Diagnostic Performance of MR Spectroscopy in differentiating Brain Lesions

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ABSTRACT

Magnetic resonance spectroscopy (MRS) has emerged as an important advanced magnetic resonance imaging technique that provides non-invasive metabolic information beyond the anatomical details obtained from conventional MRI. By evaluating the biochemical composition of brain tissue through metabolites such as N-acetylaspartate (NAA), choline (Cho), creatine (Cr), lactate, lipids, and myo-inositol, MRS enhances tissue characterization and improves the differentiation of various intracranial lesions. Characteristic metabolite profiles and metabolite ratios, including Cho/NAA and Cho/Cr, have demonstrated significant value in distinguishing neoplastic from non-neoplastic lesions, grading gliomas, differentiating primary brain tumors from metastases, and identifying tumor recurrence following therapy. The integration of MRS with advanced MRI techniques, including diffusion-weighted imaging (DWI) and perfusion-weighted imaging (PWI), further improves diagnostic accuracy and clinical confidence by combining structural, physiological, and metabolic information. Despite its promising clinical applications, factors such as technical variability, spectral overlap, prolonged acquisition time, and the lack of standardized acquisition protocols continue to limit its widespread implementation. Recent advances in high-field MRI, artificial intelligence, radiomics, and quantitative metabolic analysis are expected to further enhance the diagnostic performance and clinical utility of MRS. This review summarizes the fundamental principles, metabolite characteristics, diagnostic performance, clinical applications, advantages, limitations, and future perspectives of MR spectroscopy in differentiating brain lesions, highlighting its growing role as a valuable adjunct to conventional neuroimaging.

Keywords: Magnetic resonance spectroscopy (MRS); Brain lesions; Brain tumors; Magnetic resonance imaging (MRI); Metabolite profiling; Neoplastic and non-neoplastic lesions; Glioma; Diagnostic imaging.

1. INTRODUCTION

Brain lesions encompass a broad spectrum of pathological conditions, including primary and metastatic tumors, inflammatory and infectious diseases, demyelinating disorders, vascular abnormalities, and treatment-related changes (1). Conventional magnetic resonance imaging (MRI) remains the primary imaging modality for detecting intracranial lesions because of its excellent soft-tissue contrast and

multiplanar imaging capability (2). However, considerable overlap in the morphological appearance of different brain lesions often limits the specificity of conventional MRI, making accurate lesion characterization a persistent diagnostic challenge (1,3).

Magnetic resonance spectroscopy (MRS) is an advanced, non-invasive MRI technique that provides metabolic information by evaluating the biochemical composition of brain tissue (4). Unlike conventional MRI, which primarily demonstrates anatomical changes, MRS measures metabolites such as N-acetylaspartate (NAA), choline (Cho), creatine (Cr), lactate (Lac), lipids, and myo-inositol (mI), thereby offering valuable insight into tissue metabolism and cellular integrity (5,6). These metabolic alterations improve tissue characterization and complement conventional MRI findings, particularly in lesions with similar structural appearances (4,5).

Numerous clinical studies have demonstrated that MRS improves the differentiation of neoplastic and non-neoplastic brain lesions by identifying characteristic metabolite patterns and metabolite ratios (7,8). Furthermore, MRS has shown promising diagnostic value in glioma grading, distinguishing recurrent tumor from radiation-induced injury, and differentiating tumors from inflammatory or pseudotumoral lesions (9,10). The integration of MRS with advanced MRI techniques, such as diffusion-weighted imaging (DWI) and perfusion-weighted imaging (PWI), has further enhanced diagnostic confidence and contributed to more accurate clinical decision-making (2,11).

Despite its considerable diagnostic potential, several factors continue to limit the widespread clinical application of MRS, including technical variability, prolonged acquisition time, susceptibility to artifacts, and overlapping metabolic profiles among different pathological conditions (5,12). Consequently, a comprehensive understanding of its diagnostic performance is essential for appropriate interpretation and clinical utilization **(1,4)**.

2. FUNDAMENTALS OF MR SPECTROSCOPY

Magnetic resonance spectroscopy (MRS) is an advanced magnetic resonance technique that complements conventional MRI by providing metabolic information about tissues in a non-invasive manner (4). Unlike structural MRI, which depicts anatomical abnormalities, MRS analyzes the chemical composition of tissue by measuring resonance signals from endogenous metabolites, thereby offering valuable insight into normal physiology and pathological alterations (3,5). Understanding the basic principles of MRS is essential for accurate interpretation of metabolic spectra and their application in the characterization of brain lesions (4,6).

