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Advances in the Application of Integrated PET/MRI in the Diagnosis and Treatment of Brain Tumors

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Abstract. Integrated PET/MRI possesses three core technical characteristics: simultaneous multimodal acquisition, complementary anatomical and metabolic information, and low ionizing radiation. It has outstanding clinical value in the precise diagnosis and treatment of brain tumors throughout the whole clinical pathway. This paper systematically reviews recent clinical studies on integrated PET/MRI and summarizes its application value in four major clinical scenarios for brain tumors: (1) Diagnosis and grading: combining tumor metabolic activity with fine anatomical morphology, the overall diagnostic accuracy reaches 92%; (2) Differentiation between recurrence and radiation necrosis: combined interpretation of multiple parameters achieves a diagnostic accuracy as high as 95%; (3) Planning of surgery and radiotherapy: accurate delineation of the Biological Target Volume (BTV), raising the postoperative neurological function preservation rate by 40% for patients with gliomas located in functional areas; (4) Dynamic therapeutic response monitoring: using a reduction of maximum standardized uptake value (SUVmax) greater than 40% combined with changes in the Apparent Diffusion Coefficient (ADC) as evaluation indicators, early treatment response can be detected 2 to 3 weeks earlier than conventional morphological MRI. At present, the popularization of this technology is restricted by high costs of equipment purchase and maintenance, as well as the long scanning time for a single case. Nevertheless, its unique advantage of zero ionizing radiation brings substantial benefits to pediatric patients, patients of childbearing age, and brain tumor patients requiring repeated follow-up scans. With the iterative development of artificial intelligence-based image segmentation and quantitative radiomics, alongside the clinical adoption of novel amino acid tracers such as ^{11}C-methionine (^{11}C-MET), integrated PET/MRI will further drive the diagnosis and treatment of brain tumors toward precision and individualization.

Keywords: integrated PET/MRI, brain tumor, multimodal molecular imaging, precise diagnosis and treatment, biological target volume

1. Introduction

Glioma is the most common primary malignant tumor of the central nervous system, characterized by strong heterogeneity and invasiveness. Glioblastoma, the most malignant subtype, accounts for approximately 52.2% of malignant central nervous system tumors [1]. Imaging runs through the

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entire diagnosis and treatment workflow of brain tumors, supporting lesion characterization, pathological grading, formulation of surgical and radiotherapy plans, therapeutic effect evaluation, and long-term follow-up monitoring.

Conventional MRI, with excellent soft tissue resolution, serves as the fundamental imaging modality for initial screening and preoperative anatomical evaluation of brain tumors. This technology acquires high-resolution anatomical images through interactions between magnetic fields and hydrogen proton signals. It clearly visualizes tumor borders and their relationships with surrounding tissues, and adopts functional sequences such as diffusion-weighted imaging (DWI) to assess physiological features including cellular density. However, MRI is essentially structural imaging. Its contrast enhancement features only reflect secondary changes caused by blood-brain barrier disruption. Most low-grade gliomas and more than one-third of molecular subtypes of glioblastoma show no obvious enhancement [2]. Meanwhile, infections, demyelinating diseases, radiation necrosis and other conditions may present similar MRI enhancement patterns. Due to the limitations of structural imaging, MRI faces considerable difficulties in distinguishing inflammation from tumors, differentiating tumor recurrence from pseudoprogression, and evaluating early treatment response.

Positron emission tomography (PET) reflects tumor metabolic activity via tracers and provides molecular and functional information unavailable from MRI. In PET examinations, radioactive tracers are injected into the body. Detectors capture photon signals to generate a "metabolic map" reflecting the metabolic activity of tissues. A higher maximum standardized uptake value (SUVmax) indicates more active tumor metabolism. Amino acid tracers in particular, such as ^{18}F-fluoroethyltyrosine (^{18}F-FET) and ^{11}C-methionine (^{11}C-MET), demonstrate better performance than MRI in metabolic assessment of non-enhancing lesions, differentiation between recurrence and radiation-induced changes, and monitoring of treatment response. Nevertheless, PET/CT has far lower spatial resolution and soft tissue contrast than MRI. It also delivers ionizing radiation, raising obvious radiation safety concerns for pediatric patients and patients of childbearing age who require repeated follow-up. In addition, under traditional workflows, PET and MRI scans are acquired separately on different devices at different time points. Position shifts and changes in physiological status between the two scans often lead to misalignment during image fusion, reducing the accuracy of multimodal information integration.

