ADVANCES IN MENINGIOMA DIAGNOSIS AND TREATMENT: A COMPREHENSIVE REVIEW

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Abstract
Meningiomas, the most prevalent primary intracranial tumors, account for over one-third of brain neoplasms. Though often benign, their diagnosis and treatment are complex due to variability in clinical presentation, anatomical location, and biological behavior. This review examines cutting-edge diagnostic tools, including MRI, PET, and molecular profiling, alongside treatment modalities such as surgery, radiotherapy, and emerging targeted therapies. We address challenges in managing atypical and malignant meningiomas, emphasizing recurrence and resistance to conventional approaches. The integration of multidisciplinary strategies and future research directions, including immunotherapy and precision medicine, are highlighted as critical for improving patient outcomes.

Keywords: Meningioma, diagnosis, treatment, surgery, radiotherapy

ДОСТИЖЕНИЯ В ДИАГНОСТИКЕ И ЛЕЧЕНИИ МЕНИНГИОМ: ВСЕСТОРОННИЙ ОБЗОР

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Аннотация
Менингиомы, наиболее распространенные первичные внутричерепные опухоли, составляют более трети новообразований мозга. Хотя они часто доброкачественные, их диагностика и лечение сложны из-за вариабельности клинической картины, анатомического расположения и биологического поведения. В этом обзоре рассматриваются передовые диагностические инструменты, включая МРТ, ПЭТ и молекулярное профилирование, наряду с такими методами лечения, как хирургия, лучевая терапия и новые таргетные методы лечения. Мы рассматриваем проблемы в лечении атипичных и злокачественных менингиом, подчеркивая рецидивы и устойчивость к традиционным подходам. Интеграция междисциплинарных стратегий и будущих направлений исследований, включая иммунотерапию и прецизионную медицину, подчеркивается как критически важная для улучшения результатов лечения пациентов.

Ключевые слова: Менингиома, диагностика, лечение, хирургия, лучевая терапия.

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Introduction

Meningiomas arise from arachnoid cap cells in the meninges and constitute approximately 36% of primary intracranial tumors [1]. The World Health Organization (WHO) classifies them into Grade I (benign), Grade II (atypical), and Grade III (malignant) based on histopathological and molecular features, with recurrence risk escalating across grades [2]. Often asymptomatic and detected incidentally via imaging, meningiomas can also present with seizures, focal deficits, or intracranial hypertension, necessitating intervention. Advances in diagnostic imaging and molecular understanding have refined detection and prognosis, while treatment options—ranging from observation to surgery and novel therapies—continue to evolve. This review comprehensively explores these advancements, focusing on diagnostic precision and therapeutic innovation.

Comprehensive Review

Literature Review

Epidemiology and Risk Factors

Meningiomas predominantly affect adults, with incidence peaking between 60 and 70 years and a notable female predominance (2:1), potentially linked to hormonal influences like progesterone receptor expression [3]. Ionizing radiation, a well-established risk factor, increases incidence decades after exposure, as seen in atomic bomb survivors and patients treated with cranial irradiation [4]. Neurofibromatosis type 2 (NF2), caused by mutations in the NF2 gene on chromosome 22, predisposes individuals to multiple meningiomas, often presenting in younger patients [5]. Emerging research also explores obesity, diabetes, and head trauma as potential contributors, though causality remains debated [1]. Environmental and genetic interactions likely underpin meningioma etiology, warranting further longitudinal studies.

Diagnostic Advances

Neuroimaging drives meningioma diagnosis, with MRI as the cornerstone due to its ability to delineate tumor margins, dural attachment, and edema. Typical features include a homogeneous, contrast-enhancing mass, often with a "dural tail" sign [6]. Advanced MRI techniques—diffusion-weighted imaging (DWI), perfusion imaging, and magnetic resonance spectroscopy—enhance differentiation of tumor grade by assessing cellularity, vascularity, and metabolic profiles [5]. For example, lower apparent diffusion coefficient (ADC) values on DWI correlate with higher-grade meningiomas due to increased cellular density [6].

Positron emission tomography (PET) with somatostatin receptor ligands (e.g., 68Ga-DOTATATE) has emerged as a powerful adjunct, particularly for skull base meningiomas or post-treatment evaluation, distinguishing tumor from scar tissue with high specificity [7]. Histopathology, guided by the 2021 WHO classification, remains definitive, incorporating molecular markers like TERT promoter mutations, CDKN2A/B deletions, and SMARCE1 alterations to predict aggressive behavior [2]. Liquid biopsies detecting circulating tumor DNA are under investigation, offering a non-invasive diagnostic frontier [8].

