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CLINICAL APPLICATIONS OF FUNCTIONAL MAGNETIC RESONANCE IMAGING

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Abstract
Functional magnetic resonance imaging (fMRI) has progressed from a research tool for mapping human brain activity into a proven constituent of clinical imaging. By exploiting the blood oxygen level dependent (BOLD) signal, fMRI offers a non-invasive means of localizing eloquent cortex, characterizing functional networks, and assessing disease related changes in brain function. Its most wise clinical role is presurgical mapping in patients going through resection of brain tumors or epileptogenic foci, where it reduces dependence on invasive procedure such as Wada test and intraoperative cortical stimulation. Developing applications extend to stroke recovery, neurodegenerative disease, psychiatric and pain disorders, increased backing by resting-state fmri, artificial intelligence-based analysis and multimodal imaging. This review condenses the physiological principles underlying fMRI, its acquisition and analysis techniques, its principle clinical applications, the role of the MRI technologist in delivering a diagnostic quality scan, and current restrictions and future directions relevant to trainee radiologists.

Keywords: fMRI; BOLD imaging; Brain mapping; Functional brain imaging; Neuroimaging; Presurgical brain mapping; Neurological disorders; Neurosurgical planning; Cognitive neuroscience; Functional connectivity; Resting-state fMRI; Clinical neuroimaging.

Introduction

Functional MRI spot changes in regional brain activity indirectly, through the coupling between neuronal activation, local metabolic demand, and cerebral blood flow. Since its inception in the early 1990s, the expertise has evolved from a purely investigational tool into one that inform real clinical decisions, most particularly in the planning of neurosurgical procedures near eloquent cortex. Different from positron emission tomography or invasive electrophysiological mapping, fMRI requires no ionizing radiation or intracranial electrodes, can be repeated freely, and can be merged with the anatomical MRI sequences already obtained as a part of routine preoperative work-up. For the trainee radiologist, understanding fMRI is increasingly relevant not only to neuroradiology subspecialisation but also to multidisciplinary tumor boards, epilepsy surgery conferences, stroke rehabilitation planning, and the broader move toward network-based models of brain disease.

Principle of fMRI

The BOLD Effect

Functional MRI in clinical practice depends almost solely on the blood oxygen level dependent (BOLD) contrast mechanism. Neuronal activation raises local oxygen consumption, but this is exceeded by a disproportionate increase in regional cerebral blood flow, resulting in a net growth in the ratio of oxyhemoglobin to deoxyhemoglobin within activated tissue. Because deoxyhemoglobin is paramagnetic and oxyhemoglobin is diamagnetic, this shift yields a small, detectable increase in T2 weighted signal- the BOLD response. The BOLD signal is therefore a hemodynamic surrogate for neuronal activity rather than a direct measure of it.

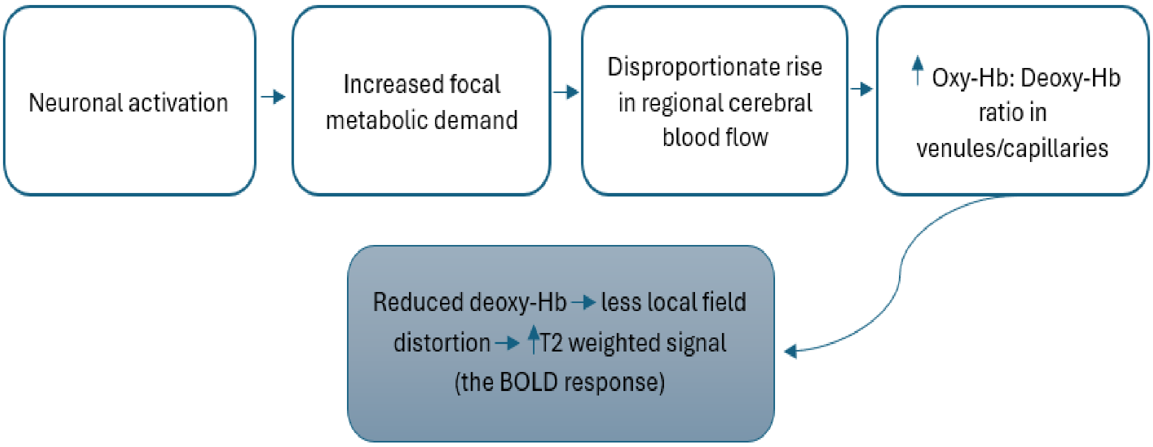

Figure 1. neuronal activation increases regional blood flow disproportionately to oxygen extraction, raising the oxy-to-deoxy-hemoglobin ratio and producing the measurable BOLD signal increase.