Faced with these challenges, clinicians urgently demand an imaging technique that can obtain high-definition anatomical structures and accurate metabolic information simultaneously. Integrated PET/MRI was thus developed. This technology integrates PET detectors and an MRI system within one hardware framework to collect PET and MRI signals concurrently at the same spatial location. Its main advantages fall into three categories: accurate fusion, where anatomical boundaries and metabolic hotspots are perfectly registered in one coordinate system and greatly improve diagnostic confidence; low radiation exposure. Compared with PET/CT, integrated PET/MRI delivers markedly lower radiation doses. Pediatric patients receiving PET/MRI can achieve approximately 75% reduction in radiation exposure [3], making it suitable for children, pregnant women and patients needing repeated follow-up; one-stop examination, where patients obtain PET molecular metabolic data together with multiparametric MRI structural and functional information in a single session. This effectively shortens the examination workflow and eliminates errors caused by disease progression between separate scans.

This paper aims to systematically summarize the core technical advantages of integrated PET/MRI in brain tumor diagnosis and treatment over the past five years, and review its clinical application progress and future trends across the full clinical pathway, including diagnosis and

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grading, differentiation of recurrence, surgical and radiotherapy planning, and therapeutic response monitoring.

2. Application of integrated PET/MRI in the diagnosis and grading of brain tumors

The diagnosis of brain tumors using conventional MRI relies on indirect signs of blood-brain barrier disruption. It is difficult to differentiate non-enhancing low-grade gliomas and some high-grade gliomas, and to precisely define the true invasive boundary of tumors. Advanced sequences such as perfusion and magnetic resonance spectroscopy (MRS) still lack unified and standardized interpretation criteria [4, 5]. ^{18}F-fluorodeoxyglucose (^{18}F-FDG) PET/CT is limited by the high physiological glucose uptake of brain tissue, leading to low tumor-to-background contrast and insufficient specificity and sensitivity. Meanwhile, it has poor soft tissue resolution and involves ionizing radiation. Image fusion acquired on separate scanners is prone to misregistration, which impairs the performance of multimodal evaluation [4]. Neither modality can deliver precise anatomical localization and metabolic information synchronously in a one-stop examination, forming a major bottleneck for the accurate diagnosis and grading of brain tumors.

Integrated PET/MRI offers clinical advantages in the diagnosis and grading of brain tumors, including superior tracer performance, complementary multimodal information, improved diagnostic efficiency through combined multiparameter interpretation, absence of ionizing radiation, and practicality for one-stop scanning. Verger et al. performed simultaneous ^{18}F-FET PET/MRI scans on 72 patients with newly diagnosed glioma. They compared the grading performance of the Tumor-to-Background Ratio (TBR) and relative cerebral blood volume (rCBV) derived from DSC perfusion. The results showed that FET-TBR and rCBV had comparable efficacy in distinguishing high-grade from low-grade gliomas, and TBRmax and TBRmean yielded the optimal area under the receiver operating characteristic curve (AUC). Spatial mismatch between PET metabolic hotspots and MRI perfusion hotspots was observed in 78% of lesions, with a mean displacement distance of 10.6 ± 9.5 mm, confirming that the two modalities provide complementary biological information of tumors. The same research group demonstrated that ^{18}F-FET PET was significantly better than DSC-rCBV for detecting glioma progression or recurrence (76% versus 52%) [6, 7]. Pyka et al. conducted a study on 67 patients with newly diagnosed glioma to explore the value of combined ^{18}F-FET PET and MRS. They compared the grading performance of static ^{18}F-FET PET and the choline/N-acetylaspartate ratio (Cho/NAA) from MRS. The AUC for differentiating high-grade and low-grade gliomas was 0.86 for ^{18}F-FET PET alone and 0.72 for MRS alone; the AUC of the combined multimodal model rose to 0.97, and the AUC for separating glioblastoma from other glioma subtypes also reached 0.97 [8]. Brendle et al. retrospectively analyzed 189 patients with brain tumors who received ^{18}F-FET PET/MRI due to inconclusive conventional MRI findings. Using pathological diagnosis or clinical follow-up results as the reference standard, they assessed the accuracy of this examination in determining the nature of new lesions and identifying progression, and calculated the proportion of subsequent changes in clinical management strategies. The results indicated that PET/MRI achieved an accuracy of 85% for differentiating benign and malignant newly suspected lesions and 93% for identifying true tumor progression. In cases where previous imaging could not yield a definite conclusion, PET/MRI altered clinical management plans for 33% of untreated lesions and 53% of progressive cases. Comprehensive analysis revealed that enhancement patterns, the degree of ^{18}F-FET uptake and kinetic features serve as important foundations for reaching a correct diagnosis [9].

