Journal of Multidisciplinary Healthcare
Dovepress
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REVIEW

Systematic Review Between Resting-State fMRI and Task fMRI in Planning for Brain Tumour Surgery

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Abstract: As an alternative to task-based functional magnetic resonance imaging (T-fMRI), resting-state functional magnetic resonance imaging (Rs-fMRI) is suggested for preoperative mapping of patients with brain tumours, with an emphasis on treatment guidance and neurodegeneration prediction. A systematic review was conducted of 18 recent studies involving 1035 patients with brain tumours and Rs-fMRI protocols. This was accomplished by searching the electronic databases PubMed, Scopus, and Web of Science. For clinical benefit, we compared Rs-fMRI to standard T-fMRI and intraoperative direct cortical stimulation (DCS). The results of Rs-fMRI and T-fMRI were compared and their correlation with intraoperative DCS results was examined through a systematic review. Our exhaustive investigation demonstrated that Rs-fMRI is a dependable and sensitive preoperative mapping technique that detects neural networks in the brain with precision and identifies crucial functional regions in agreement with intraoperative DCS. Rs-fMRI comes in handy, especially in situations where T-fMRI proves to be difficult because of patient-specific factors. Additionally, our exhaustive investigation demonstrated that Rs-fMRI is a valuable tool in the preoperative screening and evaluation of brain tumours. Furthermore, its capability to assess brain function, forecast surgical results, and enhance decision-making may render it applicable in the clinical management of brain tumours.

Keywords: resting-state functional magnetic resonance imaging, Rs-fMRI, pre-operative mapping, Brain Tumours

Introduction

The advent of functional magnetic resonance imaging (fMRI) has transformed the practice of neurosurgery by offering unparalleled insights into the brain's functioning structure.[1,2] This imaging approach, which does not require penetration of the body, is crucial for pinpointing important brain areas that are at risk of damage during surgery.[3] Recent research has emphasized the crucial importance of fMRI in improving the accuracy of cortical mapping, which helps in performing brain tumor removal surgery while safeguarding vital neurological processes.[4,5] Neurosurgical efforts focus on maximizing tumor removal while minimizing neurological impairments.[5] Having a proper balance is essential for enhancing the quality of life after surgery and prolonging the survival of patients, especially in cases of glioma, where the degree of resection is closely linked to better treatment results. Yet, attaining this equilibrium is filled with obstacles, as the elimination of brain tissue heightens the likelihood of functional impairment.[6,7] Therefore, the advancement and improvement of brain mapping techniques before and during surgery have become a central focus of study in neurosurgery.[8,9] However, intraoperative mapping demands a substantial amount of effort in the operating room, particularly when working on the brain of a conscious patient.[10,11] Using modern neuroimaging techniques, preoperative functional mapping strategies may assist in identifying individuals who are best suited for mapping in the waking state and provide direct activation of areas of highest interest.[12] In addition to these methods, functional magnetic resonance imaging is one of the most important procedures for preoperative mapping.[13]

Received: 26 March 2024
Accepted: 13 May 2024
Published: 18 May 2024

Task-based functional magnetic resonance imaging (T-fMRI) has been the primary method used to locate language and motor functions by analyzing changes in the blood oxygen level-dependent (BOLD) signal while performing certain activities.[14,15] However, there are some drawbacks associated with T-fMRI which include long scanning time and requires that the patient must be awake, cooperative, and actively participate during the task, which is sometimes not possible, especially in pediatric or patients' populations with neurologic frailties as well as those with brain tumours.[14,15] The fact that in the brain tumours practice, maximizing the tumour resection while conserving brain function is the basic goal of the surgery. Resting-state functional magnetic resonance imaging (Rs-fMRI) is a useful method for assessing functional connectivity and network dynamics in patients without requiring them to do any tasks.[16] Its incorporation into clinical processes offers the potential to improve surgical techniques, perhaps reducing operative time and improving postoperative recovery.[17,18]

Resting-state functional magnetic resonance imaging (Rs-fMRI) is an alternate technique for localizing the representation of a function in the brain. Rs-fMRI delineates topographies linked with certain tasks, such as somatomotor, executive control, and language tasks. These topographies are sometimes referred to as resting state networks (RSNs).[19–21] Rs-fMRI and T-fMRI are fundamentally distinct in terms of their analytical approach and methodology. RS-fMRI centers on the spontaneous fluctuations in blood oxygen level-dependent (BOLD) signals observed during a resting state, devoid of any specific task execution, as opposed to T-fMRI, which measures brain activity by comparing BOLD signals during specific tasks to baseline periods.[22] Rs-fMRI can identify regions of the brain that exhibit synchronous, low-frequency oscillations, generally falling below 0.1 Hz.[23] These oscillations are hypothesized to indicate functional connectivity between distinct brain areas.[24,25] It is believed that brain areas with synchronized spontaneous oscillations of their BOLD signal belong to the same resting-state functional network (RSN).[26] Functional maps derived from Rs-fMRI have been used to identify eloquent brain areas and overcome the constraints of T-fMRI for preoperative planning.[27,28] During scanning, patients are not expected to do any specific tasks other than minimizing head movement.[29] Therefore, the behavioral protocol is rather straightforward ("keep waiting and try to remain awake"), and no extra task-related devices, such as MR-compatible display systems, are needed.[30,31] Additionally, Rs-fMRI is compatible with light or sleep sedation and may be performed on young children; consequently, the conclusions are more difficult.[32,33] Therefore, this study intends to comprehensively examine the relevance of fMRI in the neurosurgical planning of brain tumor resections, specifically focusing on the shift from task-based to resting-state modalities. The study will evaluate the influence of different imaging methods on surgical results, analyzing their effectiveness in achieving a balance between tumor removal and the preservation of cognitive and motor skills.

Methods of the Systematic Article

Search Technique and Study Choice

The present investigation adheres to the requirements set forth by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and has been duly registered in the International Prospective Register of Systematic Reviews (PROSPERO) database under the identifier CRD42022364693. The study encompassed the following components: The process involves many key steps: (1) clearly delineating the objectives, (2) establishing specific criteria for inclusion and exclusion, (3) precisely describing the relevant information to be retrieved from the articles, (4) conducting a thorough analysis of the collected data, (5) interpreting the obtained results, and (6) engaging in a comprehensive discussion of the findings.

We conducted a comprehensive search of PubMed, Scopus, and Web of Science to locate all relevant papers published before October 2022. The search uncovered studies that reported the use of ("resting-state fMRI" OR "functional magnetic resonance imaging" OR "rs-fMRI" OR "resting-state functional MRI" OR "functional neuroimaging") AND ("preoperative planning" OR "pre-surgical planning" OR "neurosurgery" OR "preoperative assessment" OR "surgical planning" OR "preoperative evaluation" OR "surgical decision-making") AND ("brain tumor surgery" OR "brain tumor" OR "neuro-oncology" OR "brain neoplasm" OR "glioma" OR "brain cancer") AND ("reliability" OR "clinical utility" OR "surgical outcomes" OR "surgical success" OR "patient outcomes")I, and default mode network (DMN) were among the key terms employed. In addition, we monitored referrals to pertinent literature to identify more qualified research. The publication status and publication date stated in Systematic Research Strategies are largely from the last five years (from 2018 to 2022). Furthermore, we conducted a systematic review of relevant literature to ascertain additional scholarly studies. The publication status and publication date reported in Systematic Research Strategies predominantly encompass the period spanning from 2018 to 2022, with a focus on recent scholarship.

Inclusion and Exclusion Criteria

The study employed specific criteria for inclusion, which were as follows:

- English-language manuscript.
- Case studies and cross-sectionals for Rs-fMRI research.
- Investigations of all types of brain cancer.
- Studies on paediatric patients.

