Original Article

Diagnostic accuracy of glioma pseudoprogression identification with positron emission tomography imaging: a systematic review and meta-analysis

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Background: Positron emission tomography (PET) imaging is a promising molecular neuroimaging technique and has been proposed as one of the criteria for glioma management. However, there is some controversy concerning the diagnostic accuracy of PET using different radiotracers to differentiate between glioma pseudoprogression (PsP) and true progression (TPR). The purpose of this meta-analysis was to systematically evaluate the methodological quality and clinical value of original studies for distinguishing PsP from TPR in glioma.

Methods: The Medline, Web of Science, Embase, Cochrane Library, and ClinicalTrials.gov were searched from inception until September 1, 2022. Retrieved clinical studies only investigated the PsP cases but did not include the cases of radiation necrosis or other treatment-related changes. Eligible studies were screened for data extraction and evaluated by 2 independent reviewers using the Quality Assessment of Diagnostic Accuracy Studies 2 (QUADAS-2) tool. A random effects model was used to describe summary receiver operating characteristics. Meta-regression and subgroup analyses were applied to identify any sources of heterogeneity.

Results: The meta-analysis included 20 studies, comprising 317 (30.9%) patients with PsP and 708 (69.1%) with TPR. The summary sensitivity and specificity of general PET for identifying PsP were 0.86 [95% confidence interval (CI): 0.77–0.91] and 0.84 (95% CI: 0.79–0.88), respectively. The statistical heterogeneity was explained by sample size, study design, World Health Organization (WHO) grade, gold standard, and radiotracer type. The summary sensitivity and specificity of O-(2-^{18}F-fluoroethyl)-L-tyrosine (^{18}F-FET PET) were 0.80 (95% CI: 0.68–0.88) and 0.81 (95% CI: 0.75–0.85), respectively. The maximum tumor-to-brain ratio (TBRmax) and the mean tumor-to-brain ratio (TBRmean) both showed excellent diagnostic performance in ^{18}F-FET studies, the summary sensitivity was 0.83 (95% CI: 0.72–0.91) and 0.79 (95% CI: 0.65–0.98), respectively, and the specificity was 0.76 (95% CI: 0.68–0.84) and 0.78 (95% CI: 0.64–0.88), respectively.

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Conclusions: PET imaging is generally accurate in identifying glioma PsP. Considering the credibility of meta-evidence and the practicability of using radiotracer, ^{18}F-FET PET holds the highest clinical value, while TBRmax and TBRmean should be regarded as reliable parameters. PET used with the radiotracers and multiple-parameter combinations of PET with magnetic resonance imaging (MRI) and radiomics analysis have broad research and application prospects, whose diagnostic values for identifying glioma PsP warrant further investigation.

Keywords: Glioma; positron emission tomography (PET); pseudoprogression (PsP); true glioma progression; meta-analysis

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Introduction

Pseudoprogression (PsP) of glioma generally refers to a phenomenon of mimicking tumor progression, which is a consequence of a subacute treatment-related local tissue reaction, and can be caused by inflammation, edema, and increased permeability of the blood-brain barrier (BBB) (1,2). Studies in recent years have reported an incidence of glioma PsP exceeding 20% due to the increase of nonsurgical treatment, such as radiotherapy, chemotherapy, antiangiogenic therapy, checkpoint inhibitor immunotherapy, and targeted therapy (3-6). Importantly, there are substantial ramifications for patients and clinicians when PsP is not identified, as the appearance of the PsP phenomenon usually indicates the efficacy of early treatment, which may be associated with a better prognosis (7). In contrast, for those patients with true progression (TPR), it is necessary to terminate the current treatment and perform reoperation or make a new treatment plan.

At present, pathologic confirmation is still considered the most reliable method to differentiate PsP from TPR in glioma. However, to avoid unnecessary surgery, most clinicians evaluate the progression pattern according to the Response Assessment in Neuro-Oncology (RANO) criteria (2). Specifically, a diagnosis of TPR should be made when progressive contrast-enhancing lesions are noted on initial magnetic resonance imaging (MRI) and when further progression of contrast enhancement ensues at least 4 weeks later. By contrast, a diagnosis of PsP should be applied when follow-up MRI shows stabilization or regression of the contrast-enhanced lesions. Obviously, the extended period of follow-up from suspicious progression to the final diagnosis of PsP or TPR after first treatment of glioma poses a problem. Therefore, prognosis could be improved if the pattern of glioma progression could be identified at the earliest possible moment when clinicians first suspect progression.

Positron emission tomography (PET) imaging as a promising molecular neuroimaging technique that by using various radiotracers, could provide information on the metabolic glucose, amino acid, and lipid content of gliomas (8). In recent years, it has repeatedly been demonstrated that PET imaging with radiotracers such as 2-^{18}F-fluoro-2-deoxy-D-glucose (^{18}F-FDG), O-(2-^{18}F-fluoroethyl)-L-tyrosine (^{18}F-FET), (S-^{11}C-methyl)-L-methionine (^{11}C-MET), and 3,4-dihydroxy-6-^{18}F-fluoro-L-phenylalanine (^{18}F-FDOPA) has good diagnostic value for distinguishing PsP from TPR (9-12). Moreover, PET imaging has been proposed as a criterion for glioma management in addition to MRI, as stated in the joint guidelines of the RANO working group and recent joint European Association of Nuclear Medicine (EANM) and European Association of Neuro-Oncology (EANO) (13,14) recommendations. However, the sensitivity and accuracy of PET imaging with different radiotracers in identifying glioma PsP are controversial or unknown (15,16). Meanwhile, the challenge of demonstrating that radiotherapy planning based on PET is superior to traditional planning either in the first-line or in the recurrent setting remains unresolved (17). Therefore, it is necessary to conduct a meta-analysis to comprehensively evaluate the diagnostic performance of PET in distinguishing PsP from TPR.

Our meta-analysis is not the first attempt to verify the diagnostic value of PET imaging for glioma prognosis. However, previous studies only investigated the accuracy

of PET imaging in distinguishing posttreatment-related changes from TPR and did not consider PsP from other treatment-related changes for specifical analysis (18-20). In order to objectively and realistically investigate the accuracy of PET imaging in distinguishing PsP from TPR, a stricter set of inclusion criteria was formulated for this meta-analysis. Specifically, all eligible patients were required to be suspected of glioma progression during the post therapeutic follow-up and ultimately defined as PsP or TPR according to the RANO criteria (2). We present this article in accordance with the PRISMA-DTA reporting checklist (21) (available at https://qims.amegroups.com/article/view/10.21037/qims-22-1340/rc).

Methods

The study protocol was prospectively registered in PROSPERO (International Prospective Register of Systematic Reviews; https://www.crd.york.ac.uk) under registration number CRD42022372687.

