesion, more common in high-grade tumors
- Evidence of parenchymal invasion, typically observed in WHO grade II or III meningiomas [3]

6.3 Complementary imaging studies

- *Magnetic resonance angiography (MRA) or digital subtraction angiography (DSA)*: Helpful for assessing tumor vascularization, particularly in skull base meningiomas or highly vascular lesions, and valuable when preoperative embolization is considered (**Figure 5**).
- *SPECT or brain PET*: Although not routinely used in the diagnostic workup, these functional imaging techniques may assist in evaluating tumor recurrence,

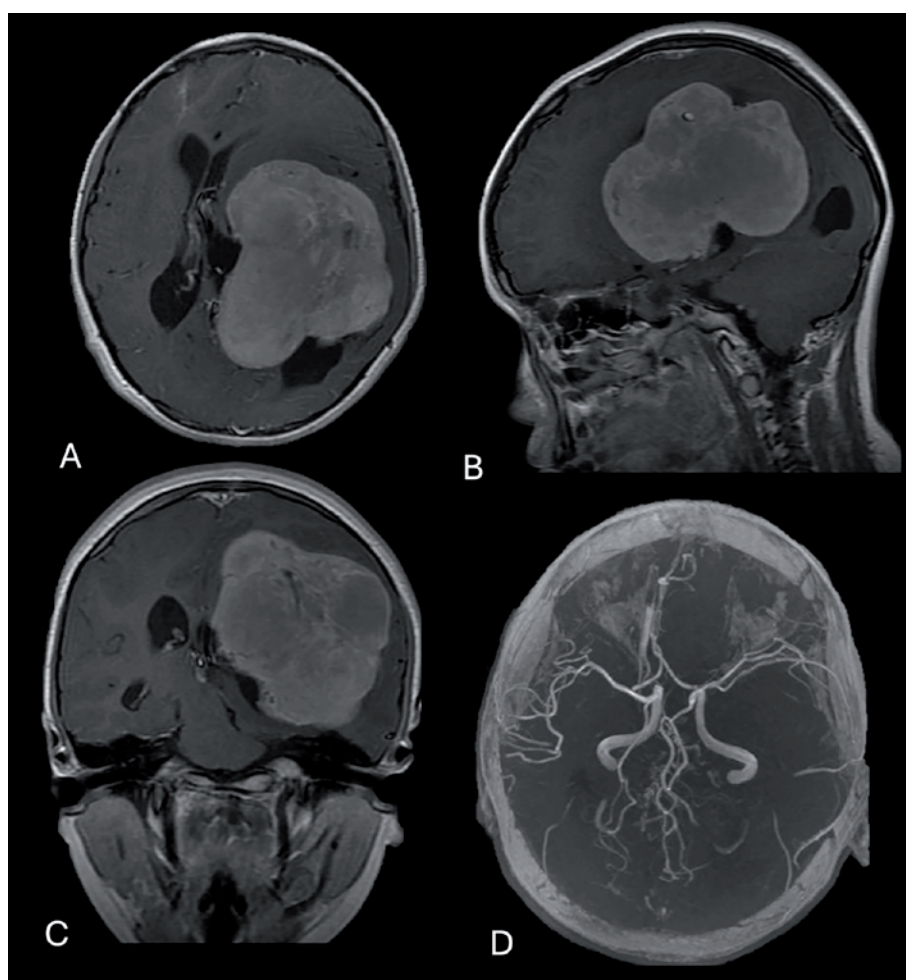


Figure 5.

A 15-year-old female patient presents with a left intraventricular meningioma. Imaging includes: A. Axial T1-weighted MRI with contrast showing the lesion in the left atrium. B. Sagittal section. C. Coronal view showing midline structure displacement. D. MR angiography revealing the middle cerebral artery displaced forward by the lesion. This case emphasizes the need for MR angiography in such diagnoses.

characterizing high-grade meningiomas, or distinguishing residual tumor tissue from postoperative scar [4].

6.4 Particularities in the pediatric population

Pediatric meningiomas can present in atypical locations such as the brain parenchyma, ventricles, paranasal sinuses, bones, or spinal canal, often lacking classic imaging features like the dural tail sign, which complicates radiologic diagnosis prior to surgery. In contrast, tumors located in typical sites such as the convexity or skull base tend to exhibit more recognizable imaging characteristics. Despite differences in location, no significant variations have been observed in age, sex, tumor grade, or histopathology between typical and atypical cases. Recognizing these atypical radiologic patterns is crucial to avoid misdiagnosis and ensure appropriate treatment in pediatric patients (see **Figure 6**) [5].

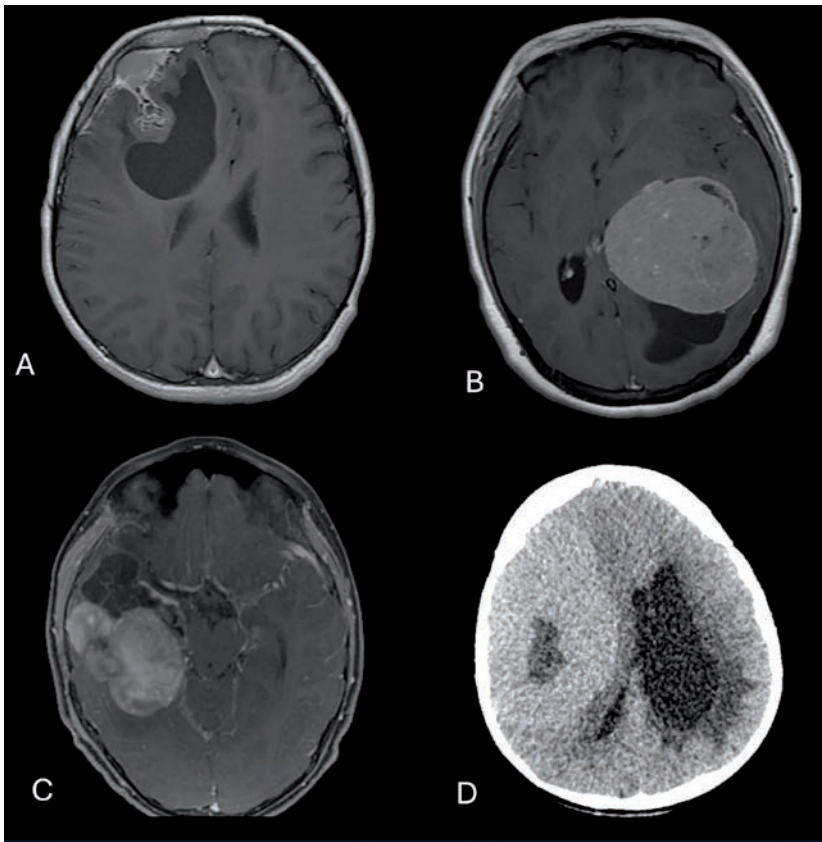


Figure 6. Pediatric meningiomas exhibit distinct locations and behaviors compared to those found in adults. The following are examples of pediatric meningiomas: A. Meningothelial and psammomatous meningioma in the orbit with cortical involvement. B. Meningothelial meningioma in the left ventricular atrium. C. Meningothelial meningioma in the tentorium accompanied by areas of encephalomalacia. D. Giant convexity meningioma with significant parenchymal involvement.

Lesion	key features
Astrocytoma	Intra-axial, no dural tail
Ependymoma	Intraventricular location, common calcifications
Brain abscess	Infectious symptoms, diffusion restriction on MRI
Hemangiopericytoma	Extra-axial, more aggressive, higher recurrence rate
CNS Lymphoma	Often, in immunocompromised hosts, it may mimic extra-axial mass

Table 4. Differential features for differential diagnosis.

7. Differential diagnosis

Differential diagnosis of meningiomas in the pediatric population is crucial due to the rarity of these tumors in children and the broad spectrum of intracranial lesions that can present with similar clinical and radiological features. Pediatric meningiomas often mimic

other entities, making an accurate distinction essential to guide appropriate management and prevent unnecessary surgical interventions. A thorough and precise diagnostic assessment is therefore critical for optimizing patient outcomes (see **Table 4**) [6].

8. Surgical treatment

Surgical treatment is the cornerstone of managing pediatric meningiomas. The primary objective is to achieve complete tumor resection while preserving neurological function and minimizing morbidity. Surgical planning should be guided by a comprehensive evaluation of the tumor's location, its relationship with critical neurovascular structures, and the patient's overall clinical status [7].

8.1 Preoperative considerations

- *Assessment of tumor extent:* Contrast-enhanced magnetic resonance imaging is essential to accurately determine the tumor's location, size, and its relationship with adjacent critical structures.
- *Surgical planning:* The choice of surgical approach should be individualized, prioritizing maximal tumor accessibility while minimizing the risk of injury to vital neurovascular structures.

8.2 Surgical techniques

- *Gross total resection (Simpson Grade I):* This involves complete removal of the tumor along with the affected dura mater and bone, and is associated with the lowest recurrence rates.
- *Subtotal resection:* When complete resection is not feasible due to infiltration of critical areas, subtotal resection is performed, followed by close radiological surveillance or adjuvant therapy depending on residual tumor behavior and histology [7].

8.3 Postoperative complications

- *Neurological deficits:* Depending on the tumor's proximity to eloquent areas, postoperative motor, sensory, or cranial nerve deficits may occur.
- *Infections:* Although uncommon, postoperative infections can occur; therefore, appropriate perioperative prophylaxis is essential.
- *Intracranial hemorrhage:* This is a rare but serious complication that necessitates close monitoring during the immediate postoperative period.

8.4 Long-term outcomes

Complete resection is associated with lower recurrence rates and more favorable functional outcomes in pediatric meningiomas. However, in cases involving high-grade tumors or incomplete resections, long-term prognosis depends on close clinical and

radiological follow-up, with consideration of adjuvant therapies such as radiotherapy or chemotherapy to reduce the risk of recurrence and improve overall outcomes [8].

9. Adjuvant therapies

Adjuvant therapies play a crucial role in the management of pediatric meningiomas, particularly when complete surgical resection is not achievable or in the presence of high-grade tumors. Radiotherapy is the most commonly employed modality in these scenarios, aiming to reduce the risk of recurrence and improve local control. Chemotherapy has a more limited role but may be considered in select cases, especially when dealing with refractory or progressive disease [9].

9.1 Radiotherapy

- *Indications:* Radiotherapy is primarily indicated in pediatric meningiomas of high grade (WHO grades II and III) or following subtotal resection when the risk of recurrence is elevated. Clinical studies have demonstrated that adjuvant radiotherapy can improve progression-free survival in these patients [10].
- *Techniques:* Several radiotherapy modalities are utilized, including three-dimensional conformal radiotherapy (3D-CRT), intensity-modulated radiotherapy (IMRT), and stereotactic radiosurgery (SRS). The selection of technique depends on factors such as tumor size, location, and proximity to critical neuroanatomical structures.
- *Considerations in children:* Due to the heightened sensitivity of the developing brain, radiotherapy in pediatric patients must be meticulously planned to minimize long-term neurocognitive and endocrinological side effects. Proton therapy has emerged as a favorable option, offering precise dose delivery with reduced radiation exposure to surrounding healthy tissues, thereby lowering the risk of late complications.

9.2 Follow-up and management of side effects

Close follow-up is essential to assess treatment response and to promptly detect disease recurrence or therapy-related complications. Pediatric patients undergoing radiotherapy require periodic evaluations to monitor for potential long-term side effects, including neurocognitive impairment, endocrinological dysfunction, and growth disturbances. Early identification and multidisciplinary management of these sequelae are critical to *optimizing* long-term outcomes and quality of life [12].