2.1 Basic Principles of MR Spectroscopy

Magnetic resonance spectroscopy is based on the phenomenon of **chemical shift**, whereby nuclei located in different molecular environments resonate at slightly different frequencies when exposed to a strong magnetic field (5). Proton (^1H) MRS is the most commonly used spectroscopic technique in clinical neuroimaging because hydrogen nuclei are abundant in biological tissues and provide excellent signal intensity (3). The resonance frequencies are expressed in parts per million (ppm), allowing identification and quantification of specific metabolites within brain tissue (1,6).

Unlike conventional MRI, which generates anatomical images from water and fat protons, MRS suppresses these dominant signals to detect metabolites present in much lower concentrations (5). The resulting spectrum consists of multiple peaks, with each peak representing a specific metabolite at a characteristic chemical shift. Variations in metabolite concentrations reflect changes in cellular metabolism, membrane turnover, neuronal integrity, and tissue viability, thereby providing information beyond conventional anatomical imaging (1,4).

2.2 Principles of Chemical Shift and Spectral Acquisition

The diagnostic capability of MRS is based on the chemical shift phenomenon, in which the local electronic environment surrounding hydrogen nuclei influences their resonance frequency (5). These small frequency differences allow metabolites such as N-acetylaspartate, choline, creatine, lactate, and myo-inositol to be identified separately within the MR spectrum (3,4). Each metabolite occupies a characteristic position on the spectrum, measured in ppm, and the relative peak height or peak area reflects its tissue concentration (5,6).

Clinical brain MRS is most commonly performed using single-voxel spectroscopy (SVS) or magnetic resonance spectroscopic imaging (MRSI) (1). Single-voxel spectroscopy provides high-quality spectra from a selected region of interest, whereas MRSI simultaneously acquires metabolic information from multiple voxels, allowing assessment of metabolic heterogeneity within lesions and adjacent brain tissue (1,5). Appropriate voxel placement, adequate shimming, water suppression, and optimization of acquisition parameters are essential for obtaining reliable spectra and minimizing artifacts (1,3).

2.3 Major Brain Metabolites and Their Diagnostic Significance

The clinical utility of MR spectroscopy primarily depends on the evaluation of endogenous brain metabolites that reflect normal cellular function and pathological alterations (3). Each metabolite produces a characteristic resonance peak at a specific chemical shift, and changes in their relative concentrations provide valuable information regarding neuronal integrity, cellular proliferation, membrane turnover, energy metabolism, inflammation, and tissue necrosis (4,5). Interpretation of these metabolite patterns forms the basis for differentiating various neoplastic and non-neoplastic brain lesions (6).

2.3.1 N-Acetylaspartate (NAA)

N-acetylaspartate (NAA), which resonates at approximately 2.0 ppm, is regarded as a marker of viable neurons and axons (5). Healthy brain tissue demonstrates high NAA levels, whereas neuronal loss, dysfunction, or replacement by pathological tissue results in a reduction of the NAA peak (3,4). Consequently, decreased NAA is frequently observed in primary brain tumors, metastatic lesions, inflammatory diseases, and radiation-induced injury, making it an important indicator of neuronal damage (1,6).

2.3.2 Choline (Cho)

Choline-containing compounds produce a resonance peak at approximately 3.2 ppm and are considered markers of cell membrane synthesis and turnover (5). Increased choline concentration reflects accelerated cellular proliferation and membrane degradation, findings that are commonly associated with high-grade gliomas, metastatic tumors, lymphoma, and other rapidly growing neoplasms (4,7). Elevated Cho, particularly when accompanied by reduced NAA, is one of the most reliable spectroscopic indicators of neoplastic brain lesions (1).

2.3.3 Creatine (Cr)

Creatine resonates at approximately 3.0 ppm and is involved in intracellular energy metabolism (5). Because creatine concentration remains relatively stable in normal brain tissue, it is commonly used as an internal reference for calculating metabolite ratios such as Cho/Cr and NAA/Cr (3). Nevertheless, creatine levels may decrease in highly aggressive tumors or severe tissue destruction, which should be considered during spectrum interpretation (6).

2.3.4 Lactate and Lipids

Lactate appears as a characteristic doublet peak near 1.3 ppm and reflects anaerobic glycolysis resulting from tissue hypoxia or impaired oxidative metabolism (5). Elevated lactate is frequently observed in high-grade tumors, cerebral abscesses, ischemic lesions, and radiation injury (7). Lipid peaks, typically detected between 0.9 and 1.5 ppm, indicate membrane breakdown, necrosis, or extensive cellular destruction and are commonly associated with glioblastoma, metastatic tumors, lymphoma, and necrotic lesions (1,4).

