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Advanced and Modern Imaging Techniques for the Evaluation of Intracranial Meningiomas

R S Pavan Kumar[1], Poojitha M[2], Adarsh GN[3], Muhammed Najah[4], Muhammad Nihal[5]
[1] Assistant Professor, Department of Medical Imaging Technology, Yenepoya Deemed to Be University, Bangalore, Karnataka
[2,3,4,5] PG - Department of Medical Imaging Technology, Yenepoya Deemed to Be University, Bangalore, Karnataka
Emails: *rspavankumar.blr@yenepoya.edu.in[1], 39187@yenepoya.edu.in[2], 47333@yenepoya.edu.in[3], 32948@yenepoya.edu.in[4], 32905@yenepoya.edu.in[5]*

Abstract
Intracranial meningiomas are the most common primary extra-axial brain tumours. These tumours constitute a considerable percentage of brain tumours occurring in adults. Although the majority of meningiomas are benign tumours, some exhibit aggressive features. These tumours have complex relationships with adjacent structures. Hence, precise investigation and treatment planning are essential. Advanced and modern imaging techniques have an important role to play in the comprehensive investigation of these tumours, which is beyond the capabilities of traditional and conventional imaging techniques. The gold standard method for examining and assessing intracranial meningiomas prior to surgery is magnetic resonance imaging (MRI). Recent advances in MRI techniques, including diffusion tensor imaging (DTI), diffusion-weighted imaging (DWI), magnetic resonance spectroscopy (MRS), perfusion-weighted imaging (PWI) and susceptibility-weighted imaging (SWI) provide useful information regarding the tumour. Computed Tomography (CT), especially when performed with bone window images, continues to be useful in the assessment of calcifications and hyperostosis. The new imaging modalities such as Positron Emission Tomography (PET), Hybrid PET-MRI systems, and the application of radiomics in imaging further help in improving the accuracy of the imaging studies and in developing patient-specific management protocols. Functional imaging techniques are increasingly being employed in the preoperative planning of neurosurgical interventions, especially in the case of lesions adjacent to eloquent areas. The limitations of advanced and modern imaging modalities in the evaluation of intracranial meningiomas. The emphasis has been placed on the role of imaging in the diagnosis, grading, preoperative planning, treatment monitoring, and prognostication of meningiomas. The integration of the multiparametric imaging techniques has become essential in achieving the best possible outcome in the neuro-oncological patient.
Keywords: *Intracranial meningiomas; Magnetic Resonance Imaging (MRI); Diffusion-weighted imaging; Perfusion imaging; Positron Emission Tomography; Radiomics; Tumor grading; Preoperative planning.*

1. Introduction

Meningiomas are slow-growing tumors that develop from the arachnoid cap cells of the meninges. Meningiomas make up 30-40% of all brain tumours. They are more common in women and in older individuals. Most meningiomas are benign (grade I). In contrast, atypical (grade II) and anaplastic (grade III) meningiomas show aggressive behaviour and have a high rate of recurrence (1). In the diagnosis of meningiomas, imaging has a crucial role. preoperative evaluation, treatment planning, and follow-up of patients with intracranial meningiomas (2). Conventional imaging modalities like CT and MRI can give information about the structural details of the tumour as well as the surrounding brain tissue. However, it is difficult to assess the grade, nature, and behaviour of the tumour with such imaging modalities (3). It is now possible to get information about the functional, metabolic, and molecular details of brain tumours with the recent advancements in neuroimaging modalities. The cellularity, vascularity, and metabolic activity of brain tumours can be better understood with advanced imaging

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modalities like diffusion-weighted imaging, perfusion imaging, magnetic resonance spectroscopy, and positron emission tomography (4). Currently, intracranial meningiomas are diagnosed using a combination of computed tomography and magnetic resonance imaging. The supratentorial location of almost 90% of intracranial meningiomas is often parasagittal along the convexity or in the sphenoid. [13-19]