Literature search strategy

A systematic search for potentially relevant articles was conducted in 5 international databases (Medline, Web of Science, Embase, Cochrane Library, and ClinicalTrials.gov) from inception until September 1, 2022. The keywords and medical subject headings (MeSH) terms were combined as follows: "glioma" and "PET" and "pseudoprogression" or "progression". The retrieval formula is provided in Appendix 1. To include all eligible studies in the search, no language restriction was applied. Moreover, references provided from relevant articles were also manually examined to identify additional studies for inclusion.

Literature selection

The inclusion criteria for the literature were as follows: (I) clinical diagnostic test using PET imaging to distinguish PsP and TPR in patients with either adult or pediatric glioma; (II) patients suspected of glioma progression during the post therapeutic follow-up; (III) a progression pattern clearly distinguished in each case with the RANO criteria (2).

The exclusion criteria were as follows: (I) informal publication types (e.g., reviews or meta-analyses, clinical guideline, case reports, conference abstracts, letters to the editor, or comments); (II) cell or animal experiments; (III) with a sample size ≤10 patients; (IV) with insufficient data to obtain or deduce a 2×2 confusion matrix or the unavailability of the absolute numbers of true-positive (TP), false-positive (FP), true-negative (TN) and false-negative (FN) cases; (V) duplicate or overlapping cohorts (in the case of an overlapping cohort, the largest was enrolled and other overlapping studies were excluded); and (VI) inclusion of radiation necrosis or other treatment-related changes.

To minimize subjectivity, screening was completed by 2 independent reviewers (ZQ Ouyang, GR Zheng) and any discrepancies were adjudicated by a third reviewer (CD Liao).

Data extraction and quality assessment

The evaluation was based on a scale of 17 items. Quality assessment was performed independently by 2 reviewers (ZQ Ouyang, GR Zheng) using RevMan software (version 5.4, Cochrane; https://training.cochrane.org) based on the Quality Assessment of Diagnostic Accuracy Studies 2 (QUADAS-2) (22). The QUADAS-2 tool can assign a risk of bias rating of "low", "high", or "uncertain" based on a response of "yes", "no", or "uncertain" to the relevant flag questions included in each section. Specifically, if the answer to all the landmark questions in a range is "yes", then it can be rated as low risk of bias; if all the informational questions are answered "no", then the risk of bias is rated as "high" (23). Any disagreements in scoring were resolved through discussion.

Data extraction of the included studies proceeded according to a predesigned form as follows: (I) basic information of studies (author name, journal, year of publication, country of origin, study design, and begin and end time of investigation); (II) patients' demographic and clinical characteristics (mean or median age, sample size, therapeutic regimen, World Health Organization (WHO) classification, O^6-methylguanine-DNA methyl-transferase (MGMT) and isocitrate dehydrogenase [IDH(status)]; (III) PET protocol (PET modality, radiotracer type, radiotracer dose, time of PET scan after tracer injection, method of analysis, parameters, and cutoff value); and (IV) recorded or calculated absolute numbers of TP, FP, FN, and TN. The data extraction form was first piloted on 3 randomly selected studies and then completed for all items by 1 reviewer (ZQ Ouyang) and validated by another reviewer (CD Liao) to ensure a level of accuracy. The PET parameter with the highest accuracy of each study was selected. The screening protocol mandated that quantitative parameters

take precedence over qualitative parameters, combined parameters, textural parameters, and radiomics parameters.

Statistical analysis

First, we evaluated the threshold effect by using Meta-Disc software (version 1.4; https://meta-disc.software.informer.com). In brief, the Spearman correlation coefficient between the logarithm of sensitivity and the logarithm of 1 – specificity was calculated to evaluate the threshold effect. This indicated that there was an obvious threshold effect when the Spearman correlation coefficient was >0.8 and P<0.05.

In Stata software (version MP17.0, StataCorp; https://www.stata.com), the pooled sensitivity, specificity, positive likelihood ratio (PLR), negative likelihood ratio (NLR), and diagnostic odds ratio (DOR) with their 95% confidence intervals (CIs) were calculated and presented using the random effects model. In addition, the hierarchical logistic regression model was used to generate the summary receiver operating characteristic (SROC) curve and area under the curve (AUC) for evaluating diagnostic accuracy.

The Q test was evaluated to determine the between-study heterogeneity, while the discordance index (I^2) was adopted as a measure of heterogeneity. Higgins *et al.* (24) suggest that heterogeneity be assessed as low, medium, and high, with upper limits for I^2 of 25%, 50%, and 75%, respectively. For this meta-analysis, the potential influencing factors of heterogeneity included sample size (the included studies were divided by the median of sample size) (25), study design, WHO grade, gold standard, and radiotracer type. Therefore, meta-regression and subgroup analyses were performed to explore and explain the source of heterogeneity. Moreover, sensitivity analysis was performed to evaluate how robust the results were. The funnel plot was used to explore potential publication bias.

Results

Study selection

Figure 1 shows the PRISMA flowchart of this meta-analysis. A total of 1,293 records were identified, 4 of which (9,26-28) were manually retrieved from other sources. First, 401 records were removed due to being duplicates, and another 540 records were excluded based on the type of screening. The 352 remaining studies underwent tile and abstract eligibility assessment, among which 270 studies were excluded due to missing keywords. Then, the 82 remaining studies underwent full-text eligibility assessment, which culminated in a total inclusion of 20 studies for analysis in this review. The total number of included patients was 1,018, comprising 317 (30.9%) with PsP and 708 (69.1%) with TPR (the total number of included patients did not match the sum of PsP and TPR cases, as some patients were included twice in Ullrich *et al.*'s (29) study, while the other 2 patients were excluded from Skoblar Vidmar *et al.*'s (30) study for unknown reasons). The sample sizes ranged from 12 to 151 patients, and the median sample size was 40. The male to female ratio was about 1.6:1, and ages ranged from 2 to 83 years. There were 177 (17.4%) low-grade gliomas (LGGs; WHO I–II), 262 (25.7%) WHO grade III gliomas, 529 (52.0%) WHO grade IV gliomas, and 50 (4.9%) gliomas that were not specified. Among the included patients, 594 underwent detection for MGMT methylation status, and the ratio of methylated to unmethylated was about 1.4:1. Regarding IDH mutation status, the ratio of wild type to mutant type was 1.8:1.

Study characteristics

Table 1 (9-12,16,26-40) demonstrates the characteristics of the included studies. Among the 20 included studies, 3 studies (11,12,31) had a prospective design. All studies used the RANO criteria as the gold standard to identify glioma PsP, with 14 studies (9-12,26,28,30-37) using pathology and MRI follow-up, 2 studies (27,29) using pathology as the sole reference standard, and 4 studies (16,38-40) using MRI follow-up alone. The most commonly evaluated radiotracer was ^{18}F-FET; in addition, 3 studies tested ^{11}C-MET (11,29,32), 2 tested ^{18}F-FDOPA (12,16), and 1 tested ^{18}F-FDG (9). Each study reported the treatment schemes of patients with glioma to different degrees. Except for the patients from 2 studies (28,35), in which the enrolled patients underwent additional targeted drug, immune checkpoint inhibitor, or tumor-treating field therapy, most of the patients underwent neurosurgery, radiotherapy, chemotherapy, or a combination thereof. Other characteristics of the included studies can be found in Table S1.