2.3.5 Myo-Inositol and Other Metabolites

Myo-inositol (mI), detected at approximately 3.5 ppm, is considered a glial marker and is frequently elevated in low-grade gliomas, gliosis, and certain inflammatory or demyelinating disorders (5). Other metabolites, including glutamate, glutamine, alanine, acetate, succinate, and amino acids, may also provide important diagnostic clues in selected pathological conditions (4). For example, acetate and succinate are characteristic findings in pyogenic brain abscesses, whereas alanine is frequently associated with meningiomas (3,6).

Overall, the interpretation of individual metabolite concentrations and their corresponding ratios, particularly Cho/NAA, Cho/Cr, and NAA/Cr, forms the cornerstone of MR spectroscopic evaluation and significantly enhances the differentiation of various intracranial lesions when combined with conventional MRI findings (1,7).

Table 1. Major Brain Metabolites in MR Spectroscopy and Their Diagnostic Significance

Metabolite	Chemical Shift (ppm)	Physiological Role	Clinical Significance
N-Acetylaspartate (NAA)	2.0	Marker of neuronal integrity	Decreased in brain tumors, infarction, demyelination, and radiation injury
Choline (Cho)	3.2	Cell membrane synthesis and turnover	Increased in neoplastic lesions, especially high-grade gliomas and metastases
Creatine (Cr)	3.0	Energy metabolism	Relatively stable; commonly used as an internal reference
Lactate (Lac)	1.3	Anaerobic metabolism	Increased in high-grade tumors, abscesses, ischemia, and radiation necrosis

Lipids	0.9–1.5	Membrane breakdown and necrosis	Elevated in necrotic tumors and radiation injury
Myo-Inositol (mI)	3.5	Glial cell marker	Increased in gliosis, low-grade gliomas, and demyelinating disorders
Alanine	1.48	Amino acid metabolism	Characteristically elevated in meningiomas
Acetate & Succinate	1.9 & 2.4	Bacterial metabolism	Characteristic metabolites of pyogenic brain abscess

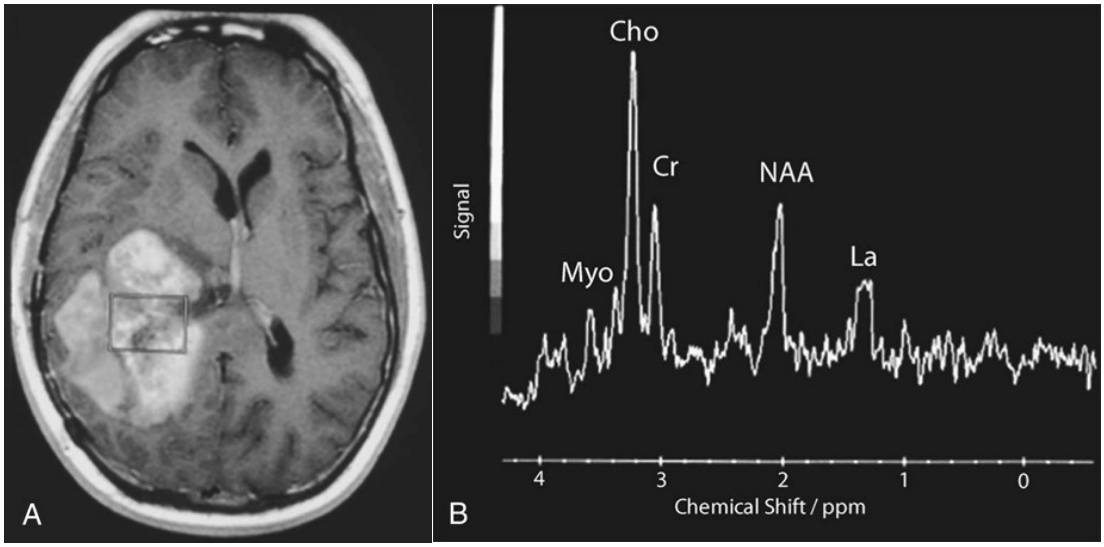

Figure 1. (A) Axial post-contrast T1-weighted MR image showing a heterogeneously enhancing right parietal mass. The square indicates the region selected for MR spectroscopy. (B) PRESS spectrum (TE = 30 ms) demonstrating elevated choline, reduced NAA and myo-inositol, with a small lactate peak, consistent with an aggressive brain lesion.(13)

2.4 SPECTROSCOPIC ACQUISITION TECHNIQUES

The diagnostic accuracy of MR spectroscopy is influenced not only by metabolite interpretation but also by the acquisition technique used during image acquisition (4). Appropriate selection of localization methods, echo time (TE), and pulse sequences is essential for obtaining high-quality spectra and minimizing artifacts (3,5). In clinical neuroimaging, the most widely used spectroscopic techniques are single-voxel spectroscopy (SVS) and magnetic resonance spectroscopic imaging (MRSI), each offering distinct advantages depending on the clinical indication (5,11).