1.1.Conventional Imaging Techniques

1.1.1. Computed Tomography (CT)

In 72–85% of cases, CT scans reveal typical diagnostic characteristics, such as a lobular mass with a broad-based dural attachment that is firmly delimited. Meningiomas usually show up on unenhanced CT as homogenous, hyperdense extra-axial masses that exhibit homogeneous enhancement once contrast is administered (5). Many meningiomas are initially discovered on CT scans taken for various purposes [1-6]. CT is useful for diagnosing meningioma because it is better at showing the effects of this tumour on surrounding bone, particularly hyperostosis linked to benign meningiomas or osseous destruction in atypical or malignant meningiomas, and is more sensitive in identifying psammomata's calcifications in the tumour (visible grossly in around 25% of meningiomas) (6).

1.1.2. MRI

Meningioma often show up as homogenous extra axial masses on MRI and depending on the degree of calcification they may also exhibit contrast enhancement because it offers higher soft tissue contrast and good contrast discrimination MRI has emerged as the preferred modality [6]. Magnetic resonance imaging (MRI) is crucial for evaluating meningiomas. T1-weighted imaging (T1WI) provides anatomical details, whereas T2-weighted imaging (T2WI) and T2 fluid-attenuated inversion recovery Soft tissue contrasts are highlighted by (T2FLAIR) imaging. Meningiomas usually exhibit enhancement in contrast-enhanced magnetic resonance imaging (MRI) because of dural infiltration or reactive vascularization (7). In neurooncology, these techniques are usually based on MRI, e.g., MR spectroscopy (MRS), perfusion-weighted imaging (PWI), positron emission tomography (PET) and diffusion-weighted imaging (DWI). Thus far, the primary identification of hemorrhage, intracranial vascular visualization, thromboembolism detection, and general discrimination of degenerative intracranial calcifications from hemorrhage have been the principal uses of SW-MRI for brain imaging.

1.1.3. Diffusion-Weighted Imaging (DWI)

Diffusion-weighted imaging (DWI) evaluates the random motion of water molecules within tissues and provides insight unto tumour cellularity. In meningiomas, highly cellular tumour tend to restrict diffusion, resulting in low apparent diffusion coefficient (ADC) values. Studies have demonstrated that atypical and malignant meningiomas often exhibit lower ADC values compared to benign (WHO Grade 1) tumors (8).

1.1.4. Perfusion-Weighted Imaging (PWI)

PWI measures tumor vascularity and hemodynamic using parameters such as relative cerebral blood volume (rCBV) and cerebral blood flow (CBF). Meningiomas typically show elevated rCBV due to their hyper vascular nature. Higher-grade tumors often demonstrate increased perfusion, reflecting enhanced angiogenesis. PWI is valuable in tumor grading, differentiation, and detection of recurrence (9).

1.1.5. Magnetic Resonance Spectroscopy (MRS)

MRS helps in the interpretation of the metabolic activity of the tumours by using biochemical parameters. Meningiomas show high levels of choline, decreased levels of NAA, and the presence of alanine. These characteristics help in differentiating meningiomas from other tumours in the brain (10).

1.1.6. Susceptibility-Weighted Imaging (SWI)

SWI is sensitive to the difference in magnetic susceptibility and is used for detecting calcification, hemorrhages, and veins within the tumor. In meningiomas, it helps in detecting the calcification within the tumor and its vascular architecture (11).

1.1.7. Diffusion Tensor Imaging (DTI)

DTI assesses the direction of water diffusion and can visualize white matter tracts. This technique is important in the preoperative assessment because it can determine if the adjacent white matter tracts are

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involved by the tumor. FA values can provide information on the tumor-brain interaction, which is important in the surgical approach (12).

1.1.8. Radiomics and Artificial Intelligence

Radiomics is based on the use of machine learning algorithms on the data extracted from images. This helps in the prediction of tumor grades, recurrence, and genetics, thereby leading to personalized medicine approaches (13).