Quality assessment

The QUADAS-2 evaluation of the included studies is shown in *Figure 2*. The 2 independent reviewers agreed that most of the studies did not specify whether patients

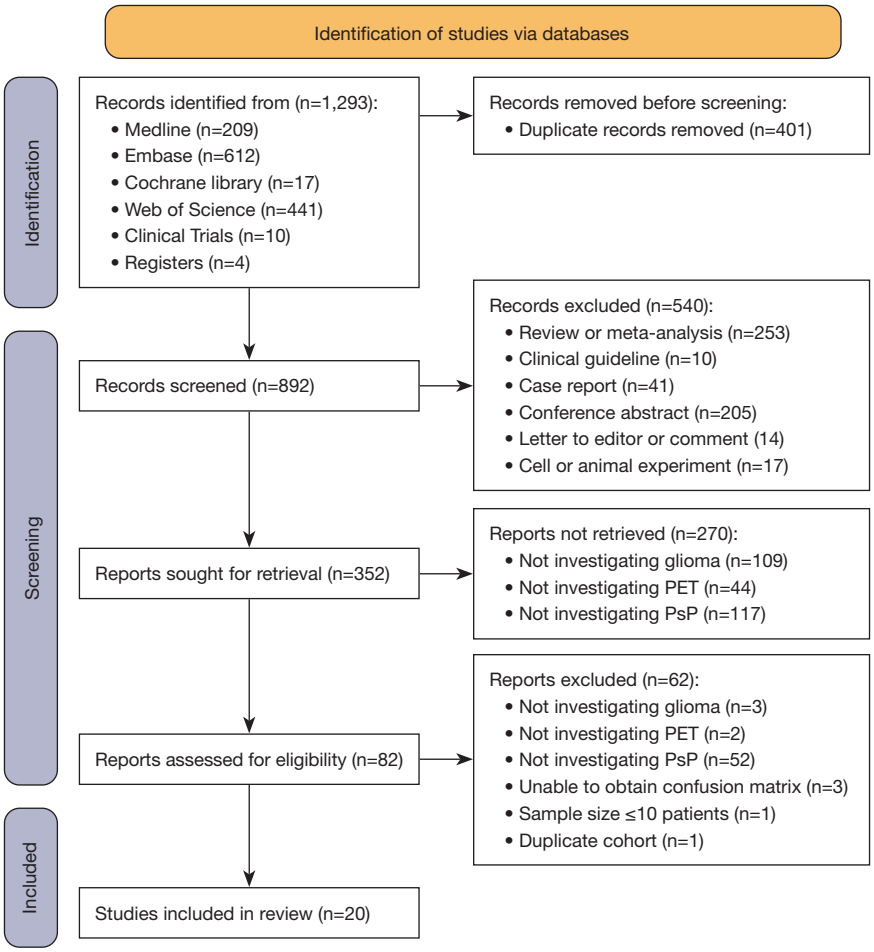

Figure 1 PRISMA flowchart of included studies. PRISMA, Preferred Reporting Items for Systematic Review and Meta-Analysis; PET, positron emission tomography; PsP, pseudoprogression.

were enrolled from a random group or a consecutive group, whether the results of PET or the gold standard were interpreted based on the double-blind method, or whether there was an appropriate interval between PET scanning and application of the gold standard, resulting in the risk of bias for patient selection, index test, reference standard, and flow and timing being unclear in 11 (55%), 15 (75%), 18 (90%), and 15 studies (75%), respectively (*Table 2*).

Threshold effect evaluation

In the correlation analysis, the Spearman correlation coefficient was –0.059 between the logarithm of sensitivity and the logarithm of 1 – specificity (P=0.806). In other words, there was no threshold effect for the included studies, and the potential heterogeneity of the included studies was not caused by the threshold effect. This confirmed that the ensuing meta-analysis was feasible and valuable.

Diagnostic accuracy

Before pooling diagnostic values, we screened the PET parameters of each study according to the principle of data extraction. Among all included studies, the most effective parameter was the maximum tumor-to-brain ratio (TBRmax) in 10 studies (10,11,16,28,30,31,33,36,38,39), the mean tumor-to-brain ratio (TBRmean) in 3 studies (34,37,40), and the relative change of TBR in 2 studies (27,29). In the 5 remaining studies (9,12,26,32,35), the most effective parameter was the metabolic tumor volume (MTV), slope, standardized uptake values of the lesion divided by

Table 1 Characteristics of studies included in the meta-analysis (9-12,16,26-40)