9.3 Immunotherapy

Recurrent WHO grade II and III meningiomas, which are frequently resistant to conventional treatments such as surgery and radiotherapy, may benefit from immune checkpoint inhibition targeting the PD-1/PD-L1 axis. Treatment with anti-PD-1 agents, including nivolumab and pembrolizumab, has demonstrated a median progression-free survival of 7 months and an overall survival of 1.75 years. Improved outcomes have been observed, particularly in patients with WHO grade III tumors and positive PD-1/PD-L1 expression, suggesting these biomarkers may serve as predictors of therapeutic response. Adverse effects were generally manageable, with symptomatic perilesional edema and

seizure exacerbations reported as the most common. These findings underscore the potential role of PD-1/PD-L1 inhibitors in select cases of aggressive meningioma, supporting the need for further evaluation in larger, prospective clinical trials [13].

10. Prognosis and long-term outcomes

The prognosis of pediatric meningiomas is influenced by several factors, including histological grade, extent of surgical resection, tumor location, and the presence of predisposing conditions such as neurofibromatosis type 2 (NF2) [1].

- *Histological grade:* Grade I (benign) meningiomas are associated with favorable outcomes, showing a 5-year survival rate exceeding 80% [2]. Grade II and III (atypical and anaplastic) meningiomas carry a significantly higher risk of recurrence and reduced overall survival. Recurrent grade III tumors, in particular, have a poor prognosis, with studies reporting a progression-free survival rate below 29% and an overall survival of approximately 71% at 6 months of follow-up [3].
- *Extent of surgical resection:* Complete tumor resection remains the most critical prognostic factor for achieving long-term remission in pediatric meningiomas. Gross total resection (Simpson Grade I) is associated with significantly lower recurrence rates compared to subtotal resections [4].
- *Predisposing conditions:* Patients with neurofibromatosis type 2 (NF2) have a higher risk of developing multiple and more aggressive meningiomas, which can adversely affect prognosis and complicate long-term management [1, 5].
- *Long-term outcomes:* While most children and adolescents with meningioma experience no or only mild long-term morbidity, approximately 25% of survivors may develop moderate to severe sequelae, particularly in cases of tumor recurrence or high-grade disease [6].

The most comprehensive survival analysis to date, encompassing over 1000 pediatric cases from 20 studies, confirmed that meningiomas in children exhibit a higher proportion of aggressive WHO grade II and III histologies compared to adults. The analysis identified neurofibromatosis—particularly NF2—as a key determinant of reduced progression-free survival. Notably, gross total resection (GTR) emerged as the most powerful predictor of both improved overall survival and decreased recurrence, regardless of tumor grade. Radiotherapy demonstrated significant benefit only in grade III tumors, supporting its selective application in high-risk cases. These findings highlight the critical importance of pediatric-specific treatment strategies that emphasize complete resection and rigorous long-term surveillance, particularly in patients with genetic predispositions or high-grade disease [6].

11. Experience of National Institute of Pediatrics

The experience at the National Institute of Pediatrics was analyzed for the period from March 1, 2019, to February 28, 2020. Data were collected from 26 pediatric

Population characteristics	n = 26	%
Sex		
Female	14	53.85
Male	12	46.15
Laterality		
Right	12	46.15
Left	4	15.38
Midline	9	34.62
Multiple	1	3.85
Location		
Convexity	6	23.08
Falx/parafalx	3	11.54
Sphenoidal plane	2	7.69
Intraventricular	3	11.54
Spinal	5	19.23
Foramen magnum	1	3.85
Pontocerebellar angle	2	7.69
Sphenoidal	3	11.54
Tentorial/falx-tentorial	1	3.85
Tumor type		
Meningothelial	6	23.08
Meningothelial and fibrous	3	11.54
Meningothelial, fibrous, and transitional	1	3.85
Meningothelial and microcystic	1	3.85
Fibrous and metaplastic	1	3.85
Transitional	5	19.23
Psammomatous	1	3.85
Clear cells	5	19.23
Anaplastic	2	7.69
Rhabdoid and papillary	1	3.85
Malignancy grade		
I	0	0
II	19	73.08
III	7	26.92
Epilepsy		
No	20	76.92
Yes	6	23.08
NF1		
No	26	100

Population characteristics	n = 26	%
Yes	0	0
NF2		
No	23	88.46
Yes	3	11.54
Surgery		
Biopsy	1	3.85
Subtotal resection (Simpson grade III-V)	12	46.15
Total resection (Simpson grade I-II)	13	50.00
Reintervention		
No	23	88.46
Yes	3	11.54
Postoperative Lansky		
30	1	4.17
40	7	29.17
60	1	4.17
70	4	16.67
80	5	20.83
100	6	25.00
Adjuvant therapy		
No	17	65.38
Yes	9	34.62
Tumor recurrence		
No	24	92.31
Yes	2	7.69

Table 5.

Characteristics of pediatric meningiomas: experience of the national institute of pediatrics.

patients with histopathologically confirmed meningiomas. The median age of the participants was 13 years, with an interquartile range of 7–15 years. The youngest patient was 1 year old, and the oldest was 17. The follow-up period had a median duration of 72 months, ranging from a minimum of 5 months to a maximum of 156 months (**Table 5**).

The majority of patients were female, representing 53.8% of cases. Radiological studies showed that the right hemisphere was the most commonly affected, observed in 46.1% of patients, with the convexity being the most frequent tumor location (23.1%), followed by the spinal regions (19.2%). The meningioepithelial variant was the most prevalent tumor type, identified in 23.1% of cases; however, mixed variants—comprising combinations with fibrous, transitional, or microcystic components—were also noted. Most tumors were classified as WHO grade II, accounting for 73.1% of the cohort. Additionally, three patients were diagnosed with neurofibromatosis type 2 (NF2).

Total resection (Simpson grade I–II) was the most common surgical approach, performed in 50% of cases. Reintervention was required in 11.5%, adjuvant therapy

was administered to 34.6%, and tumor recurrence occurred in 7.7% of patients. During the study period, two deaths were recorded at 5 and 6 months post-diagnosis, and two recurrences were documented at 12 and 36 months. Survival analysis demonstrated that by 12 years, the probability of survival exceeded 75%.

12. Surgical advances and technologies in pediatric meningiomas

Surgical resection remains the cornerstone of treatment for pediatric meningiomas. Unlike in adults, these tumors in children often arise in atypical and surgically challenging locations—such as the ventricular system, skull base, or posterior fossa—and are frequently associated with higher-grade histologies. As a result, the surgical approach in pediatric patients must be individually tailored, carefully balancing the goal of maximal tumor resection with the need to preserve neurocognitive, endocrine, and neurological function.

12.1 Goals of surgical management

The primary surgical objective in pediatric meningiomas is to achieve a gross total resection (GTR), as this remains the most significant prognostic factor for reducing recurrence and improving long-term survival. However, in pediatric populations, the definition of GTR must be applied with greater nuance, given the heightened importance of preserving neurological, cognitive, and endocrine function.

Subtotal resection (STR) may be appropriate in selected cases, particularly when:

- The tumor is adherent to vital structures such as the brainstem or cranial nerves.
- There is involvement of deep ventricular anatomy or critical vascular territories.
- Preexisting neurological deficits are present, and further resection may significantly compromise quality of life.

Surgical decision-making is increasingly informed by multidisciplinary tumor boards, incorporating the expertise of neurosurgeons, pediatric oncologists, neuroradiologists, and anesthesiologists to ensure individualized, patient-centered care.

12.2 Preoperative planning and neuroimaging integration

Advances in preoperative imaging have become essential for accurately delineating tumor boundaries and identifying critical anatomical structures. The use of diffusion tensor imaging (DTI) and tractography enables visualization of white matter tracts, particularly those involved in motor and language functions. Functional MRI (fMRI) assists in localizing eloquent cortical areas, thereby guiding safer surgical trajectories. Volumetric MRI reconstructions enhance spatial understanding of tumor relationships in anatomically complex regions such as the ventricular system or skull base. These imaging modalities are indispensable for designing surgical corridors that minimize postoperative neurological deficits and play a vital role in preoperative parental counseling, where visual tools support informed discussions about surgical risks and anticipated outcomes.

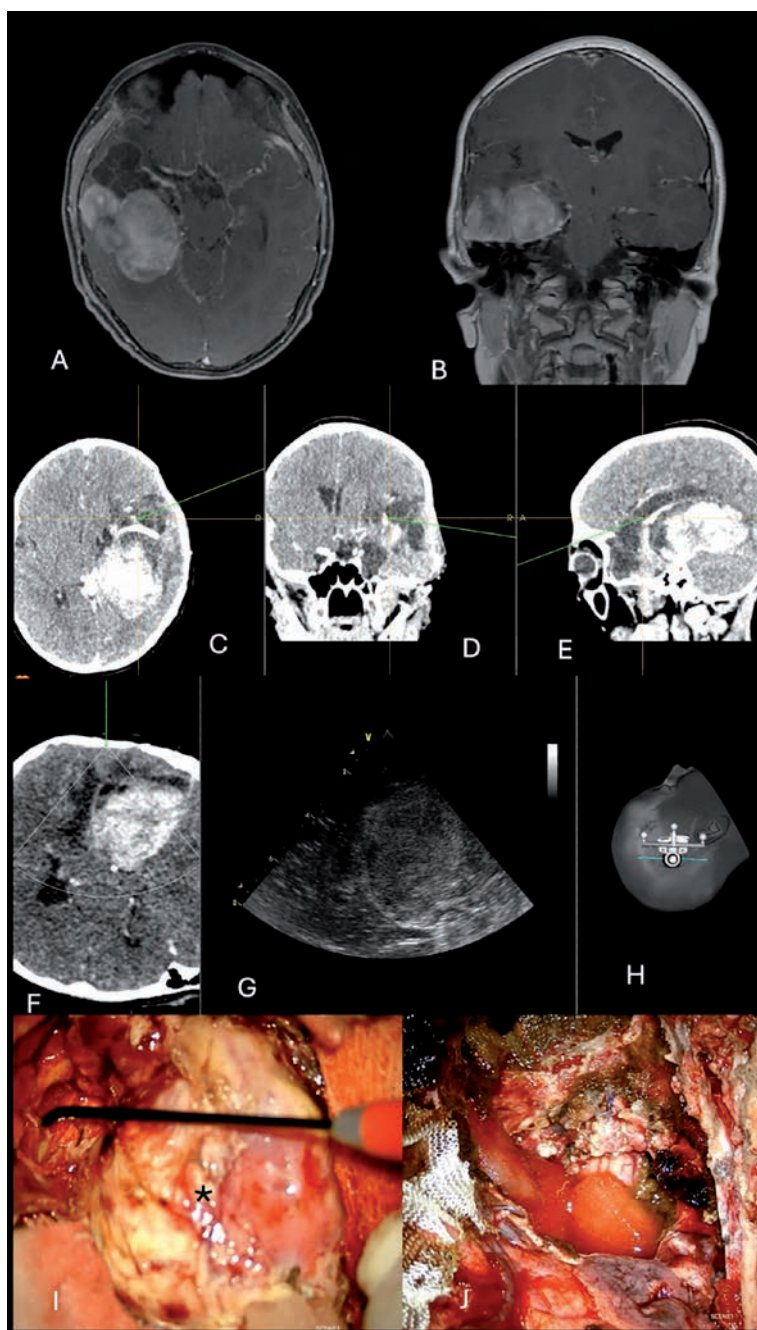


Figure 7.

A 13-year-old male patient presented with a right-sided tentorial meningioma. (A) A T₁-weighted MRI with contrast reveals a heterogeneously enhancing lesion located in the tentorium, which exerts a mass effect on the midbrain. (B) A coronal T₁-weighted MRI with contrast further emphasizes the lesion. During the surgery, neuronavigation was employed to visualize the tentorial lesion in axial (C), coronal (D), and sagittal (E) views. Intraoperative ultrasound was used alongside neuronavigation (F), as illustrated in image (G), which shows the meningioma on ultrasound and the orientation of the transducer (H). The surgical microscope displayed the lesion, indicated by an asterisk, and monopolar stimulation was performed to identify the corticospinal tract. (J) Complete resection of the lesion was successfully achieved.