2.4.1 Single-Voxel Spectroscopy (SVS)

Single-voxel spectroscopy (SVS) acquires metabolic information from a single predefined region of interest and is the most commonly used technique in routine clinical practice (4). It provides excellent spectral quality, relatively short acquisition times, and straightforward post-processing, making it particularly suitable for the evaluation of focal brain lesions (5). However, because metabolic information is obtained from only one voxel, SVS may not adequately represent heterogeneous tumors or infiltrative lesions with variable metabolic composition (3,7).

2.4.2 Magnetic Resonance Spectroscopic Imaging (MRSI)

Magnetic resonance spectroscopic imaging (MRSI), also known as chemical shift imaging (CSI), simultaneously acquires spectra from multiple voxels, enabling evaluation of the spatial distribution of metabolites throughout the lesion and surrounding brain tissue (5). This technique is especially valuable for assessing tumor heterogeneity, identifying the most metabolically active regions for biopsy, evaluating peritumoral infiltration, and monitoring treatment response (6,11). Although MRSI provides more comprehensive metabolic information than SVS, it generally requires longer acquisition times, greater technical expertise, and more complex data analysis (5,11).

2.4.3 Echo Time and Pulse Sequences

Selection of an appropriate echo time (TE) significantly influences spectral quality and metabolite detection (4). Short echo time (20–35 ms) permits visualization of a broader range of metabolites, including myo-inositol, glutamate, glutamine, and mobile lipids, but often produces more complex spectra because of overlapping resonance peaks (3,5). In contrast, long echo time (135–144 ms) generates cleaner spectra with improved baseline stability, facilitating reliable assessment of major metabolites such as choline, creatine, N-acetylaspartate, and lactate (3,7).

The two most widely used localization pulse sequences are Point-Resolved Spectroscopy (PRESS) and Stimulated Echo Acquisition Mode (STEAM) (5). PRESS provides higher signal-to-noise ratio and is therefore preferred for routine clinical applications, whereas STEAM permits shorter echo times and reduced radiofrequency power deposition, making it useful in selected clinical and research settings (5,6). The choice of acquisition technique should ultimately be guided by lesion characteristics, scanner capabilities, and the clinical question being addressed (4,11).

3. DIAGNOSTIC PERFORMANCE OF MR SPECTROSCOPY

Magnetic resonance spectroscopy (MRS) has become an important adjunct to conventional MRI by providing metabolic information that improves the characterization of intracranial lesions (1). Unlike anatomical imaging, MRS evaluates tissue biochemistry through metabolite analysis, allowing differentiation of lesions with similar morphological appearances on routine MRI (4,5). Consequently, MRS has demonstrated promising diagnostic performance in distinguishing neoplastic from non-neoplastic lesions, assessing tumor grade, identifying treatment-related changes, and improving overall diagnostic confidence (1,7).

3.1 Differentiation of Neoplastic and Non-Neoplastic Brain Lesions

Differentiating neoplastic from non-neoplastic brain lesions is one of the most established clinical applications of MR spectroscopy (1). Brain tumors generally demonstrate elevated choline (Cho) with reduced N-acetylaspartate (NAA), reflecting increased membrane turnover and neuronal loss, whereas many non-neoplastic lesions exhibit distinct metabolic patterns depending on the underlying pathology (4,5).

Several studies have shown that metabolite ratios such as Cho/NAA and Cho/Cr significantly improve lesion characterization when combined with conventional MRI (7). Nevertheless, overlapping metabolic profiles may occur in inflammatory or infectious lesions; therefore, spectroscopic findings should always be interpreted alongside clinical history and other advanced MRI techniques (1,11).

3.2 Differentiation of Primary Brain Tumors and Metastases

Magnetic resonance spectroscopy provides valuable metabolic information for differentiating primary brain tumors from metastatic lesions, particularly when conventional MRI findings are inconclusive (1). Primary gliomas usually demonstrate elevated choline and reduced NAA because of infiltrative tumor growth, whereas metastatic lesions often show relatively normal metabolite patterns within the surrounding vasogenic edema (4,5).