First author	Nation	Year	Study design	Sample size (male number)	Age [range], years	WHO classification	TPR/PsP	Reference standard (RANO)	Radiotracer type	Quantitative parameter	Cutoff	TP	FP	FN	TN
Bag (32)	USA	2022	Retrospective	27 (n=16)	14# [2–25]	III (n=23), IV (n=4)	22/5	Pathology & MRI	^{11}C-MET	MTV	0.98 cm^2	4	2	1	20
Galldiks (27)	GER	2013	Retrospective	27 (n=19)	44# [11–64]	II (n=27)	18/9	Pathology	^{18}F-FET	Relative changes of TBRmax	33%	8	5	1	13
Galldiks (10)	GER	2015	Retrospective	22 (n=14)	56# [34–76]	IV (n=22)	11/11	Pathology & MRI	^{18}F-FET	TBRmax	2.3	11	1	0	10
Imani (9)	USA	2014	Retrospective	12 (n=5)	39* [25–70]	II (n=6), III (n=6)	5/7	Pathology & MRI	^{18}F-FDG	nSUVmax	1.9	6	1	1	4
Kebir (38)	GER	2016	Retrospective	26 (n=21)	56* [23–76]	IV (n=26)	19/7	MRI	^{18}F-FET	TBRmax	1.9	6	3	1	16
Kebir (39)	GER	2017	Retrospective	14 (n=9)	52* [29–70]	III (n=3), IV (n=11)	10/4	MRI	^{18}F-FET	TBRmax	2.1	4	3	0	7
Kebir (40)	GER	2020	Retrospective	44 (n=34)	55* [34–79]	IV (n=44)	30/14	MRI	^{18}F-FET	TBRmean	1.82	5	0	9	30
Kertels (33)	GER	2019	Retrospective	36 (n=22)	54# [24–75]	IV (n=36)	28/8	Pathology & MRI	^{18}F-FET	TBRmax[1]	3.44	7	4	1	24
Lohmann (31)	GER	2020	Prospective	34 (n=21)	57# [24–79]	III (n=1), IV (n=33)	18/16	Pathology & MRI	^{18}F-FET	TBRmax	2.25	13	6	3	12
Maurer (28)	GER	2020	Retrospective	127 (n=83)	50# [20–78]	II (n=21), III (n=36), IV (n=68), NS (n=2)	94/33	Pathology & MRI	^{18}F-FET	TBRmax	1.95	23	28	10	66
Müller (26)	GER	2022	Retrospective	151 (n=97)	52* [20–78]	II (n=28), III (n=40), IV (n=83)	114/37	Pathology & MRI	^{18}F-FET	TBRmean + TBRmax	NA	8	9	4	37
Paprottka (34)	GER	2021	Retrospective	74 (n=41)	55* [NR]	II (n=4), III (n=19), IV (n=51)	57/17	Pathology & MRI	^{18}F-FET	TBRmean	2	14	11	3	46
Pellerin (12)	FRA	2021	Prospective	58 (n=34)	53# [NR]	II (n=10), III (n=21), IV (n=27)	34/24	Pathology & MRI	^{18}F-FDOPA	T-map and isocontour map	NA	22	2	2	32
Skoblar Vidmar (30)	SI	2022	Retrospective	44 (n=27)	44* [17–72]	NS (n=44)	31/11	Pathology & MRI	^{18}F-FET	TBRmax	3.03	9	7	2	24
Skvortsova (11)	RUS	2014	Prospective	72 (n=35)	36* [3–68]	I (n=17), II (n=17), III (n=34), NS (n=4)	30/42	Pathology & MRI	^{11}C-MET	TBRmax	1.9	41	5	1	25
Steidl (35)	GER	2021	Retrospective	104 (n=68)	52* [20–78]	II (n=10), III (n=24), IV (n=70)	83/21	Pathology & MRI	^{18}F-FET	Slope	0.69 SUV/h	13	13	8	70
Ullrich (29)	GER	2009	Retrospective	24 (n=14)	40# [NR]	II (n=18), III (n=6)	20/13	Pathology	^{11}C-MET	Relative changes of TBR	14.6%	12	2	1	18
Werner (36)	GER	2019	Retrospective	48 (n=29)	50# [20–83]	II (n=1), III (n=8), IV (n=39)	38/10	Pathology & MRI	^{18}F-FET	TBRmax	1.95	10	8	0	30
Werner (37)	GER	2021	Retrospective	23 (n=13)	58# [38–71]	IV (n=23)	12/11	Pathology & MRI	^{18}F-FET	TBRmean	1.95	9	1	2	11
Zaragori (16)	FRA	2020	Retrospective	51 (n=28)	51* [21–75]	II (n=18), III (n=8), IV (n=25)	34/17	MRI	^{18}F-FDOPA	TBRmax	1.61	16	1	1	33

The studies are arranged by the first author' s last name. #, mean age; *, median age. ^{11}C-MET, (S-^{11}C-methyl)-L-methionine; ^{18}F-FDG, 2-^{18}F-fluoro-2-deoxy-D-glucose; ^{18}F-FDOPA, 3,4-dihydroxy-6-^{18}F-fluoro-L-phenylalanine; ^{18}F-FET, O-(2-^{18}F-fluoroethyl)-L-tyrosine; FN, false negative; FP, false positive; MRI, magnetic resonance imaging; MTV, metabolic tumor volume; NA, not applicable; NR, not reported; NS, not specified; nSUV, standardized uptake values of the lesion divided by standardized uptake values of the normal white matter; PsP, pseudoprogression; SUV, standardized uptake value; TBRmax, maximum tumor-to-brain ratio; TBRmean, mean tumor-to-brain ratio; TN, true negative; TP, true positive; TPR, true glioma progression; WHO, World Health Organization.

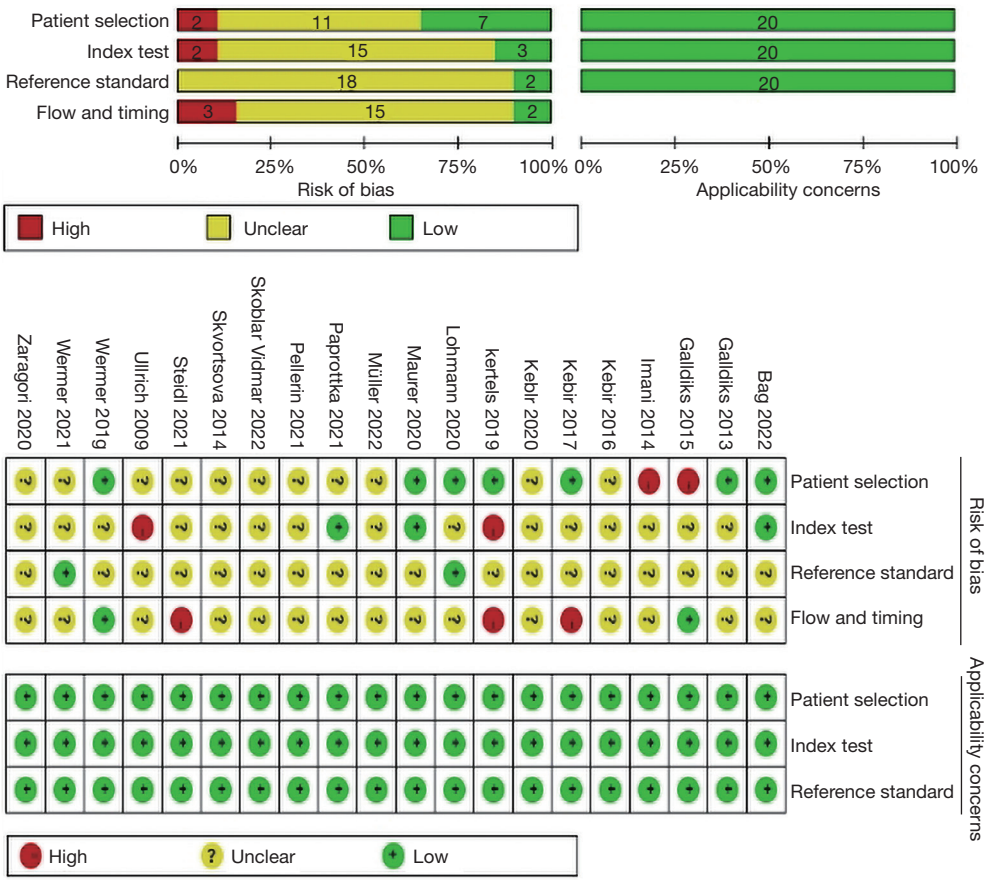

Figure 2 Risk of bias and applicability concern graph for each included study after arbitration between reviewers. –, high risk; ?, unclear risk; +, low risk.

standardized uptake values of the normal (nSUVmax), radiomics signature, and combined parameter (*Table 1*), respectively. The summarized diagnostic performance of PET is shown in *Table 2*. The sensitivity and specificity of PET for identifying glioma PsP ranged from 0.00 to 1.00 and from 0.40 to 1.00, respectively, with a summary sensitivity of 0.86 (95% CI: 0.77–0.91) and a summary specificity of 0.84 (95% CI: 0.79–0.88), as shown in *Figure 3*. The corresponding PLR, NLR, and DOR were 5.47 (95% CI: 4.10–7.31), 0.17 (95% CI: 0.10–0.27), and 32.52 (95% CI: 16.89–62.64), respectively (Figures S1,S2). The SROC is shown in *Figure 4A*. As illustrated, the summary the AUCs of the included studies was 0.91 (95% CI: 0.88–0.93).