While this study had specific exclusion criteria, which were as follows:

- Animal studies.
- Article reviews.
- Conference papers.

Through debate, an agreement on the eligibility of each research was obtained.

Results

Rs-fMRI as a Preoperative Mapping Tool

Rs-fMRI is an emerging technology that may be used to investigate brain physiology.[34] Recent research has investigated the possible uses of Rs-fMRI in various neurological disorders (eg, epilepsy, neurodegenerative, and psychiatric disorders).[35,36] Nonetheless, the efficacy of Rs-fMRI in neurosurgical planning for brain tumours has not been exhaustively studied.

Several studies have revealed a significant overlap between Rs-fMRI and T-fMRI when comparing the motor network in different neurological disorders and a high degree of concordance with cortical stimulation mapping.[37] According to one study, a change in function on the intraocular sensorimotor network (SMN) after surgery revealed a drop in functional connectivity (FC) 24 h after surgery and considerable restoration of connection at a 3 month of follow-up check, which was related to the restoration of motor skills.[38] Other investigations have revealed similar repeatability of motor maps produced from Rs-fMRI and T-fMRI in healthy people.[39] Other authors have documented FC alterations following surgery not just in the SMN but also in the DMN, SN, and LN, even at the level of a single subject.[40]

Rs-fMRI may consistently identify common functional connectivity networks in glioma patients and has the potential to predict network modifications after surgical resection. Alterations of RSNs may be studied at both the individual subject and the group level, with functional mapping revealing a good correlation with cortical stimulation mapping. Although T-fMRI can achieve preoperative localization of eloquent regions limit the risk of surgery-induced functional impairments, various functional networks, including linguistic, visual, and sensorimotor networks, may be identified using Rs-fMRI.[41,42]

Brain tumour patients exhibited a range of tumour related comorbidities, including ADHD linguistics problems, neurological impairment, and tic disorders, most of the examined trials. Due to the frequency of comorbidities in brain tumours, we decided to include these studies in our review to increase the generalizability of the results. For each of the chosen studies, we examined the previous five years to determine the most recent advancements in fMRI patient diagnosis and prediction accuracy. We had several issues regarding some of the studies that explored the diagnosis of brain tumours by fMRI, and after reviewing the complete texts, we disregarded some of these studies, leaving 18 suitable fMRI investigations, as shown in Figure 1. All test volunteers were adults and teenagers of various ages (ages 2–84 years). Table 1 provides a comprehensive overview of the neoplastic outcomes. Graph theory, independent component analysis (ICA), and seed-based analysis were frequently cited as the most employed analytical techniques.

Table 1 provides a comprehensive summary of the key characteristics of the investigation. The study was conducted in multiple countries. Five studies were conducted entirely with right-handed persons.[43–47] Eight investigations included both right-handed and left-handed individuals.[18,48–53] The remaining studies did not document the hand preference of the participants.[54–56] Most of the research used participants who were matched in terms of group, age, and gender. No analyses relevant to age or gender were conducted in the studies.

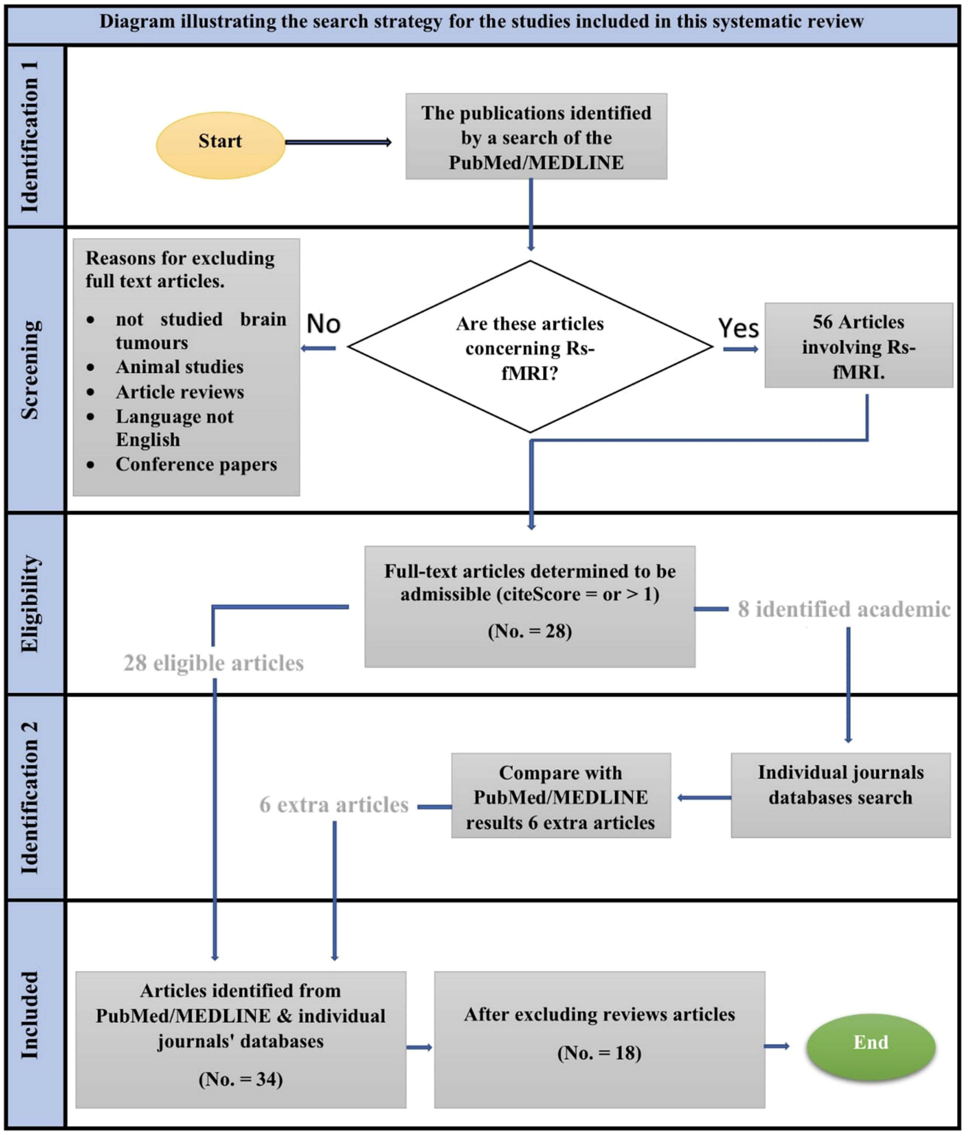

Figure 1 Diagram illustrating the search strategy used for the studies included in this systematic review.

All studies included in the analysis reported age ranges that spanned from 2 to 84 years. Table 1 enumerates the many classifications of brain tumors, as outlined in numerous scholarly investigations, encompassing low-grade gliomas. Brain tumors are categorized based on their postulated cellular source and cellular behavior, ranging from the least aggressive (benign) to the most aggressive (malignant).[57] Gliomas are the most primary intracranial tumors, including 81% of malignant brain tumors and 16% of all primary tumors.[58] Glioblastoma (GBM) is the most common and most fatal primary malignant brain tumor encountered in the adult population.[59]

Resting-State fMRI Networks

Recent implementations of the Rs-fMRI analysis for the localization of functional networks involved regions that rely heavily on independent component analysis (ICA) and neural-network (NN), which were also used in the reviewed investigations. The majority of studies concentrated on the localization of the motor network (MN) and language network (LN) since these networks are used by the T-fMRI method[37–45,48–51,54,55] to measure the quality of the reconstruction. In addition, cognitive and motor skills are among the most crucial talents that must be preserved to guarantee the patient's quality of life following surgery. However, Rs- fMRI has the potential to isolate other functional networks, as