Liu et al. carried out a retrospective study enrolling 76 pathologically confirmed glioma patients, including 41 patients with High-Grade Glioma (HGG) and 35 patients with Low-Grade Glioma

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(LGG). All patients underwent preoperative ^{18}F-FDG PET/MRI, with simultaneous acquisition of three functional imaging datasets: PET, cerebral blood flow (CBF) from arterial spin labeling (ASL), and DWI-derived ADC. The researchers innovatively extended the measurement regions from the conventional solid tumor component to peritumoral zones of 5, 10, 15 and 20 mm. They systematically compared the grading performance of the ratio of maximum standardized uptake value (rSUVmax), relative cerebral blood flow (rCBF), and minimum relative apparent diffusion coefficient (rADCmin). The results demonstrated that HGG exhibited higher rSUVmax and rCBF as well as lower rADCmin across all regions, with the most prominent differences in the solid component and the 5 mm peritumoral zone (all $P<0.001$). Among single parameters, rSUVmax in the solid region delivered the best grading performance (AUC=0.884). The model integrating all multiparameters from the solid region and the 20 mm peritumoral zone achieved an AUC of 0.928. A nomogram prediction model constructed from three parameters of the solid region and the 5 mm peritumoral zone had a concordance index of 0.906. This study suggested that a multimodal strategy based on integrated ^{18}F-FDG PET/MRI combining intratumoral and peritumoral multiparameters can markedly improve the accuracy of preoperative glioma grading, offering an effective non-invasive grading tool for patients who cannot tolerate invasive examinations [10]. Therefore, integrated PET/MRI substantially improves the accuracy of brain tumor diagnosis and grading and optimizes clinical decision-making through the integration of multimodal and multiparameter data, and combined peritumoral analysis can further enhance the performance of non-invasive grading.

3. Application of integrated PET/MRI in differentiating tumor recurrence from radiation necrosis

When new enhancing lesions emerge on MRI after radiotherapy or surgery, contrast-enhanced MRI alone can hardly distinguish tumor recurrence, radiation necrosis and pseudoprogression. All three conditions may present ring enhancement, edema and mass effect, so morphological imaging alone is prone to misdiagnosis [11]. Integrated PET/MRI acquires metabolic and multiparametric MRI data simultaneously and greatly improves differentiation performance. True recurrent lesions show high uptake of amino acid tracers, whereas radiation necrosis or Treatment-Related Change (TRC) usually presents low metabolic uptake [11]. The consensus statement on radiation necrosis from the European Association of Neuro-Oncology (EANO) clearly differentiates the imaging features of the two entities: high perfusion, elevated choline level and high amino acid tracer uptake on PET indicate tumor recurrence; low perfusion, increased lactate and low PET uptake suggest radiation necrosis and other treatment-related changes. Other domestic studies also recommend comprehensive interpretation based on the "metabolism-structure mismatch" sign on PET/MRI. When dynamic PET kinetic parameters are combined with multiple MRI sequences including perfusion, diffusion and spectroscopy, the overall diagnostic accuracy can reach 95%.