Regarding ^{18}F-FET PET, the summary sensitivity, specificity, and AUC were 0.80 (95% CI: 0.68–0.88) and 0.81 (95% CI: 0.75–0.85), and 0.86 (95% CI: 0.83–0.89), respectively (*Figure 4B*, *Table 2*). In addition, the 2 most frequently used quantitative parameters for PsP identification were the TBRmax (cutoff value range: 1.9 to 3.44; median value: 2.3) and TBRmean (cutoff value range: 1.82 to 2.19; median value: 1.95); for these 2 quantitative parameters, the summary sensitivity was 0.83 (95% CI: 0.72–0.91) and 0.79 (95% CI: 0.65–0.88), respectively, while the specificity was 0.76 (95% CI: 0.68–0.84) and 0.78 (95% CI: 0.64–0.88), respectively; the SROCs with AUCs of 0.87 (95% CI: 0.84–0.90) and 0.85 (95% CI: 0.82–0.88), respectively, are shown in *Figure 4C,4D*.

Heterogeneity analysis

The I^2 of the summary sensitivity and specificity of 63.39% and 53.51% (*Figure 3*), respectively, indicated obvious heterogeneity among the included studies. Therefore, meta-regression and subgroup analysis were applied to explore the sources of heterogeneity. The results demonstrated that radiotracer type (^{18}F-FET *vs.* non-^{18}F-

Table 2 Meta-regression analysis results of sample size, study size, WHO grade, gold standard, and radiotracer

Subgroup	Number of studies	Pooled AUC (95% CI)	Pooled sensitivity (95% CI)	P_1	Pooled specificity (95% CI)	P_2
Sample size				0.59		<0.001
<40 patients	10	0.92 (0.89–0.94)	0.90 (0.82–0.98)		0.83 (0.76 to 0.91)	
≥40 patients	10	0.91 (0.88–0.93)	0.82 (0.73–0.92)		0.85 (0.79 to 0.90)	
Study design				0.79		0.04
Prospective	3	NA	0.93 (0.85–1.00)		0.84 (0.73 to 0.95)	
Retrospective	17	0.90 (0.87–0.92)	0.83 (0.75–0.91)		0.84 (0.80 to 0.89)	
WHO grade				0.09		0.01
HGG	8	0.90 (0.87–0.93)	0.83 (0.70–0.96)		0.87 (0.81 to 0.93)	
LGG and HGG	12	0.92 (0.89–0.94)	0.87 (0.79–0.95)		0.83 (0.78 to 0.88)	
Gold standard				0.37		<0.001
Pathology & MRI	14	0.89 (0.86–0.91)	0.86 (0.78–0.94)		0.82 (0.77 to 0.87)	
Pathology or MRI	6	0.96 (0.93–0.97)	0.85 (0.71–0.99)		0.89 (0.83 to 0.95)	
Amino acid radiotracer				0.65		0.60
Yes	19	0.91 (0.88–0.93)	0.86 (0.79–0.93)		0.84 (0.80 to 0.89)	
No	1	NA	0.88 (0.57–1.00)		0.81 (0.44 to 1.00)	
^{18}F-FET PET				<0.001		<0.001
Yes	14	0.86 (0.83–0.89)	0.80 (0.68–0.88)		0.81 (0.75 to 0.85)	
No	6	0.97 (0.95–0.98)	0.93 (0.87–0.97)		0.91 (0.85 to 0.95)	

^{18}F-FET, O-(2-^{18}F-fluoroethyl)-L-tyrosine; AUC, area under curve; CI, confidence interval; HGG, high-grade glioma; LGG, low-grade glioma; MRI, magnetic resonance imaging; NA, not applicable; PET, positron emission tomography; WHO, World Health Organization.

FET) was the only factor for heterogeneity of summary sensitivity (P<0.05) (*Figure 5*). As for summary specificity, the sources of heterogeneity mainly included sample size, study design, WHO grade, gold standard, and radiotracer type (^{18}F-FET *vs.* non-^{18}F-FET) (P<0.05) (*Figure 5*). In the subgroup analysis, the diagnostic power of ^{18}F-FET PET for identifying PsP was significantly lower than that of non-^{18}F-FET, with summary AUCs, sensitivities, and specificities of 0.80 *vs.* 0.93, 0.81 *vs.* 0.91, and 0.86 *vs.* 0.97, respectively (*Table 2*). Furthermore, sensitivity analysis found that the main source of heterogeneity was the 2020 study of Kebir *et al.* (40). The heterogeneity of summary sensitivity and specificity decreased to 44.54% and 44.23% (Figure S3) when this study was removed.

Publication bias

The Deeks' funnel plot shows a symmetrical shape in *Figure 6*, suggesting no significant publication bias among the included studies (P=0.57).

Discussion

The use of noninvasive methods for the timely and accurate differentiation of PsP from TPR in glioma remains challenging (17,41). The detection and comparison of metabolic differences between tumor and normal brain tissue with PET imaging has been considered a potential clinical means to differentiating PsP from TPR (9-12). Therefore, we conducted a meta-analysis of 1,018 patients with glioma in 20 related studies. The results demonstrated that the incidence of PsP was 30.9% in patients who were suspected of progression after treatment, which is close to the incidence of 30% to 39.5% reported in other studies (4,42,43). An aggregated high diagnostic potential of PET for identifying PsP was determined using SROC analysis, with the summary sensitivity, specificity, and AUC being 0.86, 0.84 and 0.91, respectively. However,