Table 1 A Collection of Research Analyzing Brain Function Using Rs-fMRI

NO	Study location	Participants number and sex	Age	Handedness	Tumour Types	MRI Acquisition	Pre-Symptoms	Rs-fMRI Analysis
1	**Gianvincenzo et al (2020)**[48]	10 patients (7 male, 3 female)	25 to 67 years (range 51)	9 Right-handed 1 Left-handed	6 anaplastic astrocytoma 3 glioblastoma multiforme 1 anaplastic	3T MRI GE	3 Motor 6 Language 1 Visual	Seed-based
2	**Lemée et al (2019)**[49]	50 patients (34 male, 16 female)	49.6 ± 13.5 years (range 18–75)	44 Right-handed 6 Left-handed	42 glial tumors 2 metastases 6 nontumoral brain lesions	3T MRI Siemens	3 Motor 6 Language 1 Visual	Independent Component Analysis (ICA)
3	**Niu et al (2021)**[43]	50 patients (34 male, 16 female)	24–79 years (average: 54.4 ± 11.3)	109 Right-handed	58 Meningioma. 38 Glioma. 13 brain metastasis	3T MRI GE	43 motor deficits 66 no motor deficits but other symptoms	Independent Component Analysis (ICA)
4	**Liouta et al (2019)**[44]	69 patients (32 male, 37 female)	50 ± 15.5 years	69 Right-handed	33 glioblastomas 16 meningiomas 11 astrocytomas 5 oligodedrogliomas 2 hemangiomas 1 ependymoma 1 neurocytoma	1.5T MRI Siemens	8 Motor 7 Language 54 not display any symptoms	Independent Component Analysis (ICA)
5	**Leuthardt et al (2018)**[54]	191 patients (118 male, 73 female)	3 to 84 years (range 46)	Not reported	41 Low grade glioma 80 High grade glioma 32 Other tumors (DNET, Meningioma, Pilocytic Astrocytoma,	3T MRI Siemens	Not reported	Multilayer Perceptron (MLP)
6	**Metwali et al (2020)**[55]	34 patients (18 male, 16 female)	18–77 years (mean, 54)	Not reported	Ganglioglioma	3T MRI Siemens	Not reported	Region of Interest (ROI)
7	**Cho et al (2021)**[45]	29 patients (18 male, 11 female)	45 ± 14 years	29 Right-handed	5 astrocytoma 4 anaplastic 4 oligodendro 1 anaplastic 13 glioblastoma 2 glioma.	3T MRI GE	language deficits	Seed-based

(*Continued*)

https://doi.org/10.2147/JMDH.S470809

https://doi.org/10.2147/JMDH.S470809
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Table 1 (Continued).

NO	Study location	Participants number and sex	Age	Handedness	Tumour Types	MRI Acquisition	Pre-Symptoms	Rs-fMRI Analysis
8	**Yordanova et al (2019)**[50]	23 patients 15 male, 8 female)	23–65 years (mean= 38)	18 Right-handed 3 Left-handed 2 Ambidextrous	15 frontal lobes 2 temporo-occipital lobes 6 adjacent frontal and temporal regions	1.5T & 3T MRI Siemens	Not reported	Seed-based
9	**Daniel et al (2021)**[51]	57 patients (42 male, 15 female)	57.8 ± 13.9 years	22 Right-handed 29 Lift-handed 6 bilateral	57 glioblastoma	3T MRI Siemens	Not reported	Seed-based
10	**Thakkar et al (2022)**[52]	71 patients (34 male, 37 female)	18–75 years (mean= 45.29)	68 Right-handed 3 Left-handed	65 primary tumours 6 metastasis	3T MRI Philips	4 severe linguistic deficits. 17 moderate language disorders 49 mild language disorders	Seed-based
11	**Wongsripuemtet et al (2018)**[18]	66 patients (38 male, 28 female)	40.8 ± 14.6 years	63 Right-handed 3 Left-handed	6 Diffuse astrocytoma 1 Fibrillary astrocytoma 9 Infiltrative astrocytoma 8 Anaplastic astrocytoma 8 Glioblastoma 26 Glioblastoma 3Anaplastic oligoastrocytoma 1 Myeloid sarcoma 1 Metastatic melanoma 1 Metastatic adenocarcinoma 2 No pathologic report	3T MRI Siemens	Not reported	Seed-based
12	**Cai et al (2021)**[46]	126 patients (72 male, 54 female)	42.21 ± 12.74 years	126 right-handed	30 astrocytoma 19 anaplastic 16 oligodendroglioma 1 anaplastic 22 oligoastrocytoma 8 anaplastic 30 glioblastoma	3T MRI Siemens	Not reported	Multilayer Perceptron (MLR)

13	**Zacà, D et al (2018)**[47]	6 patients (4 male, 2 female)	18–45 years	6 right-handed	1 glioma 1 oligodendroglioma 1 anaplastic astrocytoma 2 Cavernoma 1 astrocytoma.	1.5T MRI GE	Not reported	Independent Component Analysis (ICA)
14	**Kumar et al (2020)**[53]	49 patients (28 male, 21 female)	17–78 years (mean= 47.5)	45 Right-handed 2 Left-handed 2 Ambidextrous	10 astrocytoma 5 Anaplastic astrocytoma 22 Glioblastoma 6 Oligodendroglioma 3 Metastasis 1 Pleomorphic xanthoastrocytoma 2 Anaplastic pleomorphic xanthoastrocytoma.	3T MRI GE	12 poor performance 7 suffer from severe impairment (such as aphasia) 20 is weak in the language area. 8 no BOLD activation near tumour. 2 patient motion artifact	Seed-based
15	**Anwar et al (2022)**[56]	22 patients (15 male, 7 female)	2–18 years (mean= 8.6)	Not reported	4 Ganglioglioma 3 Xanthoastrocytoma 3 meningioma 3 dysembryoplastic neuroepithelial tumour 2 Anaplastic Ependymoma 1 Aneurysmal fibrous histiocytoma 1 Pilocytic astrocytoma 1 glioblastoma multiforme 1 Anaplastic astrocytoma 1 Low grade glioma 1 embryonal tumour with multilayered rosettes 1 Ewinga	3T MRI Philips	9 increased ICT or generalized seizures 2 motor seizures 10 neurological deficits 1 motor seizures	Seed-based & ICA

(*Continued*)

Table 1 (Continued).

NO	Study location	Participants number and sex	Age	Handedness	Tumour Types	MRI Acquisition	Pre-Symptoms	Rs-fMRI Analysis
16	**Luckett et al (2020)[60]**	35 patients (23 male, 12 female)	23–71 years (mean= 44.8)	23 Right-handed 3 Left-handed 9 Not reported	10 Glioblastoma 1 Anaplastic glioma 2 Anaplastic mixed oligoastrocytoma 7 Mixed oligoastrocytoma 3 Anaplastic oligodendroglioma 5 Oligodendroglioma 1 Metastatic lung carcinoma 1 Low-grade diffuse glioma 1 Meningioma 1 Ependymoma 1 Low-grade glioneuronal tumour 1 Ganglioglioma 1 Anaplastic astrocytoma	3T MRI Siemens	35 Language	3D convolutional Neural Network (3D CNN)
17	**Yahyavi et al (2017)[15]**	26 patients (15 male, 11 female)	21–69 years (mean = 43.6)	Not reported	Not specific	3T MRI Siemens	26 Ventral Somatomotor Network	Independent Component Analysis (ICA)
18	**Nandakumar et al (2021)[61]**	62 patients (37 male, 25 female)	32–43 years (mean= 38.3)	Not reported	Not specific	3T MRI Siemens	62 Motor and Language deficits	CNN-MTL /Graph Neural Network (GNN)

demonstrated by Lemée et al,[49] who demonstrated that Rs-fMRI could detect brain language regions during cortical mapping (CM) with a sensitivity level 100% compared to 65.6% with T-fMRI.