Hemodynamic Response

The hemodynamic response function (HRF) illustrates the time course of the BOLD signal following a brief period of neuronal activity. An ordinary HRF starts 1-2seconds after the stimulus onset, peaks at roughly 4-6 seconds and returns to standard over 15-20 seconds, occasionally preceded by a small initial dip and obeyed by a post-stimulus undershoot. Because the HRF is slow relative to the foundational neuronal events, fMRI has excellent spatial resolution but fairly poor temporal resolution compared with electrophysiological techniques such as EEG or MEG. Statistical models used in fMRI analysis fuse the expected task timing with a canonical HRF to guess the expected signal time course, against which the observed data are compared.

Neurovascular Coupling

Neurovascular coupling is the physiological mechanism connecting neuronal activity to the local hemodynamic changes that the BOLD signal depends upon, mediated by astrocytes, pericytes, and the cerebral microvasculature. Because fMRI depends totally on intact neurovascular coupling, any disease process that disturbs this relationship-tumor neovascularity, ischemia, prior radiotherapy, or the ageing or atherosclerotic vasculature-can cause a discrepancy between true neuronal activity and the measured BOLD response. This, phenomenon, called neurovascular uncoupling, is one of the most important sources of false negative activation in clinical fMRI and must be considered when interpreting studies in patients with brain tumors, cerebrovascular disease, or prior brain injury.

fMRI Techniques

Task-Based fMRI

Task-based fMRI (tb-fMRI) detects BOLD signal changes when a patient follows a structured paradigm, such as finger tapping for motor mapping or covert word creation for language mapping, and identifies active areas by contrasting task and rest (or control) blocks or events. Task design is either a block design, in which task and control periods alternate over blocks of 15-30 seconds, or an event-related design, in which brief discrete trials are modelled separately. Task-based fMRI has the highest concordance with direct cortical stimulation, particularly for language localization, but it requires the patient to understand, comply with, and consistently complete the paradigm.

Resting-State fMRI

Resting-state fMRI (rs-fMRI) measures spontaneous low-frequency BOLD fluctuations while the patient lies passively in the scanner and employs methods such as seed-based correlation or independent component analysis in order to identify functionally connected networks-such as the sensorimotor, language, or default mode networks-without the need for active task performance. It is especially useful in patients who cannot consistently complete activities, such as young children, sedated patients, or those with cognitive, sensory, or motor disability, and can map numerous networks from a single, brief acquisition.