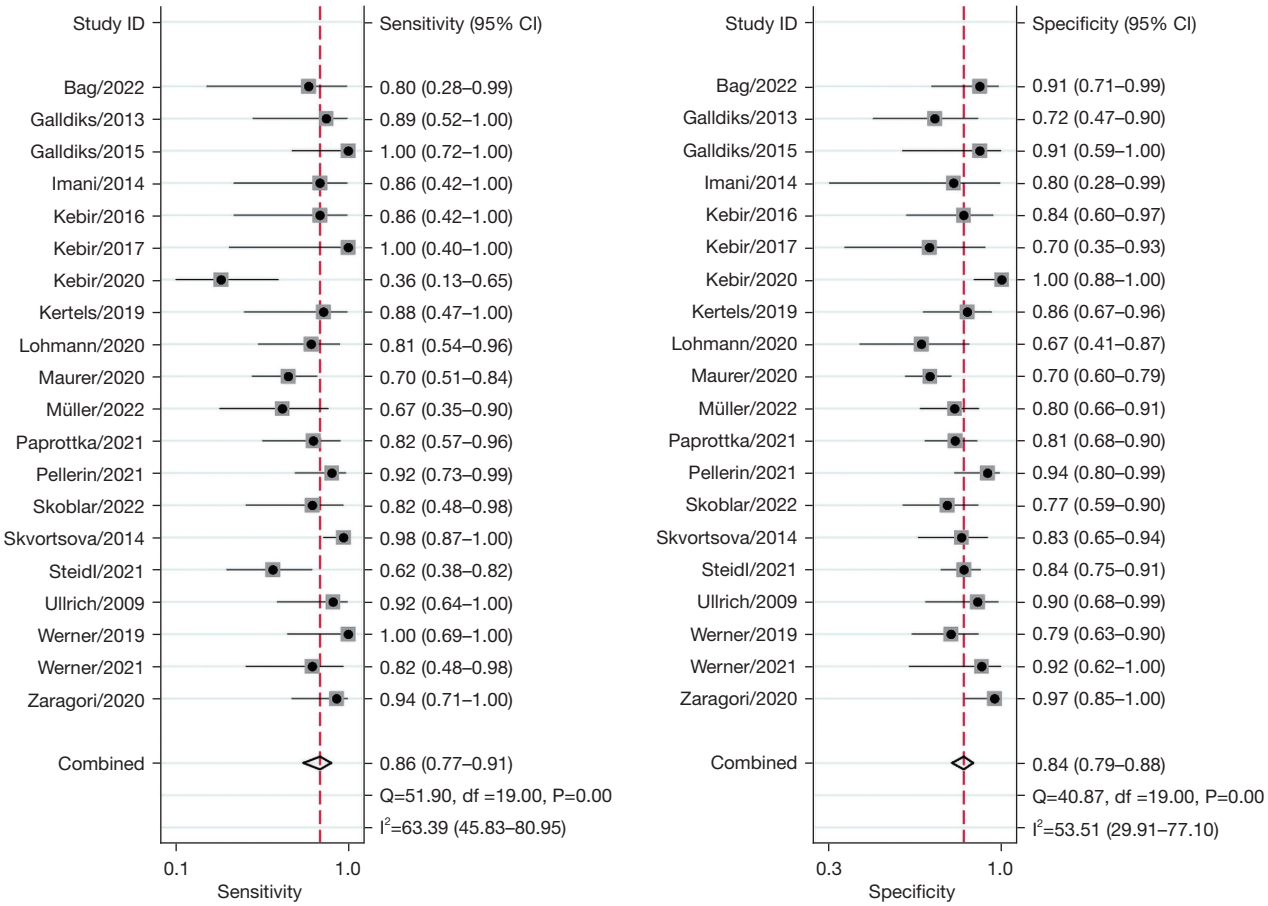

Figure 3 Forest plot of sensitivities and specificities of the included studies.

there was obvious heterogeneity among the included studies, which compelled us to explore the possible sources of heterogeneity.

First, the results of Spearman correlation analysis indicated that the heterogeneity was not caused by the threshold effect. Subsequently, meta-regression and subgroup analysis revealed that sample size, study design, WHO grade, and gold standard were the main sources of summary specificity heterogeneity. The influence of studies with an adequate number of participants was slightly higher than that of the smaller-scale studies (0.85 *vs.* 0.83; P<0.05). Empirically, smaller samples cannot provide meaningful estimates of accuracy (18,44). Although we excluded the case reports and studies with sample sizes ≤10 patients, the heterogeneity of the summary specificity due to the higher risk of selection bias in the small-sample studies could not be avoided, as confirmed by the quality assessment of the included studies. In addition, compared with the studies which only included patients with high-grade gliomas (HGGs; WHO III–IV), the summary specificity of those studies which enrolled patients with LGGs (WHO I–II) and HGGs was lower (0.87 *vs.* 0.83; P<0.05). We believe this may be attributable to an increase in radiotracer uptake with increasing glioma grade (45-49). Usually, HGGs have a greater tumor cell density, microvascular density, and more efficient amino acid transport system, which can more quickly absorb amino acid radioactive tracers from blood pools (50,51). Moreover, HGGs tend to lead to more serious damage to the BBB. Although the disruption to the BBB is not a prerequisite for intratumoral accumulation (52), more serious damage to the BBB will lead to passive inflow of radiotracers and aggravate the original high uptake state in HGGs (49,53). Therefore, the difference of radiotracer metabolism between those with TPR and PsP is more obvious in HGGs than in LGGs, and static or multidynamic amino acid PET imaging can more accurately distinguish