Gianvincenzo et al[48] reliably reported common functional connectivity networks in patients with glioma and were able to anticipate network changes after surgical removal through an Rs-fMRI. Moreover, Met- wally et al[55] showed that the conversion rate between networks is significantly higher in patients with brain tumours than in healthy subjects. Although brain tumours affect FC and RSNs, their study showed by analysing data that Rs-fMRI indicates higher baseline connectivity between networks in patients with brain tumours, which may suggest an intrinsic neural compensatory mechanism.

Seed-Based Analysis

Six studies employed a seed-based approach to examine brain activity.[18,45,48,50,51,53] Various brain regions were employed as seed regions to assess the locations of different cancers and networks. A study was conducted that combined seed-based analysis with independent component analysis (ICA).[56] The study included individuals diagnosed with brain tumors in the sensorimotor area who exhibited normal motor strength, individuals diagnosed with brain tumours in the sensorimotor region who exhibited low motor strength, and a group of healthy individuals serving as controls. Before the surgical excision procedure, a certain researcher successfully ascertained the precise topology of the eight resting-state networks of each participant.[48] Furthermore, it was determined by neurosurgeons that resting-state functional magnetic resonance imaging (Rs-fMRI) proved to be unequivocally beneficial in 26 cases (60%) and moderately beneficial in 13 cases (30%) for the purpose of identifying potentially significant eloquent language areas.

However, in six cases, the utilization of Rs-fMRI was unsuccessful due to factors such as head movement, non-specific functional connectivity beyond the posterior language network, or system instability of unknown origin.[53] According to previous studies,[18] it has been demonstrated that the localization of the supplementary movement region by the utilization of manual motor seed regions yields higher rates of success compared to seeding with the orofacial motor areas for individual patients with brain tumors. In their study, Cho et al[45] discovered that brain tumors had a disruptive effect on the language network within the cerebral and cerebellar regions. This observation suggests the presence of neuronal impairments and cortical reconfiguration as a consequence of the lesions.

In a study conducted by Daniel et al,[51] it was shown that functionally linked pixels, which are not evident in conventional structural images, were frequently observed within the tumor mass. Notably, these linked pixels did not exhibit a significant correlation with tumor size. After accounting for clinical and demographic variables, it was observed that a higher level of functional connectivity (FC) within the network of Glioblastoma (GBM) tumors was associated with a better overall survival outcome in persons with documented survival periods (n = 31).

Independent Component Analysis (ICA)

Six investigations scanned the brain using an ICA method.[43,44,47,49] Lemée et al[49] identified cerebral language areas during CM with a sensitivity level of 100% when using Rs-fMRI compared to a sensitivity level of 65.6% when using the fMRI task; this improves the use of Rs-fMRI for preoperative language mapping. Liouta et al[44] found that Rs-fMRI BOLD signalling of motor and linguistic networks was considerably impacted by tumours, demonstrating the method's utility for measuring baseline functioning in patients with brain tumours. Alternatively, Sharaev et al used a three-step method for the efficient and automated mapping of functional brain areas. For both the T-fMRI and Rs-fMRI approaches, blind and semi-cryptic ICA analysis was used. The findings demonstrated that the semi-blind ICA had more specificity than the blind ICA.

Rs-fMRI is an excellent approximation for T-fMRI maps, particularly in cases with nearly full ICA decomposition. Zacà, D. et al[47] demonstrated that Rs-fMRI networks, including the pleura cortex, are automatically spatially adjacent to the excised lesion in all patients. For 78% of motor instances, 100% of visual cases, 87.5% of language cases, and 100% of speech-expression mapping cases the estimated distance between direct electrical stimulation (DES) sites and matched Rs-fMRI networks is smaller than 1 cm. Lastly, Yahyavi et al[15] reveal the identification of ventral somatomotor network in 81% of the 26 patients by Rs-fMRI presented for presurgical brain mapping. Enhanced Rs-fMRI reliability in ventral motor network mapping with higher ICA orders was similarly observed. At the single-subject level, mutable concordance of the ventral somatomotor network between Rs-fMRI and T-fMRI was demonstrated.

Convolutional Neural Networks Analysis

Two investigations scanned the brain using convolutional neural networks method.[60,61] Recently, well recorded transformation in image classification and subnetworks or segmentation related problems by deep CNN method was achieved. Language network was specifically and precisely localized using three dimensional CNN in subjects with brain tumors by Luckett and his colleagues. The investigators demonstrate that with limited quantities of data and patient cooperation the method was able to deliver strong results which is an added advantage in clinical practice.

The utilization of noninvasive resting-state functional magnetic resonance imaging (Rs-fMRI) at the preoperative planning stage holds significance for localizing the eloquent cortex. This application serves to expedite and improve the involved processes, despite the inherent challenges it presents. In their study, Nandakumar et al[61] employed a convolutional neural network (CNN) that leverages the generalization capabilities of multi-task learning, a unique deep learning technique. The aim was to achieve simultaneous localization of various areas of eloquent cortex using resting-state functional magnetic resonance imaging (Rs-fMRI) connections. This technique effectively captured shared representation among various subnetworks of interest by employing a graph-based design. Following a thorough process of quantitative validation and evaluation, the researchers discovered that the utilization of resting-state functional magnetic resonance imaging (Rs-fMRI) in this innovative approach holds significant promise in enhancing the preoperative assessment by facilitating faster and more reliable tumor removal.

Comparison of Rs-fMRI and T-fMRI

The present review centers on the utilization of resting-state functional magnetic resonance imaging (Rs fMRI) as a preoperative mapping technique for the identification of functional areas. Out of the total of eighteen studies examined, seven of them employed the combination of task-based functional magnetic resonance imaging (T-fMRI) and resting-state functional magnetic resonance imaging (Rs-fMRI) to accurately identify and map language and sensorimotor regions in the brain. The aforementioned investigations are delineated in Table 2.

Table 2 A Comparison of Rs-fMRI and T-fMRI Studies

Author(s)	Type of task	Coefficient of concordance and correlation between rs-fMRI and T-fMRI
Lemée et al (2019)[49]	Sentence generation (SG) Tone Listening (TL)	The use of Rs-fMRI for presurgical language mapping is straightforward, allowing for the identification of functional brain language networks with more sensitivity than T-fMRI
Niu et al (2021)[43]	Hand Movement	Using T-fMRI activation as a benchmark, the general linear model-based machine learning (GLM-ML) model demonstrated that it can accurately predict individual variations in task activation using low-resolution conventional Rs-fMRI data
Luckett et al (2020)[60]	Language task (word-stem completion)	State of rest fMRI can be utilised on all patients, and because it has a lower failure rate than T-fMRI, it is advantageous for patients who cannot participate in task-based tests.
Yahyavi et al (2017)[15]	Tongue Motor	At the single-subject level, there is variable concordance between Rs-fMRI and T-fMRI for the ventral somatomotor network
Kumar et al (2020)[53]	Letter Fluency Category Fluency Sentence Completion	This study suggests that in the absence of T-fMRI, Rs-fMRI may be a good alternative for clinical language mapping.
Liouta et al (2019)[44]	Assessment for Apparent (Paresis) Finger Tapping Assessment for Apparent (Paresis) Mild Language (Phonological Verbal Fluency)	The findings revealed that the Rs-fMRI BOLD signal of the motor and language networks was considerably altered by the tumours, indicating the method's utility for measuring basic functioning in patients with brain tumours
Nandakumar et al (2021)[61]	Finger Tapping Tongue Moving Foot Tapping	The results clearly highlight the advantages of the study-specific graph convolution design combined with multitask learning and the potential for Rs-fMRI to be used as a preoperative mapping instrument

Four studies[15,43,44,49] utilized independent components analysis (ICA) to evaluate the Rs-fMRI data, and the T-fMRI task paradigm consisted of performing the various activities listed in Table 2. Lemée et al[49] discovered that using Rs-fMRI for preoperative language mapping is simple and permits the identification of functional brain language networks with better sensitivity than T-fMRI. Liouta et al[44] discovered that tumours significantly impacted Rs-fMRI BOLD signals of motor and linguistic networks, showing the method's utility for assessing baseline function. Yahyavi et al[15] demonstrated consistency in the somatic network between Rs-fMRI and T-fMRI at the level of the individual participant.