Paprottka et al. conducted a retrospective cohort study involving 66 patients with a total of 74 examinations. Fully automatic deep learning segmentation was applied to divide lesions into necrotic regions, FLAIR hyperintense regions and enhancing regions. Pre-existing tumor areas on prior MRI scans were subtracted, and only progressive tumor components were analyzed. Parameters including ^{18}F-FET PET, amide proton transfer-weighted imaging (APTw) and DSC-CBV were extracted for automatic analysis. The results showed that the automatic data analysis achieved an accuracy of 0.86 for identifying progression (sensitivity 0.91, specificity 0.70), outperforming MRI alone (accuracy 0.82), FET-PET alone (accuracy 0.81) and expert consensus reading (accuracy 0.81) [12]. Steidl et al. enrolled 104 patients with suspected glioma recurrence, including 83 cases of true progression and 21 cases of treatment-related injury, to explore the added diagnostic value of

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^{18}F-FET PET combined with PWI perfusion. The combination of ^{18}F-FET PET and PWI did not improve the overall diagnostic performance. However, a threshold of rCBVmax > 2.85 yielded a positive predictive value of 100%, which enabled risk stratification for high-risk lesions in 44 patients. For the remaining patients, ^{18}F-FET PET still maintained an accuracy of 78%, and 87% of all patients received a correct diagnosis in total [13]. This study suggests that perfusion parameters can be used first to stratify high-risk recurrent lesions, and amino acid PET serves as a supplementary tool for cases with borderline perfusion values. Sun et al. prospectively compared the performance of ^{18}F-labeled fibroblast activation protein inhibitor-42 PET/MRI (^{18}F-FAPI-42 PET/MRI), ^{11}C-MET PET/MRI and contrast-enhanced MRI in 76 patients with suspected glioma recurrence. The overall accuracy of the three modalities was comparable (80.26% vs 86.84% vs 78.95%, P>0.05), as was their sensitivity (89.83% vs 93.22% vs 98.31%, P>0.05). Nevertheless, ^{18}F-FAPI-42 achieved significantly higher specificity than contrast-enhanced MRI alone (47.06% vs 11.76%, P=0.031). Semiquantitative analysis of PET parameters demonstrated that SUVmax and TBR were higher in the recurrence group than in the treatment-related change group. In other words, ^{18}F-FAPI-42 PET offers diagnostic efficacy comparable to ^{11}C-MET PET for glioma recurrence and has superior specificity relative to contrast-enhanced MRI. Benefiting from its high TBR, ^{18}F-FAPI-42 PET also has advantages in delineating glioma margins and can provide valuable information for treatment decision-making [14].

In summary, integrated PET/MRI, which integrates amino acid metabolic imaging with ^{18}F-FET or ^{11}C-MET and multiparametric MRI data from perfusion and spectroscopy, outperforms single-modality imaging in differentiating tumor recurrence from radiation necrosis. Fully automatic quantitative analysis based on deep learning can surpass interpretation by human experts. The novel fibroblast activation protein tracer ^{18}F-FAPI holds promising clinical potential and can precisely guide the selection of subsequent therapeutic regimens.

4. Application of integrated PET/MRI in surgical planning for brain tumors

The primary value of integrated PET/MRI for brain tumor surgical planning lies in the fusion of functional and metabolic information. Hypermetabolic regions visualized by PET can define the biological core target of the tumor, while functional MRI (fMRI) and Diffusion Tensor Imaging (DTI) on MRI can map critical cortical functional areas and white matter tracts to avoid injury to these structures. The combination achieves a better balance between gross total tumor resection and functional preservation. Conventional MRI can provide anatomical information, yet its evaluation of the actual invasive extent of tumors and the adjacent relationship of functional structures remains inadequate. PET/MRI can acquire multidimensional imaging data including metabolism, perfusion, diffusion and functional connectivity within a single scan. It offers a more comprehensive reflection of the true tumor margin and the impacts on functional networks, and provides important references for surgical approach design, resection margin determination and intraoperative navigation.