1.1.9. Arterial Spin Labelling (ASL)

ASL is an non-invasive perfusion imaging technique, and it utilizes magnetically labeled arterial blood as an imaging tracer. It is able to quantitatively measure tumour blood flow without needing any contrast agents, which is useful for patients with renal impairment and contrast allergies. (14)

2. Method

PubMed, Web of Science, and Google Scholar were used to do an extensive literature review for research published between 2000 and 2025, using keywords such as “intracranial meningioma,” “advanced MRI,” “diffusion-weighted imaging,” “perfusion imaging,” “MR spectroscopy,” “PET imaging,” “radiomics,” and “artificial intelligence.” Studies were included if they were original research articles, review articles, or meta-analyses published in English and focused on advanced imaging techniques for intracranial meningiomas in human subjects.

3. Discussion

Modern imaging particularly CT, MRI, and advanced radiologic methods has grown into a very reliable and non-invasive tool for identifying and treating meningiomas. It not only identifies and monitors tumours with accuracy, but is increasingly capable of giving biological and prognostic information (such as predicting cancer grade), therefore playing a vital role in treatment planning and outcome evaluation. (15)
Advanced imaging techniques, particularly advanced MRI and PET (including SSTR-targeted ligands), as well as emerging approaches such as radiomics and AI-based analysis, have a high potential for improving meningioma diagnosis, characterization, and clinical management [13-19]. Hybrid PET/MRI and ultra-high-field MRI improve these capabilities even more. However, for these approaches to become part of ordinary clinical practice, their findings must be confirmed against neuropathological norms. (16)
The evaluation of meningiomas has significantly improved thanks to ongoing advancements in imaging modalities, particularly MRI and CT, which provide high-resolution structural features along with practical functional insights like diffusion and perfusion properties. These features, along with new techniques like intra-arterial contrast MR perfusion, have made modern imaging an essential and highly successful tool for meningioma assessment and treatment. [17] Diffusion-weighted MRI (DWI) is a valuable tool for differentiating atypical or malignant meningiomas from benign ones, as the more aggressive tumors typically exhibit significantly lower apparent diffusion coefficient (ADC) and normalized ADC (NADC) values. Using specific threshold values—such as an ADC of 0.80×10^{-3} mm^2/s and an NADC of 0.99—provides high sensitivity and specificity, making these quantitative markers clinically useful [7-12]. Additionally, a decline in ADC or NADC on follow-up imaging may indicate tumor growth or progression to a higher grade, enabling earlier detection of aggressive disease. Imaging features like irregular margins, peritumoral edema, and adjacent bone destruction further support the diagnosis of more aggressive meningiomas. DWI is also effective for monitoring recurrence, as changes in signal intensity and decreasing ADC/NADC ratios can suggest tumor progression over time. (18) Atypical and malignant meningiomas can be distinguished from normal (benign) meningiomas using diffusion-weighted MRI; the intratumoral ADC values of atypical and malignant tumors are significantly lower. Additionally, ADC values can help distinguish between histological subtypes of typical meningiomas, such as meningothelial, transitional, fibroblastic, and angiomatous, which have distinct diffusion characteristics. Diagnostic reliability is demonstrated by the statistically significant difference in ADC values between normal and atypical/malignant meningiomas. Nevertheless, there is little variation in ADC values for peritumoral edema across tumor types, which limits its use in grading. (19)

Conclusion

In order to diagnose, characterize, and treat meningiomas without invasive procedures, radiology imaging modalities like CT and MRI are essential. Advanced methods like diffusion-weighted imaging, perfusion imaging, and innovative approaches like radiomics and artificial intelligence (AI) now offer important biological and prognostic information like tumor grading and behavior prediction in addition to precise tumor detection and monitoring. When it comes to identifying tumor progression or recurrence, as well as differentiating benign from atypical or malignant meningiomas, quantitative metrics such as ADC and NADC have demonstrated exceptional diagnostic performance.

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