12.3 Intraoperative technologies

Modern pediatric neurosurgical centers rely on a comprehensive array of intraoperative tools to enhance surgical safety, precision, and efficacy. Neuronavigation systems provide real-time spatial orientation by integrating preoperative imaging datasets, enabling accurate localization and trajectory planning. Intraoperative MRI (iMRI) is particularly valuable for evaluating the extent of resection during surgery, especially in deep-seated or poorly visualized tumors. Ultrasound guidance, while more readily available, also aids in intraoperative identification of tumor margins (see **Figure 7**). Electrophysiological monitoring—including motor evoked potentials, somatosensory evoked potentials, and direct cortical stimulation—has become standard in procedures involving motor, sensory, or cranial nerve pathways, helping to preserve neurological function. Endoscopic assistance is increasingly employed in the resection of ventricular meningiomas, offering minimally invasive access and enhanced visualization in narrow operative corridors. Fluorescence-guided surgery, using agents such as 5-aminolevulinic acid (5-ALA) or fluorescein sodium, is currently under investigation for pediatric meningiomas with anaplastic features or indistinct margins; however, its use in children remains off-label and requires further validation.

12.4 Surgical approaches for complex locations

12.4.1 Intraventricular meningiomas

Intraventricular tumors, which are more frequently observed in pediatric patients than in adults, commonly arise near the trigone of the lateral ventricles. These lesions may lead to hydrocephalus or elevated intracranial pressure due to obstruction of cerebrospinal fluid (CSF) pathways.

Surgical approaches include:

- *Transcortical transventricular route*: Offers direct access to the tumor but carries a risk of cortical disruption and postoperative seizures (**Figure 8**).
- *Interhemispheric transcallosal route*: Preferred for midline or deep-seated lesions; it minimizes cortical injury but poses a risk of callosal disconnection syndromes.

The choice of surgical approach is determined by factors such as tumor size, location, lateralization, and proximity to eloquent cortical regions. Preoperative neuroimaging and functional mapping are essential for selecting the safest and most effective route.

12.4.2 Skull base and posterior fossa meningiomas

Meningiomas located in the skull base and posterior fossa present significant surgical challenges and require highly specialized approaches tailored to the lesion's anatomical location.

Retrosigmoid, far lateral, or petrosal approaches are commonly employed for posterior fossa or petroclival meningiomas, providing access to the cerebellopontine angle and ventral brainstem while minimizing neurovascular injury.

Endonasal endoscopic approaches are being increasingly explored for anterior skull base lesions in select pediatric cases, offering a minimally invasive route with reduced surgical morbidity and improved cosmetic outcomes.

Microsurgical techniques, enhanced by high-definition optics and angled instrumentation, are essential for safely navigating the narrow and complex anatomical corridors characteristic of these regions. Careful preoperative planning and intra-operative neurophysiological monitoring are critical to maximize resection while preserving neurological function.

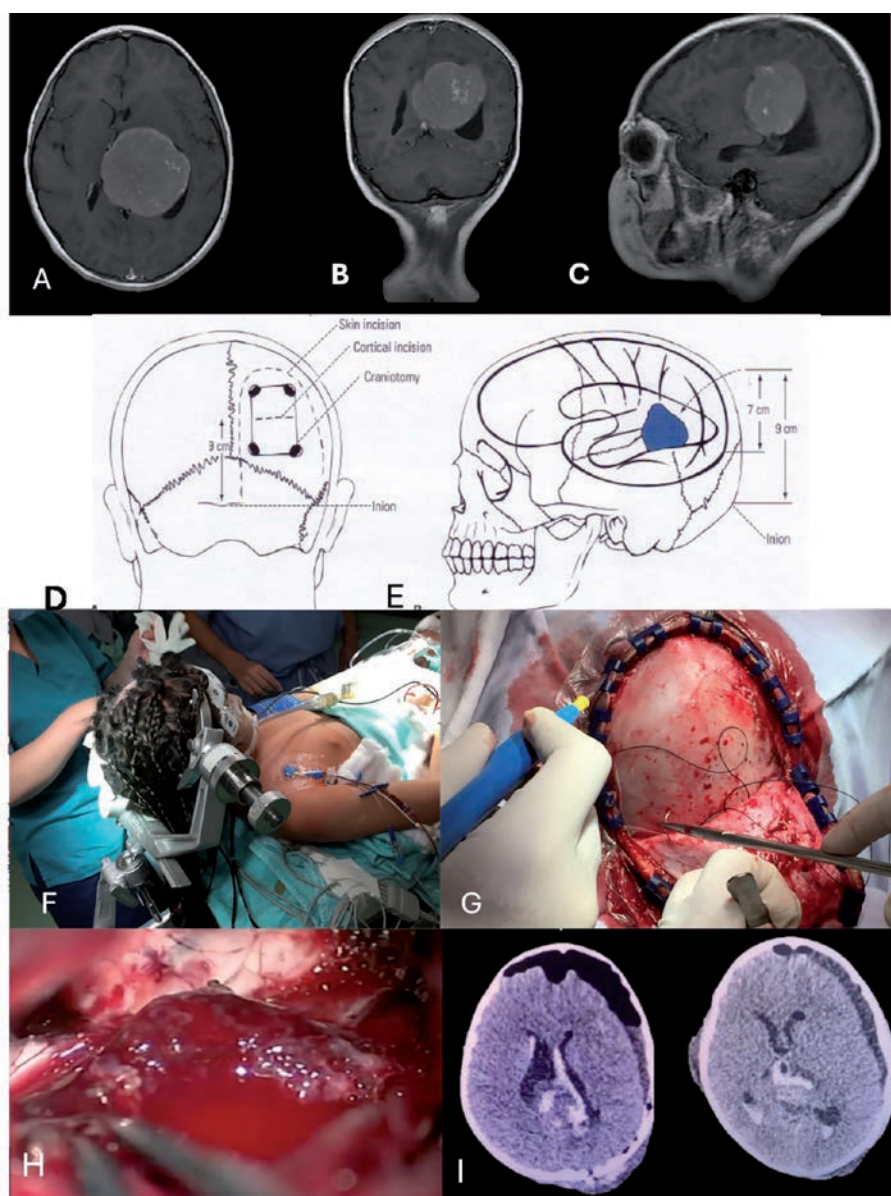


Figure 8.

The image shows an intraventricular meningioma in an 8-year-old female patient. The MRI reveals the intraventricular lesion in axial (A), coronal (B), and sagittal (C) T1-weighted images with contrast. Surgery is planned, which will involve an occipital craniotomy (D and E). The patient will be positioned in a semi-sitting posture (F). A horseshoe-shaped incision will be made, and the skull will be exposed (G) to perform the craniotomy. Under the surgical microscope, the vascularized lesion is visible within the ventricular atrium (H). Postoperative CT scan (I) shows complete resection of the lesion, along with a small amount of blood remaining in the surgical bed.

12.5 Postoperative considerations and complications

While the pediatric brain demonstrates a remarkable degree of plasticity, it is also more susceptible to surgical insult, necessitating careful postoperative management. Common complications include:

- *Cerebrospinal fluid (CSF) leaks*, particularly following skull base resections, which may require lumbar drainage or surgical repair.
- *Hydrocephalus*, either preexisting or postoperative, which may necessitate ventriculoperitoneal shunt placement.
- *Endocrine dysfunction*, especially in cases involving hypothalamic or parasellar tumors, requiring long-term hormonal monitoring and replacement therapy.
- *Neurological deficits*, such as cranial nerve palsies or hemiparesis, depending on tumor location and surgical manipulation.

Routine postoperative MRI within 24 to 48 hours is recommended to evaluate the extent of resection, identify early complications, and establish a baseline for future surveillance imaging.

12.6 Extent of resection and recurrence risk

Multiple studies have demonstrated a strong correlation between the extent of resection and progression-free survival (PFS) in pediatric meningiomas [1, 2]. However, even in cases of gross total resection (GTR), recurrence remains a significant concern, particularly in tumors classified as WHO grade II or III [1]. In instances of subtotal resection, the decision between adjuvant radiotherapy and close surveillance should be guided by factors such as patient age, tumor histology, and molecular profile [2].

While the Simpson grading system continues to be referenced, its predictive utility is limited in pediatric populations due to distinct anatomical constraints and biological tumor behavior. As a result, emerging prognostic models are increasingly incorporating the extent of resection alongside molecular and imaging biomarkers to more accurately predict recurrence risk and long-term outcomes [1].

13. Conclusions

Pediatric meningiomas represent a rare yet clinically and biologically distinctive subset of central nervous system (CNS) tumors. Their management poses unique challenges that differ fundamentally from those encountered in adult populations. These tumors are characterized by a higher prevalence of WHO grade II and III histologies [2], atypical anatomical locations [7], and stronger associations with hereditary syndromes such as neurofibromatosis type 2 (NF2) and SMARCE1-related familial meningiomatosis [8]. Consequently, they require individualized, multidisciplinary treatment strategies informed by modern neuro-oncological principles and tailored to the specific needs of the pediatric population.

One of the defining challenges in pediatric meningiomas is balancing oncological control with the preservation of neurodevelopment. Unlike adults, children have a

long life expectancy following tumor treatment and are in a critical period of cognitive, emotional, and physical development. As such, the impact of surgical, pharmacologic, or radiotherapeutic interventions must be carefully weighed not only in terms of tumor-recurrence risk but also with regard to long-term functional outcomes, including cognitive performance, hormonal integrity, and overall quality of life.

The cornerstone of treatment remains maximal safe surgical resection, which offers the greatest prognostic benefit [4, 6]. Advances in neuroimaging, intraoperative navigation, and electrophysiological monitoring have increasingly enabled gross total resection even in anatomically complex locations while minimizing surgical morbidity. In cases involving surgically challenging tumors or those with high-grade or recurrent behavior, adjunctive modalities such as proton-beam radiotherapy [9] and emerging targeted or immune-based therapies [10] offer promising alternatives that help preserve healthy tissue and neurological function.

The incorporation of molecular biology and genetic profiling into clinical decision-making is rapidly transforming the classification and therapeutic strategies for pediatric meningiomas. Genetic alterations—such as those in NF2, SMARCE1, SUFU, and chromatin-remodeling genes—are reshaping the diagnostic landscape, enabling precision-medicine approaches and paving the way for biologically targeted therapies [8, 11–13]. However, these strategies remain largely investigational in the pediatric setting, highlighting the urgent need for dedicated clinical trials to evaluate their efficacy and safety in children. Furthermore, recent advances in artificial intelligence and radiogenomics point toward a future in which non-invasive diagnostics, risk stratification, and surgical planning are enhanced by machine-learning tools trained on multimodal datasets; although still exploratory, consensus reviews already underline their potential to predict tumor behavior, recurrence risk, and treatment response, guiding clinicians toward more personalized, evidence-based care for each pediatric patient [9].

Yet, despite these advances, significant gaps persist. There is a notable lack of high-quality, long-term data on functional outcomes, neurocognitive effects, and psychosocial development in children treated for meningiomas. The rarity of the disease, combined with the heterogeneity of treatment approaches across institutions, hampers the ability to draw definitive conclusions or establish standardized guidelines. To overcome these limitations, the development of international registries, collaborative consortia, and multi-institutional studies is essential to consolidate clinical experience and generate robust, generalizable evidence that can inform best practices in pediatric meningioma care.

In summary, the care of pediatric meningioma patients is undergoing a paradigm shift from histology-based algorithms to biology-informed, precision-guided models of treatment. This evolution is driven by advancements in surgical technology, neuroimaging, molecular diagnostics, and multidisciplinary collaboration. Clinicians must aim not only for tumor control and survival but also for the preservation of the child's long-term potential—academic performance, social development, emotional well-being, and independence. Through continued research, global collaboration, and a steadfast commitment to excellence in pediatric neuro-oncology, it is possible to offer children with meningiomas not just extended survival, but the opportunity for a full and meaningful life.