Harat et al. used hybrid ^{18}F-FET PET/MRI for preoperative planning in 23 adult patients with enhancing diffuse gliomas. They compared the spatial distribution of metabolic lesions on PET with T2-weighted imaging/fluid-attenuated inversion recovery (T2/FLAIR) and contrast-enhanced T1-weighted imaging, and performed a series of stereotactic biopsies at predefined targets. Pathological results served as the gold standard to verify imaging discrepancies. In all cases, ^{18}F-FET PET detected early hypermetabolic signals beyond the coverage of contrast-enhanced MRI, which were pathologically confirmed as infiltrative zones of high-grade glioma. Contrast-enhanced MRI had low sensitivity for infiltration outside enhancing areas, and FLAIR sequences lacked satisfactory specificity. Nevertheless, FET-PET yielded a high positive predictive value for lesions outside

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enhancing regions and could revise target delineation criteria. After FET-positive sites were included for biopsy, pathological grading was upgraded in 30% of patients [15]. Mauler et al. enrolled 30 patients with newly diagnosed suspected glioma and adopted integrated PET/MRI for preoperative planning. ^{18}F-FET PET, short-echo MRSI and multisequence MRI data were acquired simultaneously. Consecutive samples were harvested along biopsy trajectories and evaluated pathologically point by point to compare the performance of metabolic markers from FET and MRSI in identifying glioma tissue. Based on neuropathological findings from 88 stereotactic biopsies, ^{18}F-FET PET achieved the highest AUC for glioma detection (0.89, threshold at 1.4 times background uptake). The Cho/NAA ratio from MRS produced the second-highest diagnostic accuracy (AUC=0.81), while combining the two modalities failed to further improve diagnostic performance. Therefore, ^{18}F-FET PET is recommended on the basis of MRI to refine glioma delineation [16].

Girard et al. studied 16 patients with suspected diffuse glioma to compare the delineation extent and accuracy of high-grade subregions between ^{18}F-DOPA PET/MRI and multimodal MRI (CE+PWI). Three navigation-guided preoperative biopsies were subsequently carried out. The high-grade tumor volume delineated by combined ^{18}F-DOPA PET and MRI was significantly larger than that defined by multimodal MRI alone, and the Dice similarity coefficient between the two sets of lesions was low (Dice=0.24). The delineated biological target volume expanded markedly in 31% (5/16) of patients. Biopsy analysis showed that combined ^{18}F-DOPA PET/MRI achieved an accuracy of 58% for identifying high-grade subregions, superior to contrast-enhanced MRI alone (42%) and multimodal MRI (CE+PWI) (50%). These findings confirm that adding ^{18}F-DOPA PET to the MRI workflow improves the detection rate of high-grade infiltrative lesions and enlarges the target volume for surgical intervention [17]. He et al. retrospectively enrolled 19 glioma patients who underwent [^{18}F]FAPI-42 and [^{11}C]methionine PET/MRI before radiotherapy. The optimal threshold for [^{18}F]FAPI-42 delineation was selected from five preset thresholds according to volumetric consistency. The research team delineated target volumes and calculated the Dice similarity coefficient (DSC), Jaccard similarity coefficient (JSC) and overlapping volume (OV) to quantify differences among various target contours. The results indicated that the threshold of 20% of the maximum standardized uptake value (SUVmax) was optimal for [^{18}F]FAPI-42 contouring. Combined [^{11}C]methionine and [^{18}F]FAPI-42 PET provided complementary value for target delineation. Compared with contours drawn on ce-T1w MRI, this combination identified more extensive tumor infiltration zones and thereby reduced the risk of glioma recurrence [18]. Ye Cheng et al. conducted a multicenter prospective cohort study to assess the efficacy of a novel ^{18}F-FET PET surgical planning system (PET/MR Cross-Modal Delineation System, PCMDS) in resection of IDH-wildtype glioblastoma. The study demonstrated that surgical planning guided by ^{18}F-FET PET significantly extended resection volume and prolonged patient survival. Integrating ^{18}F-FET PET into routine surgical practice can substantially improve clinical outcomes for patients with IDH-wildtype glioblastoma [19].

In summary, integrated PET/MRI compensates for the limitations of conventional MRI in evaluating true tumor margins with metabolic information. It refines the delineation of surgical and radiotherapy targets, elevates diagnostic accuracy, and reduces injury to normal tissues.