Luckett et al[60] found that resting-state fMRI can be utilized for all patients and since it has a lower failure rate than T-fMRI, it is beneficial for patients who cannot engage in task-based testing. According to a study by Nandakumar et al,[61] the ability of Rs-fMRI as a preoperative mapping tool is supported, and the benefits of a study-specific graph convolution design coupled with multitask learning are highlighted. Kumar et al[53] demonstrated that in the absence of T-fMRI, Rs-fMRI may serve as a suitable substitute for clinical language mapping. The utility of Rs-fMRI as a preoperative mapping technique is therefore supported by these investigations. Thus, we conclude that Rs-fMRI is a potential method for evaluating and accurately mapping brain areas before surgery.

Comparison of Rs-fMRI Data to Cortical Stimulations (DCS and ECS)

Many studies have used RS-fMRI for preoperative planning, although the concordance, specificity, and sensitivity of Rs-fMRI with intraoperative cortical mapping (DCS, the gold standard or ECS) are not well studied. Researchers have found good connection between Rs-fMRI findings and DCS in locating the eloquent motor cortex, sensorimotor network, and Wernicke's region.[18,62,63] Three researchers compared preoperative Rs-fMRI data to intraoperative DES and ECS outcomes. According to Zaca et al,[47] the difference between Rs-fMRI networks and intraoperative DES results in 27 positive cortical sites from six patients with presurgical Rs-fMRI was less than 1 cm in cases involving visual and speech articulation, 78% for motor cases, and 87.5% for language mapping. This indicated good spatial agreement between Rs-fMRI and DES results during awake surgery. According to Lemée et al,[49] 32 of 50 persons with preoperative language mapping (Rs-fMRI and T-fMRI) had cerebral language areas identified by intraoperative ECS mapping. Rs-FMRI localized eloquent cerebral language networks with 100% sensitivity, while T-fMRI had 65.6%. ECS instrument confirmed the four functional brain language areas identified by Rs-fMRI, but not by T-fMRI, during surgery. The study found that the Rs-fMRI method is easy to use and more sensitive than T-fMRI in identifying functional brain language networks, although with certain restrictions. Yordanova et al[50] mapped the face-based mentalizing network using Rs-fMRI and perioperative DES. Positive stimulation locations were verified and attached to presurgical normalized MRI data, serving as seeds for subsequent seed-to-voxel functional connectivity analyses. Their findings confirmed many prior studies and showed that the combined approaches can strongly detect functional networks in brain-damaged people. See Table 3.

Table 3 Correlation and Validation of Preoperative Rs-fMRI by Intraoperative Cortical Mapping (DES and ECS)

No	Authors	Types of mapping cases	Correlation and validation of preoperative Rs-fMRI to intraoperative cortical stimulation
1	Zaca et al (2019)[47]	Motor, language, visual, and speech articulation	The use of ReStNeuMap as an Rs-FMRI processing pipeline showed an excellent spatial agreement between the predictions by preoperative Rs-fMRI and DES findings in almost all the mapping cases during the awake operation.
2	Lemée et al (2019)[49]	Language	Of the 32 brain language areas identified by intraoperative cortical mapping (ECS), Rs-fMRI data had 100% sensitivity in the eloquent brain language area identification and functional brain language areas were effectively identified in 4 patients by Rs-fMRI compared to none by T-fMRI. Similarly, Rs-fMRI successfully identified 15 brain language areas out of 18 subjects with negative cortical mapping.
3	Yordanova et al (2019)[50]	Mentalizing network	The combination of preoperative Rs-fMRI and intraoperative DES is validated as a viable approach to identify functional networks, particularly the mentalizing networks.

Discussion

A new method for localizing functional brain areas, Rs-fMRI, is gaining favor.[27] The therapeutic application of this method for diagnostic and therapeutic purposes is being worked on.[28] Niu et al[43] found that Rs-fMRI data may predict motor activation based on preoperative mapping in adult motor brain tumor patients, however they recommended include pediatric data in future studies to test the neural network (NN) technique.

Research by Li-outa et al[44] presented contrasting results. Given the limitations of T-fMRI, RS-fMRI may be a helpful supplemental method for preoperative brain mapping in a pediatric investigation. Future research is required to compare the BOLD signals of Rs-fMRI networks with the functional results after surgery to confirm the functional importance of this approach. Leuthardt et al[54] provided evidence of this. In his study, including children, the failure rate of Rs-fMRI was 13%, which was much lower than the failure rate of T-MRI (38.5%) (P 0.001). In conclusion, Daniel et al[51] found that most glioblastoma patients had functionally linked brain tissue, as shown by Rs-fMRI. The degree of functional connection inside the tumour also has prognostic significance. Based on research by Kumar et al,[53] there is evidence that Rs-fMRI may be useful for preoperative clinical language mapping when a patient cannot complete T-fMRI or if findings are insufficient. In neurosurgical procedure, accurate brain function localization is vital, while DCS is the gold standard for brain function assessment, reduction in operative time and enhanced operative planning are obtained when pre-operative Rs-fMRI a noninvasive tool is performed. Many predictions of Rs-fMRI tool have been validated by DCS and demonstrated good agreement between the two findings. Zaca et al[47] demonstrated that, excellent spatial agreement between Rs-fMRI predictions and DCS were achieved in the mapping of motor, language, visual and speech articulation areas during the awake operation.

Based on the current research, twelve out of fifteen studies (80%) concurred that Rs-fMRI is acceptable and beneficial for preoperative mapping, as illustrated in Figure 2. The study by Cho et al[45] showed that Rs- fMRI is clinically quick and effective for language network mapping. Lemée et al[49] demonstrate that Rs-fMRI is more sensitive than T-fMRI in identifying functional brain language networks. This was confirmed by Kumar et al[53] suggested that if T-fMRI was not available, Rs-fMRI might be a suitable alternative for clinical language mapping. Although these studies highlight the effectiveness of Rs-fMRI, it is important to note that direct comparative outcome studies between Rs-fMRI and T-fMRI are limited. The current data suggests that Rs-fMRI can detect the location of the cortex consistently and with a high success rate, showing outcomes that are equivalent to those of T-fMRI. This indicates that Rs-fMRI could be a promising technique for preoperative functional localization, but further comparative studies are needed to substantiate this suggestion more robustly.