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Management of Intracerebral Meningiomas in the Elderly

Collignon Frederic, Hentati Karim and Perano Francesco

Abstract

Is Management of meningiomas in the elderly different? It is important to evaluate what is the best management for elderly patients harboring intracerebral meningiomas. Indeed, Life expectancy is increasing, and more patients will be diagnosed with meningiomas. Does surgical management still have a place? What are the factors that will lead to the decision of surgical management? Defining radiological parameters that will predict potential growth and evaluating ratio risk/benefit in the management of this disease seem to be valuable. The goal of this chapter is to define an algorithm that will help neurosurgeons to improve the management of this growing pathology.

Keywords: meningioma, elderly, management, surgery, conservative, complication, prognosis

1. Introduction

Meningiomas are one of the most frequently encountered primary intracranial neoplasms in adults, comprising roughly one-third of all central nervous system tumors. Their incidence rises steeply with advancing age—from approximately 1–1.5 per 100,000 person in young adults aged 24 to 30 years, around 30 per 100,000 person in elderly patients (over 65 years old) to well over 50 per 100,000 in those older than 85 [1]—reflecting both a true age-related predilection and the widespread use of high-resolution neuroimaging. Indeed, as patients live longer due to enhanced medical care worldwide and neuroimaging becomes more sensitive, the detection of both symptomatic and incidental intracranial meningiomas has increased, creating a rising need for neurosurgical intervention—especially among older individuals.

Surgery remains the cornerstone of management for symptomatic, rapidly enlarging, or high-grade meningiomas, with the aspiration of achieving Simpson grade I–II resection to optimize long-term control. Yet in elderly patients over 65—and especially those aged 80 and above—comorbidities, reduced physiologic reserve, and challenging tumor locations (notably skull base and bone-invasive lesions) often limit the extent of safe resection. Reported perioperative mortality rates in elderly cohorts vary widely (0–45%), and complication rates may reach nearly 40% [2–6]. Very-old patients experience a 2.5-fold excess mortality in the first postoperative year

compared to age- and sex-matched peers, although long-term survival converges by the second year. Preoperative functional dependency and tumor characteristics have emerged as predictors of incomplete resection and delayed return to independent living [7].

These observations have fostered a more nuanced, individualized treatment paradigm in the elderly. Subtotal resection followed by adjuvant radiotherapy or stereotactic radiosurgery may better balance disease control with safety when gross-total removal is deemed unsafe. Conversely, active monitoring for incidental, asymptomatic meningiomas—typically over a five-year horizon—can spare frail patients from operative risk; yet untreated lesions with documented growth carry a higher tumor-related mortality, and delayed intervention may still lead to significant neurological morbidity.

Despite growing evidence, no consensus guidelines address the unique needs of elderly meningioma patients. Predictive models based on age, performance status, imaging features, and tumor location hold promise for tailoring the anticipated extent of resection and perioperative risk. In this chapter, we synthesize epidemiological trends, pathological insights, and outcome data for intracerebral meningiomas in patients aged 65 and above—with a special focus on those over 80—to delineate prognostic factors for surgical success, examine the role of adjuvant therapies, and appraise surveillance strategies. We aim from this research to provide a practical, evidence-based framework for optimizing care in this growing and uniquely vulnerable population.

2. Epidemiology through population and risk factors

The overall occurrence of meningiomas varies between 5 and 12 new cases per 100,000 person-years in Western populations such as Europe, the UK, and the USA [1]. This rate is negligible in children and young adults but begins to rise significantly beyond the fifth decade of life. In individuals aged 65–69 years, incidence rates approximate 25–30 per 100,000, increasing to over 50 per 100,000 among those aged 85 and above [1, 8]. The aging of global populations, combined with more widespread and sophisticated imaging technologies, has led to a steady rise in diagnosed cases—particularly in elderly cohorts.

This increase, however, is not solely attributable to biological incidence. Longitudinal data show that much of the observed rise reflects enhanced detection of small, asymptomatic meningiomas discovered during neuroimaging for unrelated complaints [1]. Histopathologic confirmation rates have remained relatively constant, suggesting a stable underlying tumorigenesis rate but a higher frequency of radiological identification. For instance, more than 30% of elderly patients undergoing brain MRI for unrelated reasons may show small, incidental meningiomas [1].

From a histological standpoint, the vast majority of meningiomas (approximately 80–90%) are classified as WHO Grade I (benign), while 15–20% fall under the atypical Grade II category, and fewer than 5% are considered malignant or anaplastic (Grade III) [1, 9]. Though early studies hinted at a potential increase in atypical and anaplastic meningiomas in older adults, recent data suggest that the relative risk remains low and inconsistently observed. It is worth noting, however, that even histologically benign meningiomas can cause significant morbidity in the elderly due to mass effect, peritumoral edema, or compression of critical structures.

Sex-based disparities are also evident. Women are approximately twice as likely as men to develop meningiomas, a difference attributed to hormonal influences including estrogen and progesterone receptor expression [10]. Interestingly, this female predominance intensifies with age but becomes less pronounced in malignant subtypes. The role of sex hormones is supported by data showing an association between hormone replacement therapy (HRT) and elevated meningioma risk, particularly in women using estrogen-only regimens [10]. Still, evidence remains mixed regarding whether hormone receptors directly influence tumor growth or are simply correlative biomarkers.

In addition to hormonal factors, several other risks have been identified. Exposure to therapeutic cranial radiation, even decades earlier in life (e.g., for childhood cancers), significantly increases the risk of meningioma, especially in the context of high cumulative radiation doses and large treatment volumes [11]. Obesity has also emerged as a possible risk factor, particularly in postmenopausal women, although the biological mechanisms underlying this association are not fully understood [11].

Genetic factors, such as mutations in the NF2 gene, are more commonly implicated in early-onset or familial meningiomas but appear to play a less significant role in elderly cases. Conditions like neurofibromatosis type 2 (NF2) remain well-established predisposing syndromes, though their relevance diminishes in the geriatric population due to earlier age at onset and different tumor biology [11].

Finally, racial and ethnic disparities have been noted in several large epidemiologic cohorts. Data from the Central Brain Tumor Registry of the United States (CBTRUS) reveal that Black individuals have a higher incidence of nonmalignant meningiomas compared to White, Hispanic, or Asian populations [8]. Additionally, survival data stratified by race, sex, and tumor grade suggest that elderly Black males experience worse outcomes than their non-Black counterparts, independent of treatment modality or access to care [8].

In sum, the epidemiological landscape of meningiomas in the elderly is shaped by an interplay of demographic shifts, improved imaging sensitivity, and evolving recognition of hormonal, environmental, and genetic risk factors. These variables underscore the importance of tailoring both surveillance and treatment strategies to the unique profiles of older patients diagnosed with intracranial meningiomas.

3. Diagnostic challenges and patient selections

3.1 Defining elderly patients and risk elements

In the context of meningioma management, defining what constitutes an “elderly” patient remains a point of debate. The absence of a universally accepted age threshold introduces significant variability in the literature and in clinical practice. While age 65 has traditionally marked the boundary for older adults in general medicine [1, 6–8, 12, 13], more recent studies in neurosurgical populations often set the threshold for elderly meningioma patients between 70 and 75 years [14]. Notably, in a recent survey conducted by the Italian Society of Neurosurgery (SINch®), approximately 67% of participating clinicians considered individuals above 70 years as elderly in the neurosurgical setting.

However, emerging evidence points to the need for distinguishing patients over 80 as a separate, highly vulnerable subgroup due to their increased frailty and diminished physiological reserves, which can critically influence perioperative outcomes.

Several clinical series have demonstrated disproportionately higher morbidity and mortality in this subgroup, even when adjusting for comorbidity burden and tumor characteristics [7].

To address the complexity of treating this diverse age group, several preoperative scoring systems have been proposed to aid clinical decision-making. These include the Clinical Radiological Grading System (CRGS), the Geriatric Scoring System (GSS), the Charlson Comorbidity Index (CCI), and the SKALE score [15, 16]. Each of these models attempts to predict surgical outcomes by integrating clinical and radiological variables relevant to elderly neurosurgical patients.

However, these tools vary widely in their design and scope. The CCI, while widely used in internal medicine, fails to capture tumor-specific variables such as volume, location, or degree of peritumoral edema. The SKALE score—incorporating sex, Karnofsky Performance Status (KPS), American Society of Anesthesiologists (ASA) score, tumor location, and presence of edema—offers a more tailored neurosurgical framework. Nevertheless, it still lacks critical inputs such as tumor size and preoperative neurological deficits.

Moreover, none of the commonly applied scoring systems currently incorporate patient sex as a modifying factor, despite accumulating evidence that sex hormones and gender-specific immunological differences may influence both tumor biology and treatment response. Additionally, these models largely omit geriatric-specific variables such as frailty indices, cognitive reserve, or socioeconomic conditions—all of which can materially impact postoperative function and quality of life.

Given these limitations, a more unified and comprehensive risk stratification model is needed. Such a framework should incorporate biological and chronological age, functional and cognitive baseline, imaging-based tumor characteristics, and relevant geriatric parameters.

Ultimately, defining elderly patients for the purpose of meningioma treatment should not rely on an arbitrary age cutoff but rather adopt a multidimensional lens. A multidisciplinary team approach—integrating input from neurosurgery, geriatrics, anesthesiology, radiology, and rehabilitation—remains essential in tailoring personalized, evidence-based management plans.

3.2 Modalities of diagnostic and clinical symptoms

In elderly patients, the diagnostic process for intracerebral meningiomas is often complicated by comorbidities, atypical symptom presentation, and overlapping degenerative neurological conditions. Clinical manifestations in this age group may be subtle or misattributed to normal aging or other chronic pathologies. Common symptoms include cognitive decline, gait disturbances, seizures, focal neurological deficits, or signs of increased intracranial pressure such as headache and nausea. However, many elderly patients harboring meningiomas are asymptomatic at diagnosis, with lesions discovered incidentally during neuroimaging for unrelated complaints such as falls or confusion [17, 18].

Magnetic resonance imaging (MRI) remains the gold standard for meningioma detection and characterization. MRI provides superior soft-tissue contrast, enabling precise delineation of tumor margins, peritumoral edema, and mass effect on adjacent brain structures. Typical imaging findings include extra-axial location, isointensity to gray matter on T1- and T2-weighted images, and homogeneous contrast enhancement with dural tail sign. In cases of suspected atypical or anaplastic meningioma, advanced imaging modalities such as MR spectroscopy, perfusion-weighted

imaging, and diffusion tensor imaging may aid in differentiating high-grade tumors and predicting proliferative behavior [19].

Computed tomography (CT), while less sensitive for soft-tissue contrast, remains valuable in the emergency setting and for identifying calcifications, hyperostosis, and osseous involvement—particularly relevant in elderly patients with skull base or bone-invasive lesions. CT is also often the first imaging obtained in acute presentations with altered mental status or stroke-like symptoms, which may be the initial clinical indicator of an underlying meningioma [20].

Electroencephalography (EEG) may be employed in cases presenting with new-onset seizures, while functional imaging techniques, such as PET with somatostatin analog tracers (e.g., 68Ga-DOTATATE), are gaining traction in selected centers for differentiating meningiomas from other extra-axial masses and in planning radiosurgical treatment [20].

The diagnostic workup must also include a comprehensive geriatric assessment to contextualize imaging findings within the broader clinical status of the patient. Baseline cognitive function, gait stability, comorbidity burden, and functional reserve significantly influence both treatment planning and prognosis.

3.3 Criteria of patient selections

Selecting elderly patients for intracerebral meningioma treatment necessitates an individualized and multidimensional assessment. The elderly population is highly heterogeneous, encompassing both active septuagenarians and frail nonagenarians with limited physiological reserves. Therefore, treatment candidacy must go beyond simple chronological age and incorporate a combination of functional, cognitive, anesthetic, and tumor-specific factors.