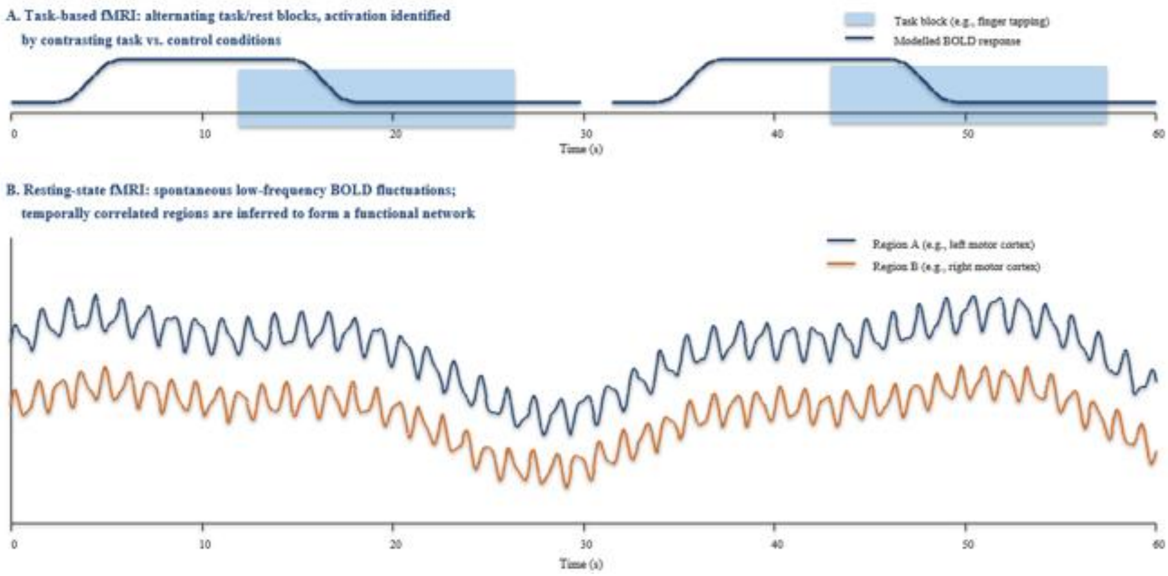

Figure 2. Task based vs. resting state fMRI acquisition paradigms.
Illustrative comparison of task-based (block-design) and resting-state fMRI acquisition strategies.
Waveforms are schematic, not real patient data.

Data Acquisition

Most clinical fMRI is acquired using T2-weighted gradient-echo echo-planar imaging (EPI), which allows whole-brain coverage every 1–3 seconds. Typical clinical protocols use field strengths of 1.5 T or 3 T, with 3 T providing a higher BOLD contrast-to-noise ratio at the expense of increased susceptibility artifact. Key acquisition parameters include repetition time (TR), echo time (TE, typically 25-35 ms at 3 T), slice thickness, and in-plane resolution, all of which must be balanced against competing needs for temporal precision, spatial resolution, and signal-to-noise ratio. A structural (anatomical) sequence, typically a 3D T1-weighted acquisition, is obtained during the same session to allow co-registration of functional activation maps onto detailed anatomy, and diffusion tensor imaging is frequently acquired alongside fMRI in presurgical protocols to provide complementary white matter tractography.

Image Processing and Analysis
Prior to statistical analysis, raw fMRI data are subjected to a standard preprocessing pipeline that includes motion correction (realignment of each volume to a reference image), slice-timing correction, spatial normalization to a standard anatomical template, and spatial smoothing to improve signal-to-noise ratio and inter-subject comparability. Statistical analysis of task-based data is typically performed using the general linear model (GLM), in which the observed time series in each voxel is modelled as a combination of the expected task-related signal (convolved with the HRF) and nuisance variables such as motion parameters, resulting in a statistical parametric map of task-related activation. Resting-state data are analyzed using functional connectivity approaches, such as seed-based correlation analysis or independent component analysis (ICA), which find groupings of voxels with statistically associated time courses and thereby construct a functional network. To avoid false-positive activation, each stage requires appropriate statistical thresholding and multiple-comparisons correction.

Clinical Applications

Preoperative Brain Mapping
The most known clinical application of fMRI is preoperative mapping in patients undergoing excision of lesions near the eloquent cortex. Two related goals are addressed: risk assessment, specifically the determination of hemispheric language dominance, which informs surgical consent and planning; and localization of "critical" motor, language, sensory, or visual cortex relative to the lesion, which allows the surgeon to plan a trajectory that maximizes resection while minimizing the risk of permanent neurological deficit. Resting-state fMRI is becoming a more popular adjunct or alternative for patients who are unable to complete task paradigms, however its concordance with direct cortical stimulation, particularly for higher-order cognitive functions, is less consistent than task-based fMRI. Expert panels have issued consensus recommendations for standardizing language fMRI paradigms, patient preparation, and reporting in the presurgical setting, reflecting the technique's evolution from a research method to one that must meet formal quality and reproducibility standards comparable to other clinical imaging tests.

Brain Tumors
In neuro-oncology, fMRI is used to plan surgical approaches for gliomas and other tumors located in the motor, language, sensory, or visual cortex. Systematic reviews and meta-analyses of preoperative fMRI mapping in brain tumor surgery show a link to lower postoperative morbidity, especially when paired with supplementary techniques like diffusion tensor tractography and intraoperative neuromonitoring. Tumor-related physiological changes, such as neovascularity and oedema, can impair the reliability of both task-based activation and resting-state connectivity measures near the lesion, emphasizing the importance of correlating fMRI findings to intraoperative direct cortical stimulation in high-risk cases.