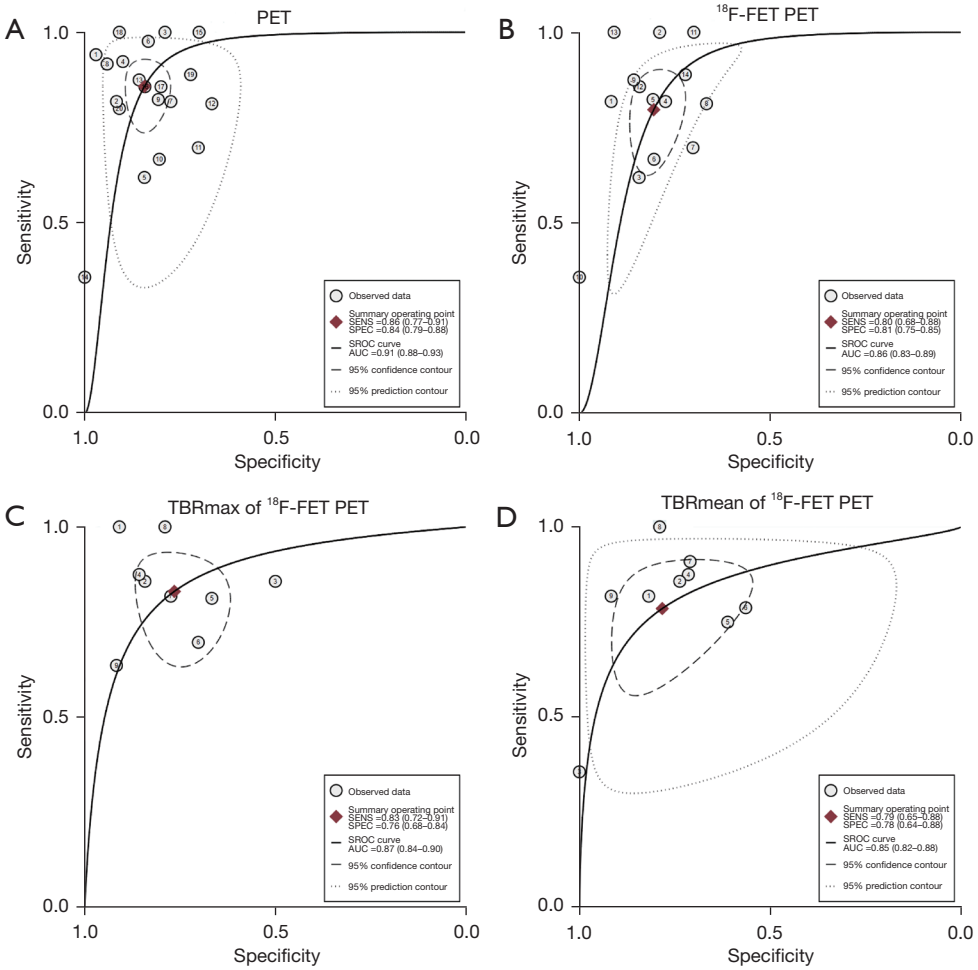

Figure 4 SROC curves for the included studies. (A) PET and (B) ^{18}F-FET PET with (C) TBRmax and (D) TBRmean. Circles indicate observed data, and the numbers inside circles indicate the numbers assigned to the given articles in the bivariate model. ^{18}F-FET, O-(2-^{18}F-fluoroethyl)-L-tyrosine; AUC, area under the curve; PET, positron emission tomography; TBRmax, maximum tumor-to-brain ratio; TBRmean, mean tumor-to-brain ratio; SENS, sensitivity; SPEC, specificity; SROC, summary receiver operating characteristic.

false progress from true progress in HGGs. Finally, the meta-regression showed that the summary sensitivity and specificity of non-^{18}F-FET PET were significantly higher than those of ^{18}F-FET PET (sensitivity: 0.93 *vs.* 0.80, P<0.001; specificity: 0.91 *vs.* 0.81, P<0.001). However, there were only six eligible studies with non-^{18}F-FET radiotracer including one ^{18}F-FDG study (9), three ^{11}C-MET studies (11,29,32) and two ^{18}F-FDOPA studies (12,16). Obviously, the present evidence is insufficiently robust to prove that the summary accuracy of imaging using other radiotracers for identification of glioma PsP is superior to that of ^{18}F-FET imaging. Because the apparently superior diagnostic accuracy, this was based on a small amount of diagnostic data and should be interpreted with caution (45).

Interest into the value of each radiotracer in PET imaging for differentiating PsP from TPR has grown. ^{18}F-FET is one of the first ^{18}F-labeled amino acids that can be produced in large amounts for scientific investigation and clinical practice (54,55). ^{18}F-FET is transported via a system of L-type amino acid transporters (LATs), particularly the subtypes LAT1 and LAT2; is not significantly incorporated into any metabolic pathway; and has no relevant participation in protein synthesis (37,56). It should be noted that overexpression of LAT1 is common in gliomas, which simultaneously facilitates the influx and causes the entrapment of ^{18}F-FET in tumor cells to form a high uptake state (57). In contrast, the expression of LAT1 is normal or even downregulated in tissue affected

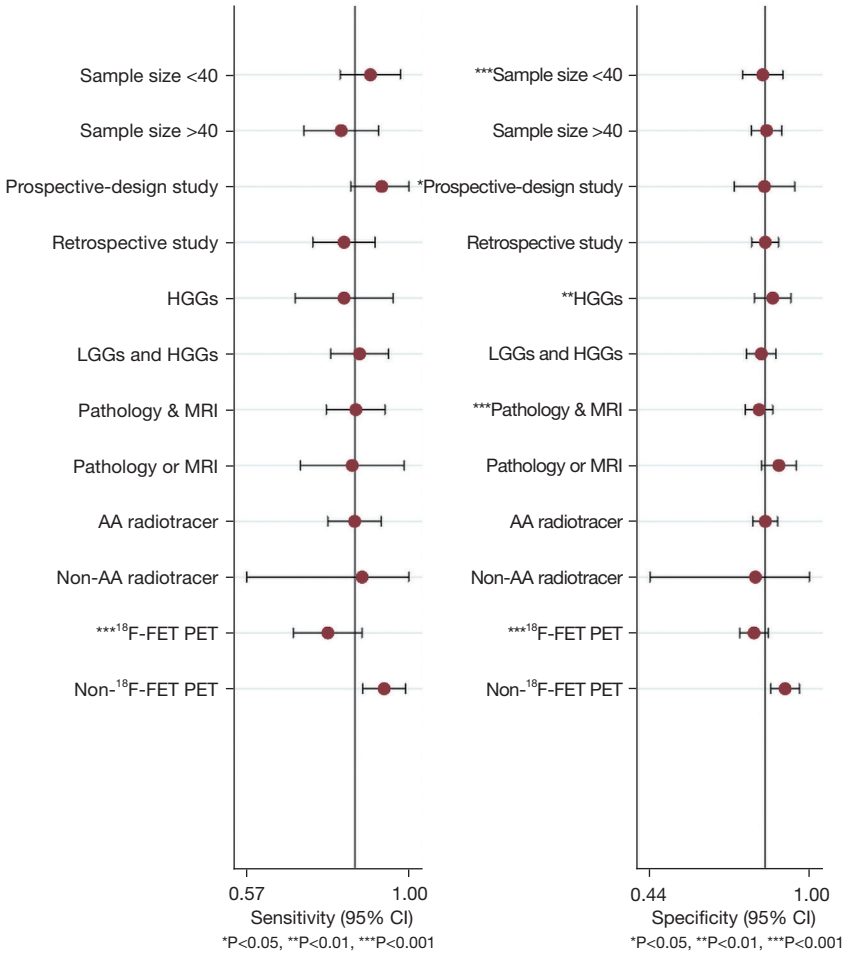

Figure 5 Univariable meta-regression and subgroup analyses. ^{18}F-FET, O-(2-^{18}F-fluoroethyl)-L-tyrosine; AA, amino acid; CI, confidence interval; HGG, high-grade glioma; LGG, low-grade glioma; MRI, magnetic resonance imaging; PET, positron emission tomography.