Functional baseline and frailty are key determinants in surgical eligibility. Widely used tools such as the Karnofsky Performance Status (KPS) and the American Society of Anesthesiologists (ASA) physical classification provide a first layer of functional evaluation. Frailty indices, including the Clinical Frailty Scale and the Modified Frailty Index, offer an additional predictive value regarding recovery capacity and complication risk [20]. Of particular utility is the SKALE score, which integrates five parameters—sex, KPS, ASA score, tumor location, and peritumoral edema—to generate a composite risk score. Patients scoring ≥ 8 on SKALE are more likely to benefit from surgical intervention with reduced perioperative morbidity and improved functional recovery [15].

Tumor-related factors are equally influential. Meningiomas located on the convexity or parasagittal regions are more accessible and less likely to result in functional deficits, making them more favorable for surgery. In contrast, skull base tumors, particularly those involving neurovascular structures or bone infiltration, present higher surgical risk and may prompt consideration of subtotal resection or radiosurgical alternatives [14].

Preoperative assessments should also consider cognitive and functional status through tools such as the Montreal Cognitive Assessment (MoCA) and the Barthel Index, which can help determine whether patients have sufficient cognitive reserve and autonomy to tolerate surgery and recover postoperatively [20]. These tools also help align expectations with the patient's baseline status, fostering better communication with family and caregivers.

Despite the existence of multiple scoring systems, real-world variability in defining surgical candidacy persists. No universal threshold or model has achieved

full consensus across institutions. The multidisciplinary tumor board model is therefore vital, allowing input from neurosurgeons, geriatricians, anesthesiologists, radiologists, and oncologists to contextualize both risks and potential benefits. This team-based decision-making structure is particularly beneficial for borderline cases or when conflicting variables—such as a high tumor burden in a patient with otherwise good function—complicate standard decisions [14].

Ultimately, the objective is not to withhold surgery based on age but to carefully identify which elderly patients are most likely to benefit—maximizing autonomy and quality of life while minimizing unnecessary risk and invasive overtreatment. A clear, consistent, and patient-centered decision framework remains essential in addressing this growing patient population.

4. Management alternatives

4.1 Conservative approach: Wait and see

4.1.1 Clinical and imagistical elements

In elderly patients with incidentally discovered or minimally symptomatic meningiomas, conservative management via close observation is increasingly recognized as a valid and often preferred strategy. This is especially pertinent when tumor characteristics suggest a benign course and when comorbidities or frailty render surgical intervention high risk. Age-related physiological decline, polypharmacy, and reduced rehabilitation capacity all contribute to making “wait and see” a rational first-line approach for selected individuals [20, 21].

Radiological assessment is crucial in identifying which lesions can be safely monitored. MRI findings such as small tumor size (<2.5–3 cm), extra-axial location, absence of significant peritumoral edema, T2-weighted hypointensity, and presence of calcifications are predictive of slow-growing, indolent behavior. Lesions located at the convexity or parasagittal region with no mass effect or midline shift are less likely to require intervention [20]. In contrast, tumors near eloquent areas, even if small, may eventually compromise function, thus necessitating closer follow-up or earlier intervention.

Some centers implement structured imaging protocols including MRI every 6 months for 2 years, followed by annual monitoring if no progression is observed. High-resolution volumetric MRI allows for more precise growth rate estimation, which is essential in decision-making. When possible, volumetric doubling time (VDT) and tumor growth rate in cm^3/year are calculated to better identify lesions with a higher risk of clinical progression [14, 21].

Moreover, cognitive status and quality of life must be weighed alongside imaging. In older adults, particularly those with early cognitive impairment, even minor increases in peritumoral edema or small mass effects may precipitate measurable neuropsychological decline. As such, periodic neurological and cognitive evaluations are often incorporated into long-term monitoring protocols at specialized centers.

4.1.2 Long-term management and results

Several large observational cohorts have shown that over 60–80% of asymptomatic meningiomas in the elderly remain radiologically stable over a 5–10 year

follow-up period [14, 21]. When growth is observed, it often proceeds slowly and asymptotically. Growth trajectories tend to follow a Gompertzian model, in which expansion slows over time as the tumor reaches spatial and vascular limitations.

However, the decision to continue observation versus switch to active treatment must be continuously re-evaluated. For example, a shift of more than 2 mm in diameter or a 15% volume increase per year may be considered a threshold to reconsider surgical or radiosurgical options [21].

The success of a conservative strategy hinges on patient engagement and caregiver involvement. Educating the patient and family on signs of potential progression—such as new-onset headaches, balance difficulties, or personality changes—can facilitate early detection of clinically relevant changes.

Importantly, the conservative approach is not synonymous with passivity. Rather, it is a proactive surveillance strategy embedded in a multidisciplinary framework, balancing life expectancy, tumor biology, and patient preferences.

A good example of the importance of getting the multidisciplinary point of view in the same time than the patient's preferences is illustrated in **Figure 1**. It shows a patient of 83 years considered “high risk” due to the age factor, but that is in good general health conditions, presenting very few comorbidities, with an MRI showing a deviation in the median line due to four different meningiomas. Although the multidisciplinary decision in this case is in favor of surgical approach due to absence of other comorbidities, in addition to the age factor but also due to the neurological symptoms the patient presented, which are left hemiparesis and two epileptic episodes, the patient and the relatives, however, chose to refuse the surgical option. So, we went with the medical treatment and simple surveillance, which turned out to be a good decision considering the stable evolution of the tumors during the

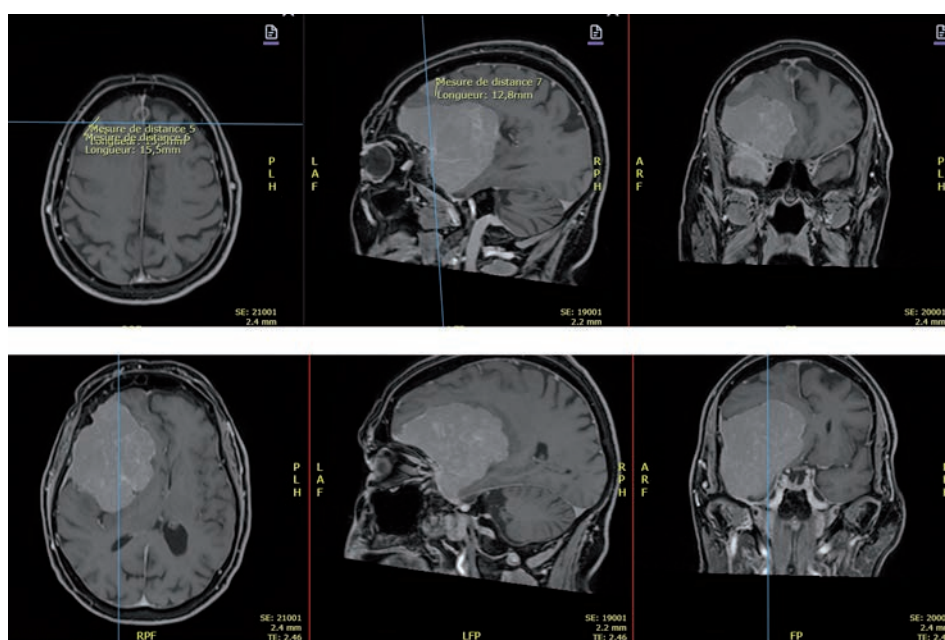


Figure 1.
 MRI of an 83-year-old patient: Identification of four meningiomas, the largest of which is located in the right frontotemporal region. It causes a midline shift and ipsilateral temporal herniation. This mass is in close contact with the right sylvian trifurcation.

MRI surveillance months later, and most importantly, the neurological status of the patient, who did not present any new symptoms along the way.

4.2 Surgical approach

Surgical resection remains the primary treatment modality for symptomatic or radiologically progressive intracerebral meningiomas, including in elderly patients who meet carefully selected criteria. However, in this population, surgical decision-making involves a delicate balance between oncological objectives and preserving neurological function, quality of life, and independence. Chronological age alone should not serve as an exclusionary factor; instead, patient selection must be grounded in comprehensive clinical, radiological, and functional assessments [14, 20].

We choose to illustrate in **Figure 2** a case of a 72-year-old patient who conducted an MRI after a single episode of epileptic seizure that showed a large tumoral nodule implanted on the right frontotemporal meninges compressing the ventricular system and the right cerebral peduncle. For this patient, the radiological elements added to the general health status discussed in a multidisciplinary meeting were in favor of a maximal resection, which was successfully obtained as shown in **Figure 3**. The neurological evolution was perfected months after the intervention with the exception of a transitional aphasia directly after the intervention that totally disappeared eight days post-op.

The patient was discharged with antiepileptic treatment and did not present any neurological symptoms five months after the intervention at the moment of redacting this article.

4.2.1 Evaluation of the risks and benefits

In elderly patients, the evaluation of surgical risks and potential benefits requires a nuanced understanding of preoperative status, tumor characteristics, and perioperative resilience. Although age-related physiological decline is a concern, studies have consistently shown that favorable outcomes are achievable in this population,

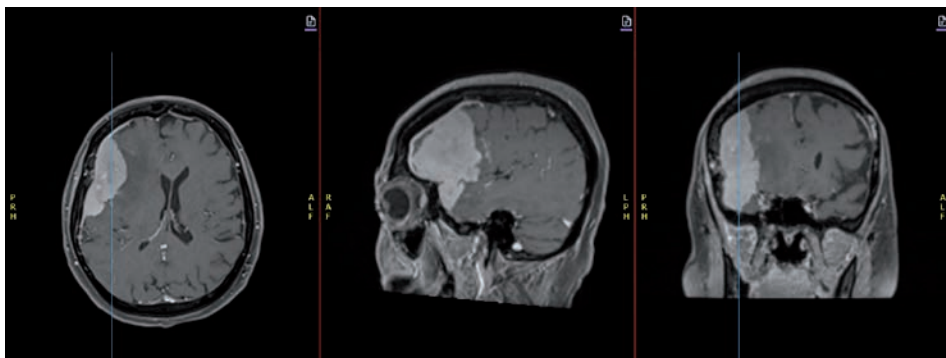


Figure 2.

MRI of a 72-year-old patient: Identification of a large tumoral nodule implanted on the right frontotemporal meninges, it measures 78 × 28 mm in diameter and exerts a significant compressive effect on the frontotemporal brain region, the ventricular system, particularly at the level of the right lateral ventricle, with leftward displacement of midline structures, and of the right cerebral peduncle. The tumor is most likely consistent with a meningioma.

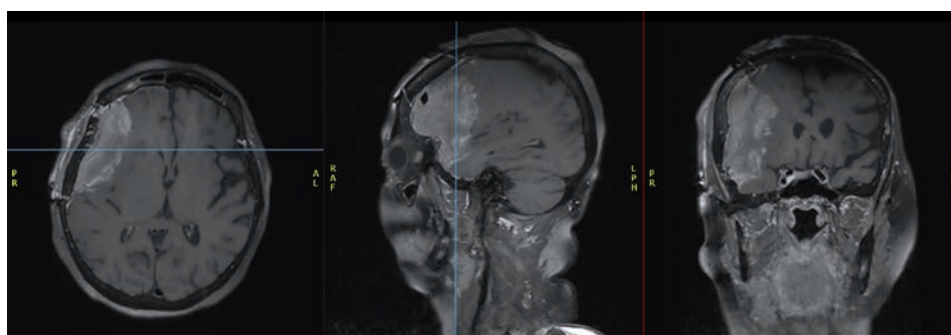


Figure 3.
 Postoperative—2 days after the intervention of the same patient from **Figure 2**: Large resection cavity/extra-axial hematoma of the right frontotemporal convexity (approximately $67 \times 22 \times 71$ mm – AP $\times$ transverse $\times$ craniocaudal), appearing to include the entirety of the previously noted large meningioma-like mass in this area. There is a reduction in the leftward subfalcine herniation (6 mm vs. 9 mm) and partial decompression of the right lateral ventricle. No other pathological enhancement was detected.

particularly when surgery is offered to those with high Karnofsky Performance Status (KPS), low ASA scores, and minimal frailty indicators [14, 15].