Previous studies indicate that Rs-fMRI is a sensitive and reliable preoperative mapping tool for detecting neural networks like RSNs efficiently and effectively. As shown in Figure 2, Rs-fMRI is a promising technology that can be used in many clinical situations where T-fMRI cannot be used and could improve surgical and therapeutic techniques and include more patients in preoperative detection and evaluation. Thus, there is evidence that Rs-fMRI has interesting clinical applications. During cDCS testing is currently the gold standard for mapping palpebral areas for neurosurgical operations. This method has several disadvantages, such as requiring the patient to stay willing and interactive during the surgical process.[64] Furthermore, there is a risk of intraoperative seizures (3 to 18%) or respiratory difficulties (15 to 24%) in infants who are awake, which might reduce overall efficacy.[65] If any of these occur during surgery, the awake part must be ended promptly; this would restrict the scope of the resection.[66] Rs-fMRI correlation mapping, on the other hand, offers information throughout the gray matter and may provide information on previously inaccessible regions, such as language regions inside the brain.[67]

Study Limitations

The implementation of numerous procedures and protocols in scientific investigations may pose challenges in regulating head movement and physiological fluctuations. MRI technique and methodological limitations in terms of technology may also compromise the dependability of results. Furthermore, a significant number of studies lack independent data examination by neuroradiologists, which underscores a deficiency in the validation procedure. In addition, further dependable validation studies are required to enhance the preoperative mapping precision of Rs-fMRI.

https://doi.org/10.2147/JMDH.S470809
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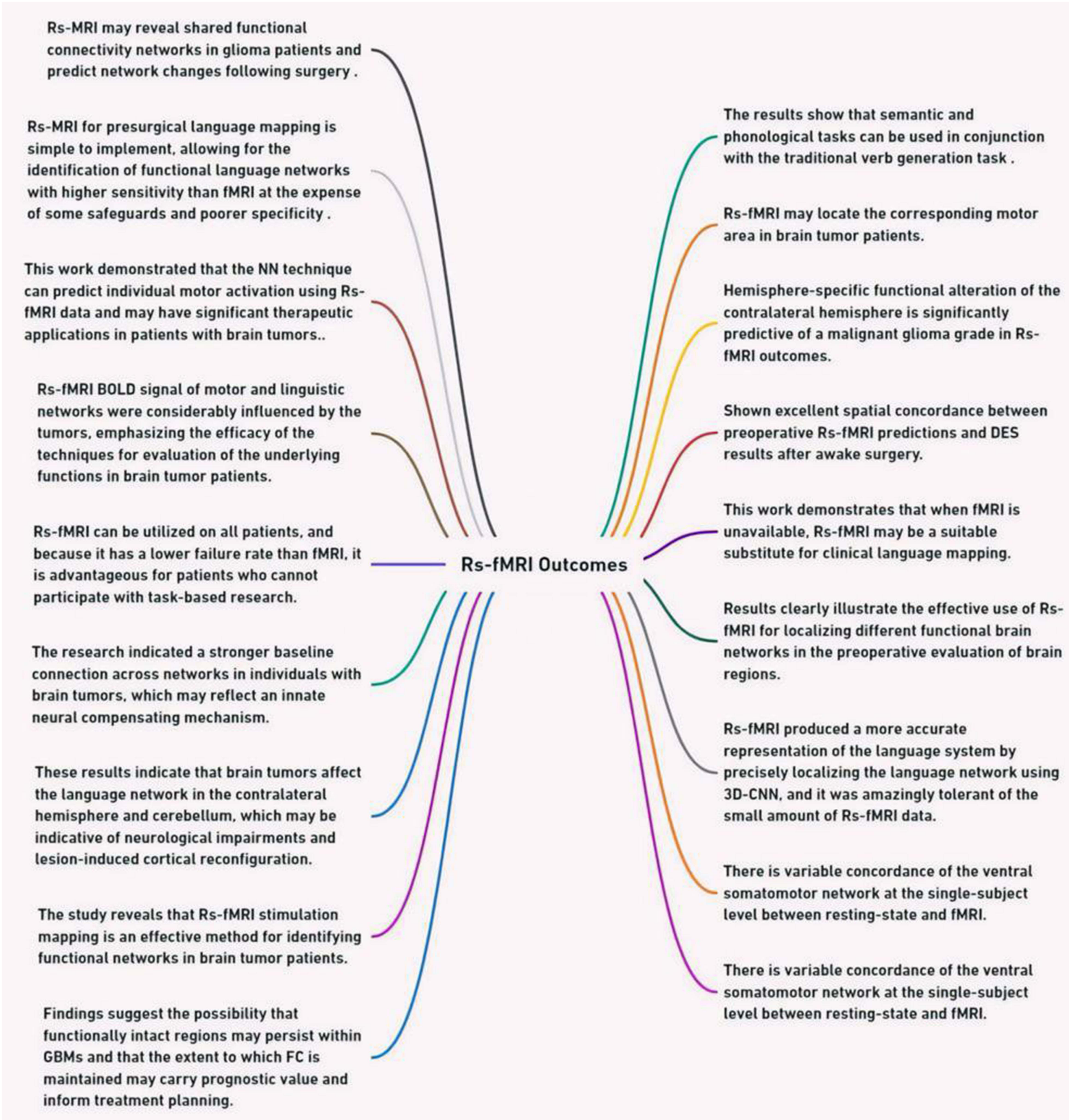

Figure 2 The findings of the content analysis of the studies included in this study.

Conclusion

Results suggest Rs-fMRI could be employed for preoperative mapping. This method may aid patients, especially those who struggle with T-fMRI tasks. When planning brain tumor surgery, Rs-fMRI may be the only option to determine functional connectivity. It serves as an essential alternative in scenarios where T-fMRI is not possible, such as language mapping. Moreover, resting fMRI may be the only tool for measuring functional connectivity in brain tumour surgical planning. Despite its significant utility, Rs-fMRI can produce incorrect results due to head movement during data collection. To tackle this issue, it is imperative to incorporate real-time motion correction algorithms, improve scanner hardware to mitigate motion sensitivity and utilize sophisticated image processing methods such as machine learning to correct artifacts. In addition, the integration of hybrid imaging modalities including diffusion tensor imaging (DTI) with fMRI could yield mappings that are more exhaustive and precise. Additionally, the incorporation of artificial intelligence can enhance interpretation and analysis, resulting in more accurate tumor mappings. These technological developments are crucial in providing neurosurgeons with the necessary tools to evaluate the advantages and disadvantages of surgical procedures, thus maximizing patient results.

Acknowledgments

H.Y.M. would like to acknowledge Universiti Sains Malaysia (USM) for the GRA-Assist Scheme provided.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis, and interpretation, or all these areas; took part in drafting, revising, or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

Disclosure

The authors declare no conflicts of interest in this work.