Epilepsy
fMRI helps with epilepsy surgery in two ways. First, functional MRI (fMRI) is increasingly being employed as a non-invasive alternative or complement to the intracarotid amobarbital (Wada) test, particularly for assessing language dominance prior to temporal lobe surgery. Second, simultaneous EEG-fMRI maps spike-related BOLD signal changes, assisting in the localization or lateralization of an epileptogenic focus in patients with non-lesional or discordant electroclinical findings, and has been shown in several small series to identify a probable focus even when structural MRI is unremarkable. Resting-state functional connectivity analysis is also being investigated as a marker of the epileptogenic zone, owing to the discovery that areas nearest to the seizure focal frequently exhibit altered baseline connection.

Stroke
fMRI plays an increasingly important role in understanding and monitoring recovery from ischemic and hemorrhagic strokes. Task-based fMRI studies have identified patterns of altered activation and recruitment of the perilesional and contralesional cortex during motor and language activities following stroke, informing models of adaptive reorganization vs maladaptive compensation. Resting-state fMRI is increasingly being used to study post-stroke network reorganization, and it has been proposed as a biomarker for stratifying patients in rehabilitation trials, such as those that combine non-invasive brain stimulation with motor training, as well as predicting motor, sensory, and language (aphasia) recovery. Although not yet incorporated into standard stroke imaging routes, these approaches are transforming fMRI from a strictly descriptive tool to one with potential prognostic and treatment-selection utility in stroke rehabilitation.

Neurodegenerative-Diseases
Resting-state fMRI has been widely utilized to characterize disruption of large-scale brain networks, particularly the default mode network, in Alzheimer's disease and mild cognitive impairment, with lower connectivity in these networks associated with disease severity in research cohorts. Task-based fMRI studies using memory-encoding paradigms have also revealed altered hippocampus and parahippocampal activation in Alzheimer's disease. More recently, machine learning models based on resting-state fMRI connectivity metrics have demonstrated high diagnostic accuracy in distinguishing mild cognitive impairment from Alzheimer's disease in pooled analyses, though such models still require prospective, multicentre validation before being implemented into routine diagnostic pathways.

Psychiatric and Neurological Disorders
A large body of research has used both task-based and resting-state fMRI to study psychiatric illnesses such as schizophrenia, major depression, anxiety disorders, substance use disorders, traumatic brain injury, and movement disorders. This research has increased our understanding of the network-level dysfunction that underpins such illnesses and discovered potential biomarkers for therapy response and neuromodulation targeting, such as in transcranial magnetic stimulation planning for depression. Individual-level diagnostic or prognostic use in psychiatry remains experimental, hampered by repeatability and standardization issues, and fMRI is not currently part of routine diagnostic procedures in these settings.

Pain and Cognitive Disorders
fMRI has significantly advanced our understanding of the brain circuitry underlying acute and chronic pain processing, revealing a distributed network — including the anterior cingulate cortex, insula, thalamus, and somatosensory cortex — that is activated during pain perception and modulated by attention, emotion, and placebo responses. In chronic pain conditions such as fibromyalgia, neuropathic pain, and chronic back pain, both task-based and resting-state fMRI have been used to characterize central sensitization and altered functional connectivity, and real-time fMRI neurofeedback is being investigated as a therapeutic strategy that allows patients to learn to modulate activity in pain-relevant regions. In general, task-based fMRI paradigms probing memory, attention, and executive function are primarily used in research settings to map the neural correlates of cognitive impairment, supplementing rather than replacing neuropsychological testing in current clinical practice.

Advantages and Limitations

Advantages
● Non-invasive and free of ionizing radiation, allowing for repeat tests without cumulative danger.
● Combines with existing structural MRI and diffusion tractography in preoperative or diagnostic protocols, eliminating the need for additional imaging or radiotracer.
● High spatial resolution compared to other functional techniques like EEG or MEG allows for millimetre-scale localization of activity.
● Available on ordinary clinical MRI scanners (1.5 T and 3 T), without the need for specialized infrastructure like PET or invasive electrophysiology.
● Flexible: task-based paradigms can be adjusted to clinical questions, whereas resting-state acquisition maps numerous networks from patients who cannot complete activities.