Lesions exerting significant mass effect, associated with peritumoral edema or presenting with seizures, cognitive decline, or motor deficits, often justify a surgical indication due to their direct impact on neurological function. In such cases, timely decompression may restore function, improve cognition, and halt deterioration. However, in patients with borderline performance status or high comorbidity burden, the benefits of symptom relief must be weighed against the risks of perioperative complications such as delirium, infection, or hematoma [14, 22].

Surgical goals in elderly patients frequently shift from curative resection to palliative debulking—aiming for symptomatic relief with minimal surgical stress. This is particularly relevant for skull base tumors, large lesions with adherence to critical neurovascular structures, or those infiltrating bone, where the morbidity of aggressive surgery may outweigh potential long-term control benefits [20, 22].

Multidisciplinary decision-making plays a central role. Discussions among neurosurgeons, anesthesiologists, geriatricians, and radiologists help determine candidacy by integrating data from neuroimaging, functional scoring systems (e.g., SKALE), and individualized surgical risk profiles. Such a team-based approach minimizes bias and ensures that no patient is excluded solely based on age, but rather on objective surgical feasibility [14, 15].

4.2.2 Perioperative management

Effective perioperative management is pivotal in improving surgical outcomes for elderly meningioma patients. The risk of complications rises substantially in the presence of polypharmacy, cardiac comorbidities, reduced pulmonary reserve, and cognitive frailty—all of which are common in this age group. Proactive strategies including prehabilitation, tight metabolic control, and geriatric co-management help mitigate these risks [14].

Anesthesia planning should account for limited physiological reserve. Short-acting anesthetics, maintenance of normothermia, early extubation, and intraoperative fluid balance are essential components of geriatric anesthesia. Minimizing time under

general anesthesia is critical, as prolonged procedures are associated with postoperative delirium and delayed mobilization [20].

Intraoperative neuromonitoring and neuronavigation assist in maximizing resection while preserving function. Microsurgical techniques, ultrasonic aspirators, and the use of hemostatic agents enable safer debulking of firm or calcified tumors, which are commonly encountered in elderly individuals. Additionally, a more conservative surgical tempo, with readiness to convert to subtotal resection if critical anatomy is encountered, reduces the risk of intraoperative complications [14, 22].

Postoperative care should be structured around early mobilization, nutritional support, and prevention of geriatric syndromes such as delirium, urinary retention, and deep vein thrombosis. Clinical protocols often integrate daily physiotherapy, cognitive monitoring, and strict medication reconciliation to reduce confusion or drug interactions. Specialized neuro-rehabilitation programs may be required for patients with preoperative deficits or slow recovery trajectories [22].

4.2.3 Assessing the extent of resection

The extent of resection remains a strong prognostic factor for recurrence-free survival in meningioma patients. However, in elderly individuals, the principle of “maximal safe resection” prevails over the historical goal of Simpson Grade I resection. Complete resection must not come at the cost of new neurologic deficits or deterioration of independence, which may outweigh any theoretical survival benefit [20].

While Simpson Grade I–II resections (complete removal including involved dura and bone) offer the best control, achieving this in deep-seated or skull base tumors may introduce undue risk. In such cases, Simpson Grade III–IV resections, which leave small residuals in difficult locations, are acceptable if followed by close imaging surveillance or stereotactic radiosurgery [15, 20].

Importantly, residual tumor volume has emerged as a more meaningful predictor of outcome than Simpson grade alone in elderly cohorts. Even subtotal resections can yield excellent results when combined with adjuvant treatments, especially for WHO Grade I tumors [22]. For patients with WHO Grade II or higher lesions, a multidisciplinary discussion often results in postoperative radiotherapy decisions based on resection extent and tumor proliferation indices.

Ultimately, the decision to pursue aggressive resection versus limited surgery must be personalized, grounded in imaging findings, anatomical constraints, histologic grade suspicion, and the patient’s recovery potential. This individualization—supported by preoperative planning and intraoperative adaptability—remains the cornerstone of successful surgical management in older adults with intracerebral meningiomas [14, 20, 22].

4.3 Adjuvant treatments

Adjuvant therapies—including fractionated radiotherapy (RT) and stereotactic radiosurgery (SRS)—have an evolving role in elderly patients with residual or high-grade meningiomas. These modalities are particularly useful when surgery is incomplete, infeasible, or contraindicated.

RT is most beneficial in WHO Grade II–III meningiomas or after subtotal resection, where recurrence risk is substantial. Despite age-related sensitivity to radiation, modern conformal techniques and hypofractionation protocols allow RT to be

delivered safely with minimal neurocognitive toxicity, especially when combined with MRI-based planning and dose constraints [20, 23].

SRS is preferred in small (<3 cm), well-defined residual tumors, particularly in surgically inaccessible locations. Control rates with SRS exceed 90% in benign meningiomas and are particularly advantageous in the elderly due to lower procedural burden and faster recovery [24]. However, caution is required when using SRS in tumors near optic pathways or brainstem, where the risk of edema or radiation necrosis is higher.

Emerging data also support early RT following subtotal resection of WHO Grade II tumors, although practice remains variable due to limited high-level evidence in elderly populations. The ongoing ROAM/EORTC 1308 and NRG-BN003 trials are expected to provide greater clarity on postoperative RT indications in this context [23, 25].

Ultimately, the use of adjuvant therapy must reflect an individualized assessment of tumor behavior, resection extent, performance status, and patient preference. The goal remains consistent: durable control with minimal impact on cognition and autonomy.

5. Conclusion

The management of intracerebral meningiomas in the elderly presents a complex clinical challenge requiring careful balancing of oncologic control, patient safety, and preservation of autonomy. As life expectancy continues to rise globally, the incidence of intracranial meningiomas among older individuals will increase, further necessitating clear, evidence-based strategies tailored to this unique population [1–6, 14–16, 18–33].

This chapter highlights the critical importance of a multifactorial approach to elderly patients, where decision-making must integrate not only chronological age but also comorbidities, performance status, cognitive function, tumor characteristics, and patient preferences. Traditional binary decisions based solely on age thresholds are no longer sufficient. Tools like the SKALE score, frailty indices, and imaging-based predictive models offer a more nuanced risk stratification, though there remains a need for broader validation across populations and care systems [15].

Surgical resection remains the cornerstone of treatment for symptomatic or progressing tumors and can be safely undertaken in selected elderly patients with favorable risk profiles. However, maximal resection should be carefully weighed against potential morbidity. In many cases, subtotal resection or adjuvant radiosurgery may offer an equivalent balance of tumor control and quality of life. When surgery is contraindicated, conservative management with imaging surveillance remains an appropriate option for slow-growing or incidental meningiomas.

The role of adjuvant treatments is evolving. Radiotherapy and stereotactic radiosurgery provide effective alternatives or supplements to surgery, particularly in high-grade tumors or where surgical risks outweigh potential benefits. Their use must, however, be tempered by considerations of radiation-induced neurocognitive effects, which are especially relevant in elderly patients with preexisting cognitive decline or low functional reserve.

Ultimately, optimal care of elderly patients with meningiomas relies on a multidisciplinary team-based strategy. Neurosurgeons, geriatricians, anesthesiologists, oncologists, and rehabilitation specialists must collaborate to formulate

individualized treatment plans that align with the patient's health status, tumor profile, and life goals.

Future research must continue to focus on prospective validation of predictive models, development of minimally invasive surgical and radiotherapeutic techniques adapted for older adults, and exploration of patient-reported outcome measures. Special attention should also be given to the underexplored domains of post-treatment quality of life, cognitive outcomes, and functional independence in this age group.

In conclusion, age alone should never be the sole determinant in therapeutic decision-making for intracranial meningiomas. With proper selection, tailored management, and holistic care, elderly patients can achieve favorable outcomes while maintaining dignity and independence—underscoring the need for personalized neurosurgical oncology in the aging population.

Conflict of interest

The authors declare no conflict of interest.

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Current Findings in Embolization of Intracranial Meningiomas: Feasibility, Utility, Classification, and Techniques

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Abstract

Intracranial meningiomas are the most prevalent primary tumors of the central nervous system. Although usually benign and slow-growing, their vascularity and strategic location often complicate surgical resection. Preoperative embolization has emerged as a valuable adjunct to reduce intraoperative blood loss, facilitate tumor removal, and improve surgical outcomes. This chapter reviews current evidence regarding the feasibility, benefits, classification, and technical aspects of embolization in intracranial meningiomas. Embolization is the most effective when the tumor is supplied by external carotid branches, whereas supply from the internal carotid or vertebrobasilar systems requires more selective techniques due to higher risks. Clinically, embolization reduces blood loss, shortens surgery, and improves gross total resection rates, particularly in large, hypervascular tumors. We also introduce the Preoperative Embolization of Meningiomas Mexican Classification (PEMMCO), a novel grading system that categorizes the depth of embolic agent penetration into four levels, ranging from proximal vessel occlusion to complete intra- and peritumoral saturation. This classification aims to predict surgical complexity and optimize outcomes. Advances such as the plug-and-push, pressure-cooker, and balloon-assisted techniques, together with modern agents like ethylene-vinyl alcohol copolymers (e.g., Onyx), have enhanced the safety and efficacy of embolization. Nevertheless, potential risks—including ischemia, edema, and cranial nerve injury—highlight the importance of careful patient selection and expert technical execution. In conclusion, preoperative embolization is a safe and effective adjunct for selected intracranial meningiomas. When planned within a multidisciplinary approach, it can significantly contribute to safer resections and better overall patient outcomes.

Keywords: preoperative embolization, intracranial meningioma, intratumoral embolic penetration, endovascular neurosurgery, novel meningioma treatment

1. Introduction

Intracranial meningiomas are among the most frequently diagnosed primary brain tumors, accounting for nearly 38% of all primary central nervous system (CNS) neoplasms [1]. These tumors originate from the arachnoid cap cells of the meninges and are typically slow-growing and benign. Despite their generally indolent behavior, their intracranial location often necessitates surgical intervention, especially when they become symptomatic or show signs of progression.

The vascular nature of meningiomas, particularly large or skull base variants, can pose significant intraoperative challenges. Excessive blood loss, prolonged operative time, and incomplete resections are not uncommon in such cases. To mitigate these risks, preoperative embolization has been adopted as an adjunctive measure in selected patients. Embolization aims to devascularize the tumor preoperatively, potentially reducing intraoperative blood loss and facilitating safer and more effective resection [2].

The application of embolization in meningioma management has evolved substantially, with advancements in endovascular techniques and embolic materials contributing to its growing safety and efficacy profile. However, the decision to proceed with embolization must be judicious, informed by the tumor's vascular architecture, location, and patient-specific factors. This chapter explores the current evidence surrounding embolization in intracranial meningiomas, with a focus on feasibility, clinical utility, classification systems, and technical approaches.

2. Feasibility of preoperative embolization

Feasibility refers to the technical and anatomical possibility of performing a safe and effective embolization procedure. The majority of meningiomas derive their blood supply from branches of the external carotid artery (ECA), notably the middle meningeal artery (MMA), ascending pharyngeal artery, and superficial temporal artery. When these vessels are the primary feeders, embolization is generally considered feasible and low risk [3].

However, challenges arise when meningiomas receive substantial supply from the internal carotid artery (ICA) or vertebrobasilar system, particularly the ophthalmic or posterior cerebral arteries. These vessels supply critical brain regions, and non-target embolization can result in catastrophic neurological deficits. In such cases, embolization may still be feasible but requires advanced imaging, skilled operators, and the use of superselective catheterization techniques [4].

Advanced imaging modalities such as digital subtraction angiography (DSA), cone-beam computed tomography (CBCT), and 3D rotational angiography have significantly improved the ability to delineate the vascular anatomy of meningiomas preoperatively. These tools assist in mapping feeder vessels and planning embolization strategies tailored to individual tumor profiles [5].

Patient selection is another critical determinant of feasibility. Ideal candidates are those with tumors that are large, hypervascular, and accessible via ECA branches. Contraindications include severe allergy to contrast agents, coagulopathy, and vascular anatomy unsuitable for catheter navigation.