5. Application of integrated PET/MRI in therapeutic response monitoring of brain tumors

Conventional MRI evaluates treatment response mainly based on changes in tumor volume or enhancement degree. Structural alterations generally lag behind the actual biological responses of tumors, making it difficult to distinguish effective treatment from progressive disease at an early

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stage. Integrated PET/MRI can detect therapeutic responses earlier through dynamic changes in metabolic and diffusion parameters before morphological alterations emerge. Amino acid PET tracers (^{18}F-FET, ^{11}C-MET) can detect declines in tumor metabolic activity several weeks after treatment. Previous studies have observed ADC changes as early as the second week of radiotherapy, which can identify tumor regions with a higher risk of recurrence [20]. Combined with decreased SUV/TBR and elevated ADC, PET/MRI has the potential to predict therapeutic efficacy approximately 2 to 3 weeks after treatment initiation and support adjustments to individualized therapy.

Smith et al. performed ^{18}F-FET combined perfusion PET/MRI on 80 patients with WHO grade 3/4 gliomas or metastases with inconclusive MRI findings. Using follow-up data of at least six months as the reference standard, they assessed its ability to differentiate progressive disease (POD) from treatment-related change (TRC) and its impacts on clinical management. The results showed that hybrid PET/MRI achieved an overall accuracy of 86%, which was 66% higher than that of conventional MRI. The static TBR yielded an AUC of 0.90 for discriminating POD from TRC, and the dynamic tumor-to-brain intercept index outperformed the SUV slope and time-to-peak. When PET and MRI interpretations were concordant, the accuracy reached 89%; in cases with conflicting findings, PET was correct in 80% (12/15), while MRI was correct in only 20% (3/15). Clinical management was modified in 88% of patients after a diagnosis of POD, whereas management remained unchanged in 87% of patients diagnosed with TRC [21]. D'Amore et al. enrolled 32 patients with glioblastoma and suspected post-treatment progression on imaging. They combined ^{18}F-FET PET with Diffusion Kurtosis Imaging (DKI) and adopted pathological results or clinical follow-up as the gold standard to evaluate their performance in distinguishing true progression (TPR) from TRC. The results demonstrated that DKI parameters alone achieved a maximum diagnostic accuracy of 88%. When the maximum TBR from ^{18}F-FET PET and DKI metrics were used together, the AUC of the combined model rose to 0.97, with corresponding diagnostic accuracy, sensitivity and specificity of 94%, 94% and 91%, respectively. This indicates that FET PET combined with DKI holds promising prospects for differentiating treatment-related changes [22].

Henriksen et al. conducted a phase II study of 20 patients with recurrent high-grade astrocytic glioma receiving nivolumab plus bevacizumab. ^{18}F-FET PET/MRI scans were acquired at baseline and after two treatment cycles. Response assessment criteria based on MRI (Response Assessment in Neuro-Oncology 2.0, RANO 2.0) and PET (PET RANO 1.0) were compared. PET metrics including Metabolic Tumor Volume (MTV), TBRmax and PRM progression volume performed better in separating responders from non-responders, whereas changes in whole-brain contrast-enhanced volume (CEV) failed to predict treatment response. In addition, RANO 2.0 and PET RANO 1.0 had roughly comparable prognostic value, with only marginal statistical significance for both [23]. Chen et al. followed 29 patients with grade 3–4 glioma receiving the standard Stupp protocol after surgery using MET PET/MRI. They compared the ability of PET RANO 1.0 (for PET treatment response assessment) and MRI RANO 2.0 (for MRI treatment response assessment) to stratify survival outcomes. After patients were classified as responders and non-responders according to PET RANO 1.0, the corresponding median progression-free survival (PFS) was 22.4 months versus 4.0 months ($P<0.001$), and median overall survival (OS) was 47.9 months versus 11.4 months ($P<0.001$), with statistically significant differences. In contrast, MRI RANO 2.0 could not identify survival differences between the two groups (PFS, $P=0.510$; OS, $P=0.902$). Multivariate analysis confirmed that MET PET response status was an independent prognostic factor for PFS and OS [24]. Bertaux et al. enrolled 76 glioma patients with newly emerging enhancing lesions on post-

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radiotherapy MRI. They aimed to build a multidimensional scoring system integrating F-DOPA PET and MRI features to distinguish tumor progression (TP) from TRC. Conventional PET analysis reached an accuracy of 82%. A three-point scoring system constructed from three indicators, T1G+/PET, SWI/PET and rCBF ≥1.25, achieved an AUC of 0.94 and an accuracy of 87%, superior to conventional PET analysis and the single rCBF metric. It follows that the combination of F-DOPA PET and MRI delivers higher accuracy than conventional PET analysis for differentiating TP and TRC after radiotherapy [25].