References

1. Hacker CD, Roland JL, Kim AH, Shimony JS, Leuthardt EC. Resting-state network mapping in neurosurgical practice: a review. *Neurosurgical Focus*. 2019;47(6):E15. doi:10.3171/2019.9.FOCUS19656
2. Fierstra J, van Niftrik C, Warnock G, et al. Staging hemodynamic failure with blood oxygen-level–dependent functional magnetic resonance imaging cerebrovascular reactivity: A comparison versus Gold Standard (15O-) H2O-Positron Emission Tomography. *Stroke*. 2018;49(3):621–629. doi:10.1161/STROKEAHA.117.020010
3. Jalilianhasanpour R, Beheshtian E, Ryan D, et al. Role of functional magnetic resonance imaging in the presurgical mapping of brain tumors. *Radiologic Clinics*. 2021;59(3):377–393. doi:10.1016/j.rcl.2021.02.001
4. Iwaszczuk P, Łosiak W, Szczeklik W, Musiałek P. Patient periprocedural stress in cardiovascular medicine: friend or foe? *Advan Interven Cardiol*. 2021;16(1).
5. Stippich C, Blatow M, Alzamora MG. *Task-Based Presurgical Functional MRI in Patients with Brain Tumors*. In: Clinical functional MRI Springer; 2022:121–195.
6. Gerritsen JKW, Dirven CMF, De Vleeschouwer S, et al. The PROGRAM study: awake mapping versus asleep mapping versus no mapping for high-grade glioma resections: study protocol for an international multicenter prospective three-arm cohort study. *BMJ open*. 2021;11(7):e047306. doi:10.1136/bmjopen-2020-047306
7. Hervey-Jumper SL, Berger MS. Maximizing safe resection of low-and high-grade glioma. *J Neuro-oncol*. 2016;130(2):269–282. doi:10.1007/s11060-016-2110-4
8. Silva AH, Aquilina K. Surgical approaches in pediatric neuro-oncology. *Canc Metastasis Rev*. 2019;38(4):723–747. doi:10.1007/s10555-019-09832-2
9. Wu J, Guo S, Li J, Zeng D. Big data meet green challenges: big data toward green applications. *IEEE Syst J*. 2016;10(3):888–900. doi:10.1109/JSYST.2016.2550530
10. Herbet G. Should complex cognitive functions be mapped with direct electrostimulation in wide-awake surgery? A network perspective. *Front Neurol*. 2021;12:635439. doi:10.3389/fneur.2021.635439
11. KKulkarni D, Moningi S. Monitoring During Epilepsy Surgery and Awake Craniotomy. *Mon Anesthesia Cril Care*. 2018;234.
12. Fox KC, Foster BL, Kucyi A, Daitch AL, Parvizi J. Intracranial electrophysiology of the human default network. *Trends in Cognitive Sciences*. 2018;22(4):307–324. doi:10.1016/j.tics.2018.02.002
13. Catalino MP, Yao S, Green DL, Laws ER, Golby AJ, Tie Y. Mapping cognitive and emotional networks in neurosurgical patients using resting-state functional magnetic resonance imaging. *Neurosurgical Focus*. 2020;48(2):E9. doi:10.3171/2019.11.FOCUS19773
14. Beheshtian E, Jalilianhasanpour R, Modir Shanechi A, et al. Identification of the so- matomotor network from language task–based fMRI compared with resting-state fMRI in patients with brain lesions. *Radiology*. 2021;301(1):178–184. doi:10.1148/radiol.2021204594
15. Yahyavi-Firouz-Abadi N, Pillai J, Lindquist M, et al. Presurgical brain mapping of the ven- tral somatomotor network in patients with brain tumors using resting-state fMRI. *Am J Neuroradiol*. 2017;38(5):1006–1012. doi:10.3174/ajnr.A5132
16. Sparacia G, Parla G, Cannella R, et al. Resting-state functional magnetic resonance imaging for brain tumor surgical planning: feasibility in clinical setting. *World Neurosurg*. 2019;131:356–363. doi:10.1016/j.wneu.2019.07.022
17. Qiu T, Yan C, Tang W, et al. Localizing hand motor area using resting-state fMRI: validated with direct cortical stimulation. *Acta neurochirurgica*. 2014;156:2295–2302. doi:10.1007/s00701-014-2236-0
18. Wongsripuemtet J, Tyan A, Carass A, et al. Preoperative mapping of the supplementary motor area in patients with brain tumor using resting-state fMRI with seed-based analysis. *Am J Neu-Roradiol*. 2018;39(8):1493–1498.
19. Yang PH, Hacker CD, Patel B, Daniel AG, Leuthardt EC. Resting-State Functional Magnetic Resonance Imaging Net- works as a Quantitative Metric for Impact of Neurosurgical Interventions. *Front Neurosci*. 2021;15.

20. Wheelock MD, Culver JP, Eggebrecht AT. High-density diffuse optical tomography for imaging human brain function. *Rev Sci Instrum*. 2019;90 (5):051101. doi:10.1063/1.5086809
21. Smyser CD, Wheelock MD, Limbrick DD Jr, Neil JJ. Neonatal brain injury and aberrant connectivity. *Neuroimage*. 2019;185:609–623. doi:10.1016/j.neuroimage.2018.07.057
22. Felouat H. *Functional and Structural Analysis of fMRI/MRI Images of the Brain Using Graph Matching According to a Parallel and Distributed Approach (Doctoral Dissertation*. University of Blida); 2021.
23. Mascali D. Physiological and pathological modulations of intrinsic brain activity assessed via resting-state fMRI; 2016.
24. Whittaker JR, Driver ID, Venzi M, Bright MG, Murphy K. Cerebral autoregulation evidenced by synchronized low frequency oscillations in blood pressure and resting-state fMRI. *Front Neurosci*. 2019;13:433. doi:10.3389/fnins.2019.00433
25. Yang L, Yan Y, Li Y, et al. Frequency-dependent changes in fractional amplitude of low-frequency oscillations in Alzheimer's disease: a resting-state fMRI study. *Brain Imag Beha*. 2020;14(6):2187–2201. doi:10.1007/s11682-019-00169-6
26. Seitzman BA, Snyder AZ, Leuthardt EC, Shimony JS. The state of resting state networks. Topics in magnetic resonance imaging. *TMRI*. 2019;28 (4):189. doi:10.1097/RMR.0000000000000214
27. Manan HA, Franz EA, Yahya N. The utilisation of resting-state fMRI as a pre-operative mapping tool in patients with brain tumours in comparison to task-based fMRI and intraoperative mapping: a systematic review. *European j Can Care*. 2021;30(4). doi:10.1111/ecc.13428
28. Rosazza C, Zacà D, Bruzzone MG. Pre-surgical brain mapping: to rest or not to rest? *Front Neurol*. 2018;9:520. doi:10.3389/fneur.2018.00520
29. Vakamudi K, Posse S, Jung R, Cushnyr B, Chohan MO. Real-time presurgical resting-state fMRI in patients with brain tumors: quality control and comparison with task-fMRI and intraoperative mapping. *Human Brain Mapp*. 2020;41(3):797–814. doi:10.1002/hbm.24840
30. Park KY, Lee JJ, Dierker D, et al. Mapping language function with task-based vs. resting-state functional MRI. *PLoS One*. 2020;15(7).
31. Bhutada AS, Sepúlveda P, Torres R, Ossandón T, Ruiz S, Sitaram R. Semi-automated and direct localization and labeling of EEG electrodes using MR structural images for simultaneous fMRI-EEG. *Front Neurosci*. 2020;14:558981. doi:10.3389/fnins.2020.558981
32. Mohammadi-Nejad AR, Mahmoudzadeh M, Hassanpour MS, et al. Neonatal brain resting-state functional connectivity imaging modalities. *Photoacoustics*. 2018;10:1–19. doi:10.1016/j.pacs.2018.01.003
33. Ji T, Li X, Chen J, et al. Brain function in children with obstructive sleep apnea: a resting-state fMRI study. *Sleep*. 2021;44(8). doi:10.1093/sleep/zsab047
34. Catal Y, Gunay MA, Li C, et al. The Intrinsic Hierarchy of Self–Converging Topography and Dynamics. *bioRxiv*. 2022.
35. Sparacia G, Parla G, Mamone G, Caruso M, Torregrossa F, Grasso G. Resting-State Functional Magnetic Reso- nance Imaging for Surgical Neuro-Oncology Planning: towards a Standardization in Clinical Settings. *Brain Sciences*. 2021;11(12):1613. doi:10.3390/brainsci11121613
36. Haghshenas Bilehsavar S, Batouli SAH, Soukhtanlou M, Alavi S, Oghabian MA. Different olfactory perception in heroin addicts using functional magnetic resonance imaging. *Basic Clin Neurosci*. 2022;13(2):257–268. doi:10.32598/bcn.12.6.2210.1
37. Dadi K, Varoquaux G, Machlouzarides-Shalit A, et al. Fine-grain atlases of functional modes for fMRI analysis. *NeuroImage*. 2020;221:117126. doi:10.1016/j.neuroimage.2020.117126
38. Vassal M, Charroud C, Deverdun J, et al. Recovery of functional connectivity of the sensorimotor network after surgery for diffuse low-grade gliomas involving the supplementary motor area. *J Neurosurg*. 2017;126(4):1181–1190. doi:10.3171/2016.4.JNS152484
39. Mannfolk P, Nilsson M, Hansson H, et al. Can resting-state functional MRI serve as a complement to task-based mapping of sensorimotor function? A test–retest reliability study in healthy volunteers. *J Magn Reson Imag*. 2011;34(3):511–517. doi:10.1002/jmri.22654
40. Fox ME, King TZ. Functional connectivity in adult brain tumor patients: a systematic review. *Brain Connect*. 2018;8(7):381–397. doi:10.1089/brain.2018.0623
41. Sair HI, Yahyavi-Firouz-Abadi N, Calhoun VD, et al. Presurgical brain mapping of the language network in patients with brain tumors using resting-state f MRI: comparison with task f MRI. *Human Brain Mapp*. 2016;37(3):913–923. doi:10.1002/hbm.23075
42. Sair HI, Agarwal S, Pillai JJ. Application of resting state functional MR imaging to presurgical mapping: language mapping. *Neuroimaging Clinics*. 2017;27(4):635–644. doi:10.1016/j.nic.2017.06.003
43. Niu C, Wang Y, Cohen AD, et al. Machine learning may predict individual hand motor activation from resting-state fMRI in patients with brain tumors in perirolandic cortex. *Eur Radiol*. 2021;31(7):5253–5262. doi:10.1007/s00330-021-07825-w
44. Liouta E, Katsaros VK, Stranjalis G, Leks E, Klose U, Bisdas S. Motor and language deficits correlate with resting state functional magnetic resonance imaging networks in patients with brain tumors. *J Neuroradiol*. 2019;46(3):199–206. doi:10.1016/j.neurad.2018.08.002
45. Cho NS, Peck KK, Gene MN, Jenabi M, Holodny AI. Resting-state functional MRI language network connectivity differences in patients with brain tumors: exploration of the cerebellum and contralesional hemisphere. *Brain Imag Behav*. 2022;16(1):252–262. doi:10.1007/s11682-021-00498-5
46. Cai S, Shi Z, Jiang C, et al. Hemisphere-specific functional remodeling and its relevance to tumor malignancy of cerebral glioma based on resting-state functional network analysis. *Front Neurosci*. 2021;14:611075. doi:10.3389/fnins.2020.611075
47. Zacà D, Jovicich J, Corsini F, Rozzanigo U, Chioffi F, Sarubbo S. ReStNeuMap: a tool for automatic extraction of resting- state functional MRI networks in neurosurgical practice. *J Neurosurg*. 2018;131(3):764–771. doi:10.3171/2018.4.JNS18474
48. Sparacia G, Parla G, Re VL, et al. Resting-state functional connectome in patients with brain Tumors before and after surgical resection. *World Neurosurg*. 2020;141:e182–e194. doi:10.1016/j.wneu.2020.05.054
49. Lemée JM, Berro DH, Bernard F, et al. Resting-state functional magnetic resonance imaging versus task-based activity for language mapping and correlation with perioperative cortical mapping. *Brain and Behavior*. 2019;9(10):e01362. doi:10.1002/brb3.1362
50. Yordanova YN, Cochereau J, Duffau H, Herbet G. Combining resting state functional MRI with intraoperative cortical stimulation to map the mentalizing network. *Neuroimage*. 2019;186:628–636. doi:10.1016/j.neuroimage.2018.11.046
51. Daniel AG, Park KY, Roland JL, et al. Functional connectivity within glioblastoma impacts overall survival. *Neuro-Oncology*. 2021;23(3):412–421. doi:10.1093/neuonc/noaa189
52. Thakkar I, Arraño-Carrasco L, Cortes-Rivera B, et al. Alterna- tive language paradigms for functional magnetic resonance imaging as presurgical tools for inducing crossed cerebro- cerebellar language activations in brain tumor patients. *Eur Radiol*. 2022;32(1):300–307. doi:10.1007/s00330-021-08137-9
53. Kumar VA, Heiba IM, Prabhu SS, et al. The role of resting-state functional MRI for clinical preoperative language mapping. *Cancer Imaging*. 2020;20(1):1–9. doi:10.1186/s40644-020-00327-w
54. Leuthardt EC, Guzman G, Bandt SK, et al. Integration of resting state functional MRI into clinical practice-A large single institution experience. *PLoS One*. 2018;13(6):e0198349. doi:10.1371/journal.pone.0198349