Limitations
● Relying on an indirect hemodynamic signal, neurovascular uncoupling near tumors, infarctions, or recent surgery might result in false-negative activation despite maintained neuronal function.
● Patient mobility, poor task compliance, anxiety, sedation, and cognitive/sensory impairment can all negatively impact task-based results.
● Echo-planar imaging can cause geometric distortion and signal dropout, especially around air-bone-tissue interfaces like the skull base and paranasal sinuses, causing apparent activation to be misplaced from its true site.
● Variability in acquisition parameters, task paradigms, and post-processing pipelines among centres hinders reproducibility and results comparison, especially for resting-state connectivity measurements.
● Some cognitive domains have limited concordance with direct cortex activation, making fMRI a supplemental planning tool rather than a replacement for intraoperative mapping in high-risk instances.

● Limited clinical fMRI expertise and infrastructure outside specialized university and tertiary centres, hindering equal access.

Role of MRI Technologists/Radiographers

The quality of a clinical fMRI examination is strongly dependent on the MRI technician or radiographer performing it, and their role goes far beyond ordinary scanner operation. Before scanning, the technologist checks the patient for conventional MRI contraindications and, for fMRI, determines if the patient is likely to cooperate with the intended task paradigm, taking into account aspects such as language, hearing, vision, motor ability, and cognitive state. Paradigms are explained and, where possible, rehearsed with the patient outside the scanner to ensure that task performance during acquisition is as reliable as possible; for resting-state acquisitions, the technologist instructs the patient to remain still, keep their eyes open or closed as specified, and avoid falling asleep, as drowsiness significantly alters resting-state connectivity.

During the examination, the technologist positions and immobilizes the patient's head to reduce motion, delivers task stimuli (via visual display, auditory prompts, or response devices) in sync with scanner acquisition, and monitors both patient compliance and real-time image quality throughout the sequence, repeating or adjusting runs where motion or poor task performance is detected. Close collaboration with the radiologist, and in many cases, a clinical neuropsychologist or physicist, is essential to pick acceptable paradigms for the clinical inquiry and to identify technical or compliance difficulties that may effect interpretation. Because fMRI reproducibility is dependent on consistent protocol delivery, technicians play an important role in maintaining standardized local acquisition protocols and quality assurance methods that support reliable, comparable fMRI results across patients and over time.

Emerging Applications

Resting State Connectivity

Resting-state functional connectivity is expanding beyond its current adjunct role in presurgical mapping to broader use as a network-level biomarker, such as tracking post-stroke reorganization, characterizing neurodegenerative disease progression, and stratifying patients for neuromodulation therapies. Its main advantage is the capacity to extract numerous functional networks from a single, very quick, task-free acquisition that is appropriate for a wide spectrum of patients.

Artificial Intelligence

Artificial intelligence and radiomics-based analysis pipelines are being created to automate activation mapping, improve resting-state network extraction, clean up data, and aid in individual-level classification in neurodegenerative and psychiatric diseases. Automated pipelines offer the potential to reduce inter-operator variability in analysis and reporting turnaround time, but clinical use necessitates rigorous external validation across scanners and patient populations.

Machine Learning

Machine learning models, ranging from classical classifiers to deep neural networks, are increasingly being used to differentiate disease states using fMRI-derived connectivity metrics, such as distinguishing mild cognitive impairment from Alzheimer's disease or predicting treatment response in psychiatric disorders.

Multimodal Imaging

Combining fMRI with complementary modalities is an active area of research. Simultaneous EEG-fMRI adds high temporal resolution to fMRI's high spatial resolution, which is very useful in epilepsy focus localization. The integration of diffusion tensor tractography connects functional activation to the underlying white matter pathways pertinent to a targeted surgical corridor. Hybrid PET-MRI enables the acquisition of functional and metabolic or molecular data in the same session, which is particularly useful in neuro-oncology and neurodegenerative disease, while functional near-infrared spectroscopy (fNIRS) is being investigated as a portable, lower-cost alternative to fMRI for populations who cannot tolerate the scanner environment. When paired with these complementing techniques, ultra-high-field imaging at 7 T or more improves spatial resolution and signal-to-noise ratio, potentially improving localization accuracy even further.