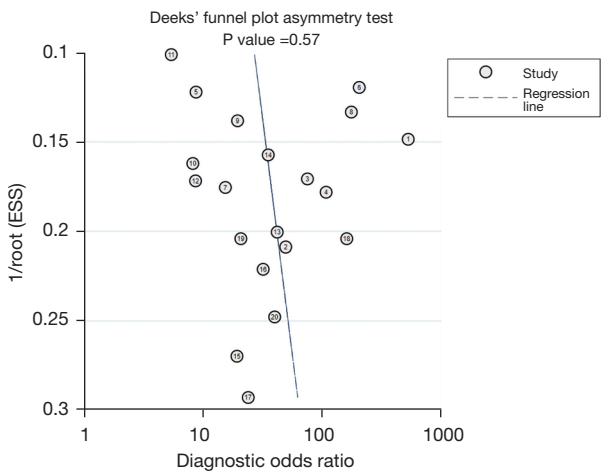

Figure 6 Funnel plot of the included studies. ESS, effective sample size.

by post therapeutic changes, and active transport of amino acid tracers into PsP tissue should be equal or less than of that into normal brain tissue. Increased ^{18}F-FET uptake in PsP tissue, therefore, could only result from the passive influx of ^{18}F-FET and has lower intensity compared with the ^{18}F-FET uptake in TPR (58). Our meta-analysis, provides sufficient evidence to show that ^{18}F-FET PET imaging displays a high accuracy for differentiating PsP from TPR, with a summary sensitivity and specificity of 0.80 and 0.81, respectively. Although our summary specificity is slightly lower than that reported in similar meta-analyses (19,20), this should not prevent clinicians from suggesting patients with glioma undergo ^{18}F-FET examination when the progression pattern is unclear during follow-up. Of course, which parameter of ^{18}F-FET PET

should be selected to discriminate PsP from TPR in clinical practice remains a problem (33,39). A subgroup analysis based on nine ^{18}F-FET PET studies (10,28,30,31,33,36-38,40) was performed, and the result being similar to that of previous studies (19), in that TBRmax and TBRmean were found to have a similar diagnostic efficiency, according to the summary sensitivities (0.83 *vs.* 0.79), specificities (0.76 *vs.* 0.78), and AUCs (0.87 *vs.* 0.85). Therefore, TBRmax and TBRmean should be equally considered when differentiating PsP from TPR using ^{18}F-FET PET imaging.

In this meta-analysis, we attempted to determine the diagnostic accuracy of other radiotracers for identification of PsP in addition to ^{18}F-FET PET. Unfortunately, the true diagnostic performances of non-^{18}F-FET PET are uncertain due to the insufficient amount of data. ^{18}F-FDG is a classic radiotracer and used in tumor imaging, but it is not ideal for detecting gliomas due to the high physiologic uptake in normal brain tissue (59-61). Nevertheless, a retrospective small-sample study by Imani *et al.* (9) revealed the potential value of ^{18}F-FDG PET imaging for identifying PsP using a semiquantitative parameter (nSUVmax), with the sensitivity, specificity, and accuracy being 0.86, 0.80, and 0.83 respectively. Additionally, ^{11}C-MET is the most widely used radiotracer for amino acid PET (62), and 3 included studies showed that ^{11}C-MET PET has excellent value for the identification of PsP: the diagnostic accuracy ranged from 0.89 to 0.92 and was markedly higher than that of ^{18}F-FET PET (11,29,32). Finally, ^{18}F-FDOPA, similarly to ^{18}F-FET and ^{11}C-MET, is transported intact through the BBB via LAT transporters (63). It has shown promising results in a small number of studies and could be comparable or perhaps superior to ^{18}F-FET and ^{11}C-MET in terms of identifying PsP (12,16).

Regarding the direction and prospect of future investigation, first, the diagnostic value of non-^{18}F-FET radiotracers need to be proved in additional cohorts. Second, only a few preliminary studies have shown that the highest diagnostic accuracy would be achieved from the combination of advanced multiparameter MRI and PET imaging (9,12,34,36,64), and therefore future research should focus on the development and validation of such bimodal or multimodal diagnostic models (65). In addition, the kinetic parameters of dynamic PET imaging have demonstrated excellent performance in glioma grading (66) and prognosis evaluation (16,35,38,40). However, irregular dynamic PET scanning limits the clinical popularization of kinetic parameters (67,68). Therefore, researchers need to devote more energy to developing and verifying better dynamic PET scanning protocols. Finally, radiomics, as a novel imaging analysis technique, can not only extract thousands of quantitative features from routinely acquired images (69) but can also link them to the genotypic and phenotypic characteristics of the tissue at the genetic and molecular level (70,71). Two recent studies have already demonstrated that PET-based radiomics is a potential method for identifying PsP in glioma (26,31). In the future, researchers should perform radiomics analysis based on existing data to fully leverage the information from medical images while exploring better diagnostic models.

There are some limitations to our meta-analysis. First, most of the included studies were retrospective, but they did not specify the source of patients in detail, thus introducing selection bias as indicated in the QUADAS-2 evaluation. In addition, only a few studies mentioned the use of blinding when gold standard or quantitative parameters were used for measurement. Undoubtedly, this further increased the risk bias. Second, the applied bivariate regression method cannot be used for multivariate evaluation. Third, we set a stricter set of inclusion criteria than did previous studies, and thus many publications related to the differential diagnosis of therapy-related changes were not considered. There were only 6 studies on non-^{18}F-FET PET, including studies on ^{18}F-FDG, ^{11}C-MET, and ^{18}F-FDOPA PET. The diagnostic accuracy of these PET imaging modalities could be calculated with the random effects model and therefore must be verified in the future when data are sufficient. Fourth, most of the included studies failed to provide a detailed treatment course of each patient, so we could not conduct subgroup analysis to explore the potential heterogeneity caused by different treatments, such as radiotherapy, temozolomide chemotherapy, checkpoint inhibitor immunotherapy, or targeted therapy. Finally, the status of MGMT methylation is an independent predictor of glioma PsP, and a previous study reported a 3.5-fold increased probability of a patient developing PsP if the MGMT promoter is methylated in glioma (72). Therefore, future studies are needed to clarify how MGMT methylation status in PET imaging affects the diagnosis of PsP in glioma.

Conclusions

This meta-analysis demonstrated that PET imaging with the inclusion of ^{18}F-FDG PET, ^{18}F-FET PET, ^{11}C-MET PET, and ^{18}F-FDOPA PET has a generally

high accuracy for differentiating between PsP and TPR. Considering the credibility of the meta-evidence and the practicability of radiotracers, ^{18}F-FET PET holds the highest value for clinical implementation. In addition, TBRmax and TBRmean should be equally considered as reliable parameters when using ^{18}F-FET PET to identify glioma PsP. Although PET with non-^{18}F-FET radiotracers showed better accuracy in identifying PsP, this needs to be confirmed with further research.

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Footnote

Reporting Checklist: The authors have completed the PRISMA-DTA reporting checklist. Available at https://qims.amegroups.com/article/view/10.21037/qims-22-1340/rc

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://qims.amegroups.com/article/view/10.21037/qims-22-1340/coif). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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