Treatment Modalities

Management hinges on tumor characteristics and patient health. Asymptomatic Grade I meningiomas, often incidental, may be monitored with serial imaging, as growth rates are typically slow (0.5–2 mm/year) [4]. Symptomatic or enlarging tumors usually require surgery, aiming for Simpson Grade I resection (complete tumor and dural removal), which minimizes recurrence to less than 10% at 10 years [5]. However, locations near critical structures—e.g.,

cavernous sinus or optic chiasm—often preclude total resection, necessitating subtotal approaches (Simpson Grade III–IV) with higher recurrence rates [9].

Radiotherapy complements surgery, particularly for Grade II/III or inoperable tumors. Stereotactic radiosurgery (SRS) delivers precise, high-dose radiation, achieving 90–95% control for small Grade I meningiomas, while fractionated radiotherapy suits larger lesions near eloquent areas [9]. Adjuvant radiotherapy post-resection reduces recurrence in atypical meningiomas, though survival benefits in malignant cases remain modest [10].

Systemic therapies have historically lagged, with chemotherapy (e.g., hydroxyurea, temozolomide) yielding limited responses [11]. However, molecular advances are reshaping this landscape. Somatostatin receptor expression has spurred trials of analogs like octreotide, with variable efficacy [12]. Angiogenesis inhibitors (e.g., bevacizumab) target VEGF in recurrent meningiomas, stabilizing disease in small cohorts [13]. Immunotherapy, including PD-1/PD-L1 inhibitors, is being explored for high-mutation-burden tumors, with early-phase trials showing promise [8] mTOR inhibitors like everolimus also target the PI3K/AKT pathway, offering a precision medicine approach [11].

Discussion

The evolution of meningioma diagnosis reflects a synergy of imaging and molecular science. MRI's precision, augmented by DWI and PET, allows earlier detection and grade prediction, yet challenges persist in distinguishing benign from malignant tumors preoperatively. Molecular profiling, integrating TERT mutations and other markers, enhances prognostic accuracy but requires broader clinical adoption and cost reduction [2]. Disparities in access to advanced diagnostics, especially in resource-limited regions, further complicate equitable care [7].

Surgery remains the gold standard for symptomatic meningiomas, yet recurrence—30–40% for Grade II and 50–80% for Grade III—underscores its limitations [5]. Intraoperative technologies like fluorescence-guided resection (e.g., 5-ALA) and neuronavigation improve extent of resection, particularly in eloquent areas, but their availability is not universal [6]. Radiotherapy's role has solidified, with SRS offering excellent control for small tumors, though long-term risks like secondary malignancies or neurocognitive decline warrant caution, especially in younger patients [10].

Systemic therapy's slow progress reflects meningiomas' molecular heterogeneity. While bevacizumab and mTOR inhibitors show potential, their efficacy is confined to subsets of patients, highlighting the need for biomarker-driven trials [11,13]. Immunotherapy's success in other cancers fuels optimism, but meningiomas' low mutational burden may limit checkpoint inhibitor efficacy, necessitating combination strategies [8]. Skull base meningiomas exemplify treatment dilemmas, balancing tumor control with cranial nerve preservation—often best achieved via subtotal resection plus SRS [9].

Patient-specific factors, including age, comorbidities, and tumor biology, increasingly guide management. Elderly patients with incidental meningiomas may benefit more from observation than aggressive intervention, while younger patients with NF2-associated tumors require lifelong surveillance [4]. Psychosocial support and shared decision-making are vital, particularly for asymptomatic cases where "watchful waiting" may provoke anxiety [1].

Future advances hinge on integrating diagnostics and therapeutics. Artificial intelligence (AI) could refine imaging interpretation, predicting tumor behavior from radiographic features, while gene-editing technologies like CRISPR may target NF2 mutations [6]. Collaborative

registries and international trials will accelerate these innovations, addressing gaps in rare Grade III meningioma management.

Conclusion

Meningiomas exemplify the intersection of diagnostic sophistication and therapeutic challenge. Advances in MRI, PET, and molecular profiling have sharpened diagnostic precision, while surgery and radiotherapy remain foundational treatments. Emerging therapies—targeting somatostatin receptors, angiogenesis, and immune checkpoints—signal a shift toward personalized care, though their full potential awaits rigorous validation. Multidisciplinary collaboration is essential to navigate meningiomas' complexity, particularly for recurrent or malignant subtypes. Future research must prioritize accessible diagnostics, novel therapeutics, and patient-centered outcomes to transform meningioma management in the coming decades.

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