Future Perspectives

Several advancements are expected to influence the next stage of clinical fMRI. Continued efforts to standardize acquisition and preprocessing protocols for both task-based and resting-state fMRI, as evidenced by recent expert consensus statements and structured reporting recommendations, aim to improve reproducibility across centres and promote wider adoption of resting-state techniques as reliability concerns are addressed. As ultra-high-field imaging and multimodal data fusion advance, fMRI will become more closely integrated with intraoperative neuron-avigation and robotic-assisted neurosurgery. In parallel, validated AI and machine learning tools may expand fMRI's role from a largely descriptive, presurgical technique to a more quantitative biomarker supporting diagnosis, prognosis, and treatment selection across stroke, neurodegenerative, and psychiatric disease-as long as reproducibility, accessibility, and rigorous multicentre validation keep up with technological advances.

Conclusion

Functional MRI has established itself as a powerful, non-invasive tool in clinical neuroradiology, with the strongest evidence coming from presurgical mapping for neuro-oncology and epilepsy. Applications in stroke, neurodegenerative disease, psychiatry, and pain are still primarily research-driven, but they are evolving rapidly thanks to resting-state approaches, standardization efforts, multimodal imaging, and artificial intelligence-based analysis. For the MSc radiology trainee, a thorough understanding of BOLD physiology, acquisition and analysis techniques, the practical role of the MRI technologist in producing a reliable examination, and the specific strengths and limitations of fMRI in each clinical context is critical to correctly interpreting this modality and appreciating its evolving role within the larger neuroimaging arsenal.

References

1. Voets NL, Ashtari M, Beckmann CF, et al. Consensus recommendations for clinical functional MRI applied to language mapping. Aperture Neuro. 2025;5.
2. Perez NA, Choi BD, Nahed BV, et al. Can preoperative mapping with functional MRI reduce morbidity in brain tumor resection? A systematic review and meta-analysis of 68 observational studies. Radiology. 2021.
3. Current state of functional MRI in the presurgical planning of brain tumors. Radiology: Imaging Cancer. 2025.
4. Vachha BA, Kumar VA, Pillai JJ, Shimony JS, Tanabe J, Sair HI. Resting-state functional MRI: current state, controversies, limitations, and future directions—AJR expert panel narrative review. AJR Am J Roentgenol. 2025;225(3).
5. Kumar VA, Lee J, Liu HL, et al. Recommended resting-state fMRI acquisition and preprocessing steps for preoperative mapping of language, motor, and visual areas in adult and pediatric patients with brain tumors and epilepsy. AJNR Am J Neuroradiol. 2024;45:139-148.
6. Sair HI, Yahyavi-Firouz-Abadi N, Calhoun VD, et al. The role of resting-state functional MRI for clinical preoperative language mapping. Cortex / J Neuroimaging, 2020.
7. Seghier ML. 7T and beyond: toward a synergy between fMRI-based presurgical mapping at ultrahigh magnetic fields, AI, and robotic neurosurgery. Eur Radiol Exp. 2024;8(1).
8. Wang C, Zhou L, Zhou F, Fu T. The application value of Rs-fMRI-based machine learning models for differentiating mild cognitive impairment from Alzheimer's disease: a systematic review and meta-analysis. Neurol Sci. 2024.
9. Azri A, Yahya N, Nabilah Ismail U, Ashari MA, Abdul Manan H. A systematic review of alterations in brain activation and intensity following stroke: implications for integration and functional outcomes. Front Neurol. 2025.
10. A comprehensive review on the role of resting-state functional magnetic resonance imaging in predicting post-stroke motor and sensory outcomes. Brain Sci. 2024;14(1):12.
11. Functional magnetic resonance imaging: an overview and applications on post-stroke rehabilitation. Cantho J Med Pharm. 2025;87:255-264.
12. Borsook D, Becerra LR. Breaking down the barriers: fMRI applications in pain, analgesia and analgesics. Mol Pain. 2006;2:30.
13. Davis KD, Flor H, Greely HT, et al. Brain imaging tests for chronic pain: medical, legal and ethical issues and recommendations. Nat Rev Neurol. 2017;13(10):624-638.
14. Matthews PM, Honey GD, Bullmore ET. Applications of fMRI in translational medicine and clinical practice. Nat Rev Neurosci. 2006;7(9):732-744.
15. Functional magnetic resonance imaging: applications in clinical neurology and psychiatry. PMC review.
16. American Registry of Radiologic Technologists (ARRT). MRI certification and task inventory overview. arrt.org.