3. Clinical utility

The clinical utility of preoperative embolization in meningioma surgery lies in its potential to improve surgical outcomes and reduce operative morbidity. Although not universally employed, embolization has shown benefits in specific contexts, which are explored below.

3.1 Reduction in intraoperative blood loss

Numerous studies have documented that embolization significantly reduces intraoperative blood loss. Meningiomas, especially those with a robust vascular supply, can bleed profusely during resection, complicating visualization and increasing the need for transfusions. Embolization reduces perfusion to the tumor, thereby limiting intraoperative hemorrhage [6].

In a retrospective review involving 117 patients, Raper et al. demonstrated that preoperative embolization led to a statistically significant reduction in intraoperative blood loss compared to non-embolized controls [2]. Another study by Chun et al. involving skull base meningiomas supported these findings, reporting a 30–50% reduction in estimated blood loss when embolization was employed [7].

3.2 Facilitation of tumor resection

By devascularizing the tumor, embolization contributes to tumor softening and reduces turgor, making surgical manipulation easier. This can translate into shorter resection times, improved resection rates, and lower surgical complexity [8].

Katz et al. reported that complete resection rates were higher in embolized patients, especially for tumors larger than 4 cm in diameter [9]. Tumor softening following embolization was particularly noted in convexity and parasagittal meningiomas, where manipulation is often straightforward but hemostasis is critical.

3.3 Impact on surgical time and complication rates

While data on operative time reduction is variable, several studies suggest modest but meaningful decreases in surgery duration. This is attributed to improved hemostasis and easier tumor mobilization. In a series by Ilyas et al., the mean operative time was reduced by 20 minutes in the embolization group [4].

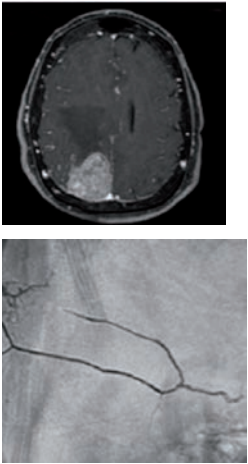
Importantly, embolization has not been shown to increase complication rates when performed under appropriate conditions. When contraindications are respected and meticulous technique is applied, the incidence of major complications remains below 5% in most series [10].

A recent comparative study by Gutiérrez-Baños et al. [11] evaluated the safety and efficacy of presurgical embolization in patients with intracranial meningiomas treated at a national center in Mexico. The authors reported a high technical success rate with no major complications and emphasized the procedure's role in improving intraoperative conditions. They also proposed a novel classification system based on the degree of embolic agent penetration, suggesting that deeper intratumoral penetration correlates with better surgical outcomes. This study reinforces embolization as a beneficial adjunct, particularly when planning complex resections of hypervascular tumors [11].

3.4 Classification based on embolic agent penetration

As part of their findings, Gutiérrez-Baños et al. also introduced a novel classification (Preoperative Embolization of Meningiomas, Mexican Classification; PEMMCO) system to standardize the evaluation of embolization depth and effectiveness. This classification is based on the intratumoral penetration of the embolic agent, categorized into four distinct grades (Table 1).

- *Grade I: Proximal or peritumoral embolization*—The embolic agent occludes only the main feeder arteries or peritumoral vessels, without significant penetration into the tumor core. This grade is often insufficient for larger or deeply vascularized tumors.
- *Grade II: Partial intratumoral penetration*—Embolic material reaches some intratumoral vessels but does not fill the tumor bed homogeneously. This level offers moderate reduction in vascularity and may aid surgery.
- *Grade III: Deep intratumoral penetration*—The embolic agent diffuses homogeneously throughout the tumor vasculature, achieving near-total devascularization. Grade

Grade	Characteristics	Images
Grade 1	Preoperative embolization involves only the main feeding artery.	
Grade 2	Preoperative embolization involves the main feeding artery + intratumoral arteries.	

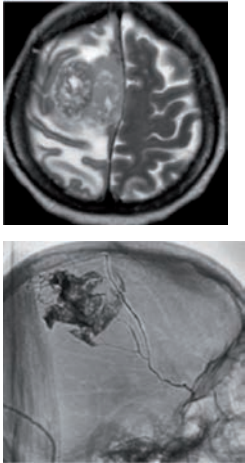
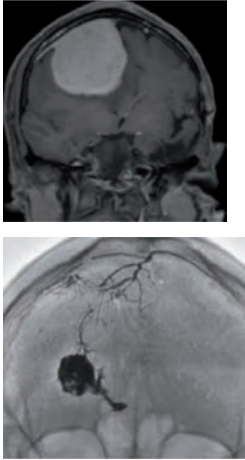
Grade	Characteristics	Images
Grade 3	Preoperative embolization involves the main feeding artery + intratumoral arteries + intratumoral sinusoidal aspect.	
Grade 4	Preoperative embolization involves the main feeding artery + intratumoral arteries + intratumoral sinusoidal aspect + one or more draining veins.	

Table 1.
 Description of PEMMCO; presurgical embolization classification using EVOH. Column A: Grade description, Column B: MRI, Column C: Fluoroscopy. PEMMCO: Preoperative Embolization of Meningiomas, Mexican Classification; MRI: magnetic resonance imaging; EVOH: ethyl-vinyl alcohol.

III is considered optimal and correlates with better intraoperative visibility, lower bleeding, and increased chances of gross total resection [11].

- Grade IV: Complete and homogeneous intratumoral and peritumoral penetration*—This grade represents the most extensive distribution of the embolic agent, reaching both the intratumoral vascular bed and adjacent peritumoral capillary networks. It is associated with maximal devascularization and optimal surgical conditions, particularly for large or complex tumors. Gutiérrez-Baños et al. suggest that Grade IV may predict superior intraoperative visibility and lower recurrence potential when followed by complete resection [11].

This classification helps guide both planning and intraoperative expectations, allowing clinicians to correlate embolization success with surgical outcomes and refine decision-making protocols.

Matsoukas et al. proposed an angiographic devascularization grading scale to standardize the evaluation of embolization efficacy based on residual tumor blush. This scale ranges from grade 0 (no embolization) to grade 4 (complete devascularization, including elimination of external, internal, and posterior circulation supply). While this system offers a structured assessment of angiographic devascularization, the PEMMCO approach emphasizes a different dimension: the degree of intratumoral penetration achieved by the liquid embolic agent within the vascular architecture of the tumor. This alternative perspective has demonstrated clinical value, as higher penetration grades have shown a consistent association with reduced intraoperative bleeding, underscoring its potential relevance for surgical planning and outcome prediction [12].

4. Classification relevant to embolization

Classification of meningiomas in the context of embolization primarily revolves around anatomical location, tumor size, vascular supply, and histological grade. These factors help guide the decision-making process regarding the potential benefits and risks of embolization.

4.1 Tumor location

The anatomical site of the tumor heavily influences both the technical feasibility and the expected benefits of embolization. Tumors located at the convexity or parasagittal region typically receive supply from the middle meningeal artery and other branches of the ECA, making them ideal candidates for embolization [3]. In contrast, skull base tumors, including petroclival and sphenoid wing meningiomas, often derive blood supply from ICA branches such as the inferolateral trunk, necessitating more complex endovascular strategies and increased caution [4].

Moreover, tumors near critical neurovascular structures such as the cavernous sinus, optic apparatus, or brainstem present unique risks during embolization due to the potential for non-target embolization and neurological deficits [13]. Thus, anatomical considerations are pivotal in planning and executing embolization safely.

4.2 Tumor size

Tumor size correlates positively with vascularity; larger meningiomas tend to be more hypervascular and consequently, more likely to benefit from embolization. A study by De Bonis et al. found that embolization was particularly advantageous in tumors larger than 4 cm, showing improved intraoperative control and more favorable surgical outcomes [8].

However, extremely large tumors may pose a paradox. Their complex and redundant vascular supply might reduce the efficacy of embolization, requiring multiple sessions or combined arterial approaches. Additionally, the risk of post-embolization edema and tumor necrosis is greater in very large lesions, which can complicate surgical planning [14].

4.3 Vascular supply

Preoperative angiographic studies aim to determine the arterial contributors to the tumor. Meningiomas that are primarily supplied by ECA branches are the safest to



Figure 1.
Lateral view of right external carotid artery angiography during the capillary phase, demonstrating distal blush consistent with a right parasagittal meningioma.

embolize (**Figure 1**). When feeders arise from the ICA, vertebral artery, or ophthalmic artery, embolization becomes more technically challenging and risky [5, 15].

In such cases, embolization may still be pursued using ultra-selective catheterization techniques and liquid embolics under continuous neurophysiological monitoring. Nonetheless, embolization is contraindicated if the vascular architecture presents an unacceptably high risk of non-target embolization leading to stroke, cranial nerve injury, or blindness [16].

5. Embolization techniques

The technical aspects of embolization have evolved considerably over recent decades. With improvements in microcatheter technology, imaging modalities, and embolic agents, modern embolization is safer and more effective than ever before. Successful embolization requires meticulous planning, an understanding of cerebral vascular anatomy, and careful execution.

5.1 Transarterial embolization and techniques used in embolization

Transarterial embolization remains the most common and widely used approach for meningiomas. This technique involves accessing the vascular supply through femoral or radial artery catheterization, followed by selective catheterization of tumor-feeding arteries (**Figure 2**). Through these microcatheters, embolic materials are introduced to occlude the blood supply to the tumor [3].

Digital subtraction angiography (DSA) is performed first to delineate the vascular architecture. The interventionalist then performs superselective catheterization of

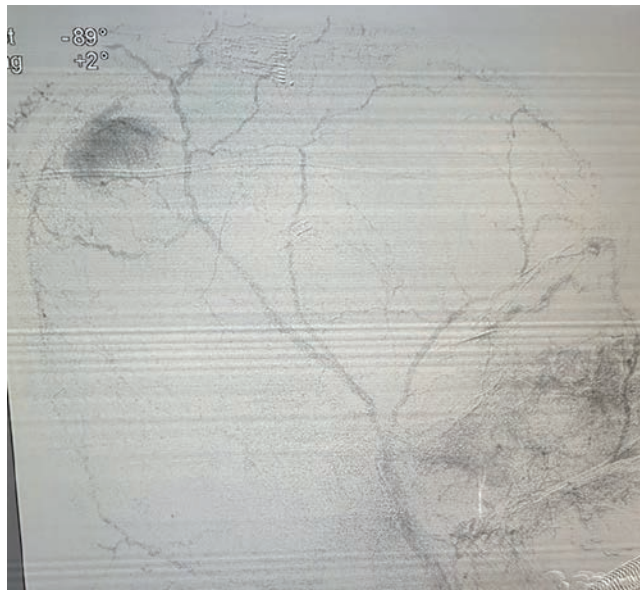


Figure 2.

Selective microcatheterization of the right middle meningeal artery in right lateral view at the tumor base, showing intratumoral capillary (sinusoidal) filling and a draining vein toward the superior sagittal sinus.

feeders, often beginning with branches of the ECA. When ICA or vertebrobasilar feeders are present, additional precautions, including the use of balloon microcatheters or flow arrest techniques, may be necessary [17].

Liquid embolics (LE) can be applied in various ways to achieve the common goal of intratumoral embolization. Many techniques described for the application of LE in arteriovenous malformations (AVMs) or dural arteriovenous fistulas (DAVFs) are also used in preoperative embolization of meningiomas. There are no clear indications as to which technique offers the best results, so the choice of technique largely depends on the neurointerventionist's experience.

Plug and push technique: In this technique, the main feature is the formation of a high-density EVOH plug (Onyx 34) around the tip of the microcatheter. This is achieved through slow and controlled initial injection, causing the cohesive agent to polymerize slowly and gradually. This process is time-dependent; it is estimated that the formation time for a competent EVOH plug is around 2–30 minutes. Once a sufficient plug (about 1–2 cm) is formed, lower-density EVOH (Onyx 18) is injected with antegrade flow to the lesion. This technique has advantages such as lower cost compared to others and high embolization rates of vascular lesions with extensive reflux control (**Figures 3 and 4**) [17].