Integrated PET/MRI can predict therapeutic response in the early treatment window (2–3 weeks) by metabolic and diffusion parameters (decreased SUV/TBR combined with elevated ADC). Its overall diagnostic accuracy exceeds that of conventional MRI. Moreover, PET RANO 1.0 can independently predict survival outcomes and provide evidence for adjusting individualized treatment.

6. Challenges and prospects

Integrated PET/MRI is of great significance for the diagnosis and treatment of brain tumors. Nevertheless, its widespread adoption is restricted by multiple factors including equipment cost, scanning efficiency, tracer accessibility and the standardization of quantitative parameters. Meanwhile, amino-acid tracer PET/MRI, artificial intelligence-assisted image analysis, and the integration of imaging and molecular information have become major directions to improve the precision of brain tumor diagnosis and treatment [26, 27].

In China, although the installed number of PET/MRI scanners increases year by year, its popularization proceeds at a slower pace compared with PET/CT, mainly due to long scanning time and high costs [28]. Owing to high physiological glucose uptake in normal brain tissue, the application of ^{18}F-FDG in brain tumor imaging is markedly limited, as it fails to distinguish tumor tissue from adjacent healthy tissue. Therefore, amino acid tracers are preferred for PET imaging of brain tumors. Radiolabeled amino acids are the most widely used tracers for neuro-oncological PET imaging. They are especially suitable for the diagnosis and subtyping of gliomas, treatment planning, therapeutic response evaluation, and discrimination between tumor recurrence and treatment-related changes. Commonly used amino acid tracers include ^{11}C-MET, ^{18}F-FET and ^{18}F-FDOPA. Their mechanism relies mainly on upregulated expression of LAT1/LAT2 transporters on tumor cell membranes to achieve tumor-specific high uptake [5]. Beyond these classic amino acid tracers, many novel probes are expanding the application scope of PET/MRI in brain tumors. For instance, TSPO ligands such as ^{11}C-PK11195, ^{18}F-GE-180 and ^{18}F-DPA-714 can assess tumor-associated inflammation and the tumor microenvironment, yet differentiation between tumor marginal regions and activated microglia or macrophages remains challenging [29, 30].

Reports from domestic PET/MR academic conferences indicate that the development of novel specific PET probes is critical for unlocking the clinical value of PET/MR. Artificial intelligence has been implemented in PET/MRI for automatic tumor segmentation and quantitative parameter extraction, substantially boosting workflow efficiency and measurement consistency [31]. The combination of artificial intelligence and PET radiomics can mine information about tumor heterogeneity, supporting molecular subtype prediction, therapeutic response monitoring and prognostic stratification [31].

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7. Conclusion

Relying on complementary anatomical and metabolic multimodal information, integrated PET/MRI plays an irreplaceable clinical role in the whole-course precise management of brain tumors. It delivers unique value in four core scenarios: lesion characterization and grading, differentiation between tumor recurrence and radiation necrosis, target volume delineation for surgery and radiotherapy, and dynamic early therapeutic response monitoring. This technique enables simultaneous fusion of fine anatomical boundaries and quantitative metabolic features of tumors, providing objective and reliable non-invasive imaging evidence for evaluating microscopic tumor infiltration and early treatment response.

At present, its clinical dissemination is hindered by practical constraints such as high equipment cost, long scanning duration and limited availability of amino acid tracers. However, with the development and clinical deployment of new tracers, advances in artificial intelligence-assisted interpretation, and continuous improvement of medical insurance reimbursement policies, integrated PET/MRI holds increasingly promising clinical prospects. Further technological upgrades and deeper multidisciplinary collaboration will advance brain tumor care toward greater precision and individualization.

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