55. Metwali H, Raemaekers M, Ibrahim T, Samii A. Inter-network functional connectivity changes in patients with brain tumors: a resting-state functional magnetic resonance imaging study. *World Neurosurg*. 2020;138:e66–e71. doi:10.1016/j.wneu.2020.01.177
56. Anwar A, Radwan A, Zaky I, El Ayadi M, Youssef A. Resting state fMRI brain mapping in pediatric supratentorial brain tumors. *Egypt J Radiol Nucl Med*. 2022;53(1):1–10. doi:10.1186/s43055-022-00713-3
57. Liyanage PY, Zhou Y, Al-Youbi AO, et al. Pediatric glioblastoma target-specific efficient delivery of gemcitabine across the blood–brain barrier via carbon nitride dots. *Nanoscale*. 2020;12(14):7927–7938. doi:10.1039/D0NR01647K
58. Ostrom QT, Gittleman H, Truitt G, Boscia A, Kruchko C, Barnholtz-Sloan JS. CBTRUS statistical report: primary brain and other central nervous system tumors diagnosed in the United States in 2011–2015. *Neuro-Oncology*. 2018;20(suppl_4):iv1–iv86. doi:10.1093/neuonc/noy131
59. Kumaria A, Teale A, Kulkarni GV, Ingale HA, Macarthur DC, Robertson IJ. Glioblastoma multiforme metastatic to lung in the absence of intracranial recurrence: case report. *British Journal of Neurosurgery*. 2022;36(2):290–292. doi:10.1080/02688697.2018.1529296
60. Luckett P, Lee JJ, Park KY, et al. Mapping of the language network with deep learning. *Front Neurol*. 2020;11:819. doi:10.3389/fneur.2020.00819
61. Nandakumar N, Manzoor K, Agarwal S, et al. Automated eloquent cortex localization in brain tumor patients using multi-task graph neural networks. *Med Image Anal*. 2021;74:102203. doi:10.1016/j.media.2021.102203
62. Sahu A, Kurki V, Vijan A, Janu A, Shetty P, Moiyadi A. Case series of applications of resting state functional MRI in brain tumor surgery: A novel technique. *Indian J Radiol Imaging*. 2021;31(04):990–997. doi:10.1055/s-0041-1741046
63. Zhang D, Johnston JM, Fox MD, et al. Preoperative sensorimotor mapping in brain tumor patients using spontaneous fluctuations in neuronal activity imaged with functional magnetic resonance imaging: initial experience. *Neurosurgery*. 2009;65(6):226–236. doi:10.1227/01.NEU.0000350868.95634.CA
64. Kim SS, McCutcheon IE, Suki D, et al. Awake craniotomy for brain tumors near eloquent cortex: correlation of intraoperative cortical mapping with neurological outcomes in 309 consecutive patients. *Neurosurgery*. 2009;64(5):836–846. doi:10.1227/01.NEU.0000342405.80881.81
65. Duffau H, Lopes M, Arthuis F, et al. Contribution of intraoperative electrical stimu- lations in surgery of low grade gliomas: a comparative study between two series without (1985–96) and with (1996– 2003) functional mapping in the same institution. *J Neurol Neurosurg*. 2005;76(6):845–851. doi:10.1136/jnnp.2004.048520
66. Giussani C, Roux FE, Ojemann J, Sganzerla EP, Pirillo D, Papagno C. Is preoperative functional magnetic resonance imaging reliable for language areas mapping in brain tumor surgery? Review of language functional magnetic resonance imaging and direct cortical stimulation correlation studies. *Neurosurgery*. 2010;66(1):113–120. doi:10.1227/01.NEU.0000360392.15450.C9
67. Brennan NP, Peck KK, Holodny A. Language mapping using fMRI and direct cortical stimulation for brain tumor surgery: the good, the bad, and the questionable. *Topic Mag Reson Imag*. 2016;25(1):1. doi:10.1097/RMR.0000000000000074