Pressure-cooker technique: First described in 2014 by René Chapot and colleagues, the pressure-cooker technique quickly gained popularity as an alternative treatment for this type of lesions. The concept of “pressure-cooker technique” derives from the analogy to a pressure cooker used in kitchen: it speeds up the cooking process; similarly, this technique is designed to significantly reduce fluoroscopy and embolization time because proximal plug formation is much faster. This technique involves navigating two microcatheters; one at the lesion site (AVM, DAVF) and another more proximally. The proximal microcatheter forms a proximal plug using a combination of coils and LE, preventing reflux and unintended embolization. Meanwhile, the LE

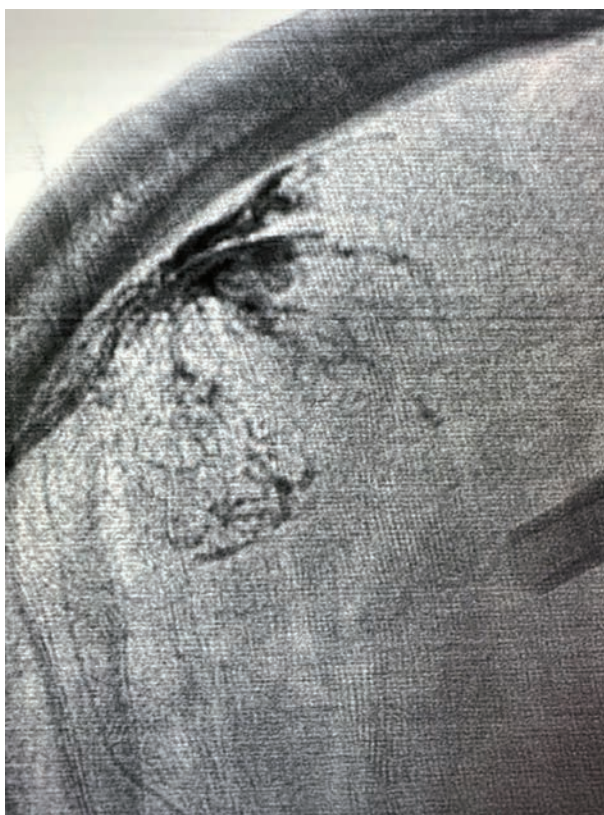


Figure 3.
Fluoroscopy, right lateral view demonstrating the EVOH cast with intratumoral penetration grade PEMMCO IV (EVOH penetration through sinusoidal structures and draining vein).

applied through the distal microcatheter aims to embolize the arteriovenous malformation [10].

Double lumen balloon-assisted technique: In this technique, a double lumen balloon is navigated through a guide catheter assisted by a 0.014×200 cm microwire to the most proximal site where embolization is to be performed. As previously mentioned, this balloon has two lumens: one for navigating the microwire, and the other for connecting to the syringe to inflate the balloon. This technique has proven very useful in preventing reflux, and it has also shown to be more efficient in terms of fluoroscopy and embolization time; additionally, it has proven to be a safe method [13].

The goal is to achieve near-complete devascularization without compromising normal brain tissue. Complete embolization is often limited by the inability to safely access all arterial feeders. Thus, embolization is typically targeted to reduce vascularity as much as possible within safe limits (**Figures 5 and 6**).

5.2 Embolic agents

Several embolic agents are available, each with unique properties, advantages, and limitations. The choice of embolic material is dictated by the size of the feeding vessel, desired permanence of occlusion, tumor characteristics, and operator experience.



Figure 4.

Fluoroscopy, anteroposterior view demonstrating the EVOH cast with intratumoral penetration grade PEMMCO IV (EVOH penetration through sinusoidal structures and draining vein).

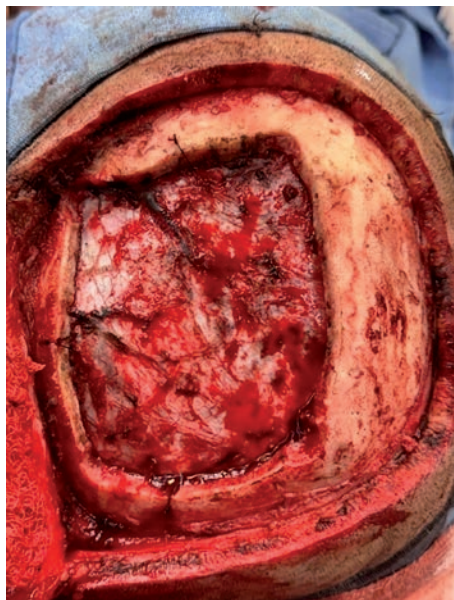


Figure 5.

Intraoperative view showing the embolic agent visible within the middle meningeal artery, demonstrating a bloodless surgical field with minimal bleeding.

- *Polyvinyl alcohol (PVA) particles:* Irregularly shaped, non-absorbable particles that induce mechanical occlusion and endothelial damage. Sizes between 150 and 300 microns are standard [18].

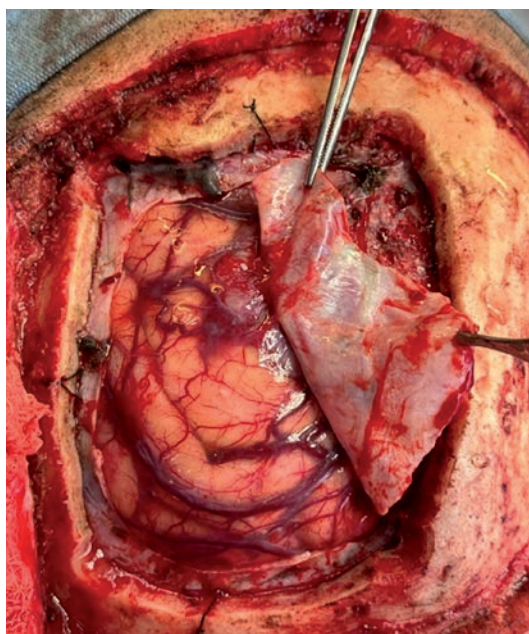


Figure 6.
Intraoperative view showing dural opening without the need for prior coagulation, highlighting the effectiveness of devascularization.

- *Trisacryl gelatin microspheres*: More uniform than PVA, offering better flow control and deeper penetration [19].
- *Ethylene-vinyl alcohol (EVOH) copolymer dissolved in dimethyl sulfoxide, with suspended tantalum powder for radiopacity (Onyx, Squid)*: Allow deep vessel penetration and permanent occlusion. Require expertise due to higher complication risk [20].
- *Gelfoam®*: A temporary embolic for proximal occlusion, used selectively when permanence is not essential [21].

The selection must balance efficacy with safety, taking into account the risk of reflux and proximity to eloquent regions.

5.3 Timing of embolization and surgery

Most studies support surgery within 24–72 hours post-embolization to optimize tumor devascularization and reduce the risk of inflammatory complications. Delays beyond this window may result in revascularization or increased edema and fibrosis [22].

A study by Wan et al. showed better outcomes when surgery was performed within 48 hours post-embolization [23]. Steroid use may help mitigate post-embolization edema.

6. Complications and considerations

Despite the numerous advantages of preoperative embolization, it is not without risks. Understanding potential complications and strategies to mitigate them is essential for patient safety and procedural success.

6.1 Ischemic complications

Non-target embolization can result in ischemia in critical neural structures [15]. Superselective catheterization and real-time angiographic monitoring are vital for minimizing this risk. High-risk ICA or ophthalmic feeders should only be embolized by experienced operators [16].

6.2 Hemorrhagic complications

Sudden ischemia can lead to tumor necrosis and intratumoral hemorrhage. Though rare, this can necessitate emergency surgery [13]. Controlled embolic injection and immediate imaging help mitigate this risk.

6.3 Post-embolization edema

Ischemia may lead to peritumoral edema, especially in large tumors. This can cause new or worsening neurological symptoms [19]. Corticosteroids are typically employed to manage this response.

6.4 Cranial nerve deficits

Cranial nerve damage may occur in skull base tumors due to embolization-induced ischemia or edema [11]. Careful mapping of tumor-vessel relationships can reduce this risk.

6.5 Allergic and contrast-related reactions

Contrast agents can provoke allergic reactions. Pre-medication and use of low-osmolar contrast are standard precautions [21].

6.6 Technical failures and incomplete embolization

Some tumors are not amenable to complete embolization due to inaccessible feeders or dangerous anastomoses. Partial embolization can still be beneficial, but its limitations must be communicated to the surgical team [22].

6.7 Cost and resource utilization

Embolization adds procedural costs and logistical demands. Its use should be justified based on surgical risk reduction and institutional capability [24].

6.8 Complications in global experience

International experience corroborates the overall safety profile of preoperative embolization when performed in specialized centers by experienced operators. Raper

et al. [2], in a retrospective series of 117 patients at Stanford University, reported a low complication rate (3.4%), with most adverse events being transient neurological deficits and no procedure-related mortality. Bendszus et al. [10] observed a 6% incidence of neurological complications in a German cohort, largely attributed to non-target embolization with PVA particles. In Japan, Terada et al. [23] documented intratumoral hemorrhage in approximately 5% of cases, highlighting the importance of controlled embolic injection, particularly in highly vascular tumors. A systematic review by Ilyas et al. [4] analyzing skull base meningiomas from multiple centers found that embolization, when guided by advanced imaging and meticulous technique, consistently resulted in low complication rates (<5%) and improved surgical conditions. These findings underscore the critical role of technical expertise, case selection, and institutional experience in reducing embolization-associated risks and optimizing outcomes worldwide [2, 10, 23].

7. Conclusion

The preoperative embolization of intracranial meningiomas has become a well-established adjunct in neurosurgical oncology. Its value lies in reducing intraoperative blood loss, softening tumor texture, and facilitating more efficient and complete surgical resections. Advances in imaging, embolic agents, and microcatheter technologies have enhanced both the safety and precision of these procedures, expanding their indications and improving outcomes.

However, embolization is not universally applicable. Its utility is influenced by tumor size, location, vascular supply, and the skill level of the interventionalist. Proper patient selection, thorough pre-procedural planning, and adherence to meticulous technique are fundamental to achieving optimal results. While complications such as ischemia, edema, or cranial nerve deficits remain potential risks, they are largely preventable through careful practice and technological support.

The current body of evidence suggests that embolization should be strongly considered in cases involving large, hypervascular meningiomas, particularly those with a dominant supply from branches of the external carotid artery. In contrast, tumors with significant ICA or ophthalmic artery contributions require heightened caution or may not be suitable for embolization at all.

Future directions include the development of novel embolic materials with enhanced targeting capabilities, real-time perfusion monitoring during procedures, and integration of artificial intelligence in vascular imaging to predict outcomes. Additionally, randomized controlled trials are needed to more precisely define the cost-effectiveness and long-term surgical benefits of embolization.

In conclusion, embolization represents a powerful tool in the multidisciplinary management of meningiomas. When applied judiciously and executed with expertise, it can significantly enhance surgical outcomes, reduce perioperative morbidity, and contribute to overall treatment success.

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As meningioma is one of the most common intracranial tumors, understanding it is crucial to improve survival, reduce recurrence, and enhance patients' quality of life. Today, we have the resources that enhance neurosurgeons' skills to perform highly complex surgical procedures safely and confidently. Current neurosurgery tools and technologies are enabling a new dimension of precision care medicine. In this book, we present the state of the art in the neurosurgical treatment of meningiomas, including the most common complications and current alternatives for their solution. A review of the current molecular fingerprints of meningiomas is presented to inform the development of targeted therapies for this condition. Besides, its diagnosis is more common in adulthood. We present the experience and particularities of surgical treatment of meningioma in the pediatric population and review the current evidence and recommendations for meningioma treatment in the elderly. A discussion of a new classification based on meningioma angioarchitecture is offered to anticipate intraoperative complications.

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