Assessment of the peritumoral region has been reported to improve discrimination between infiltrative gliomas and metastatic tumors (5). However, because metabolic overlap may occur in high-grade lesions, MRS should be interpreted together with structural MRI and other advanced imaging modalities to maximize diagnostic accuracy (1,3).

3.3 Glioma Grading

Accurate preoperative grading of gliomas is essential because tumor grade strongly influences treatment planning and prognosis (1). High-grade gliomas typically demonstrate markedly elevated choline with reduced NAA and creatine, while prominent lipid and lactate peaks indicate necrosis and aggressive tumor behavior (4,5).

Several investigations have shown that metabolite ratios, particularly Cho/NAA and Cho/Cr, correlate with glioma grade and improve diagnostic performance compared with conventional MRI alone (1,14). Although overlap may occur between intermediate-grade tumors, MRS provides valuable metabolic biomarkers that complement histopathological assessment and other advanced imaging techniques (4).

3.4 Differentiation of Tumor Recurrence and Radiation Necrosis

Distinguishing recurrent tumor from radiation-induced injury remains one of the greatest challenges in neuro-oncology because both conditions often demonstrate similar enhancement patterns on conventional MRI (10). Recurrent tumors generally exhibit elevated choline with reduced NAA, whereas radiation necrosis is more commonly associated with reduced metabolite concentrations and prominent lipid peaks due to tissue necrosis (4,15).

Clinical studies have demonstrated that MRS improves diagnostic confidence in differentiating these entities, particularly when interpreted together with perfusion and diffusion imaging (1). Combined multiparametric MRI has consistently shown superior diagnostic performance compared with any single imaging technique alone (12,15).

3.5 Differentiation of Tumors from Inflammatory, Infectious, and Demyelinating Lesions

Inflammatory, infectious, and demyelinating lesions frequently mimic brain tumors on conventional MRI, creating diagnostic uncertainty (9). MR spectroscopy assists in lesion characterization by identifying disease-specific metabolite profiles. Pyogenic abscesses commonly demonstrate amino acids, acetate, succinate, and lactate, whereas neoplastic lesions usually exhibit elevated choline and reduced NAA (3,6).

Demyelinating lesions may demonstrate mild choline elevation with relatively preserved neuronal metabolites, distinguishing them from aggressive neoplasms (11). Nevertheless, interpretation should always consider the clinical presentation because metabolite overlap may occur in atypical inflammatory disorders (3,9).

3.6 Pediatric Brain Lesions

MR spectroscopy has become increasingly valuable in the evaluation of pediatric brain lesions because it provides metabolic information without exposing children to ionizing radiation (3). Characteristic metabolite patterns assist in differentiating pediatric brain tumors, congenital disorders, and inflammatory lesions while improving preoperative assessment (4).

Although pediatric metabolite concentrations differ from those observed in adults, elevated choline and reduced NAA remain important indicators of neoplastic disease (5). When integrated with conventional MRI findings, MRS contributes to more accurate diagnosis and treatment planning in pediatric neuroimaging (3,4).

Table 2. Characteristic MR Spectroscopic Findings in Common Brain Lesions

Brain Lesion	NAA	Cho	Cr	Lactate/Lipids	Characteristic MR Spectroscopy Findings
Low-grade glioma	↓	↑	Normal/↓	Usually absent	Mildly increased Cho with reduced NAA
High-grade glioma	↓↓↓	↑↑↑	↓	↑	High Cho/NAA ratio with lipid-lactate peaks
Brain metastasis	↓	↑↑	↓	↑	Elevated Cho; relatively normal peritumoral metabolites
Primary CNS lymphoma	↓	↑↑	↓	±	Markedly elevated Cho with reduced NAA
Radiation necrosis	↓	↓	↓	↑↑	Prominent lipid peaks with low metabolite levels
Brain abscess	↓	Low	↓	↑	Amino acids, acetate, and succinate peaks
Demyelinating lesion	Mild ↓	Mild ↑	Normal	Usually absent	Mild Cho elevation with relatively preserved NAA

4. COMPARISON OF MR SPECTROSCOPY WITH OTHER ADVANCED MRI TECHNIQUES

Although MR spectroscopy (MRS) provides unique metabolic information, it is most effective when interpreted alongside other advanced MRI techniques (3). Diffusion-weighted imaging (DWI) and perfusion-weighted imaging (PWI) evaluate tissue cellularity and vascularity, respectively, while MRS provides insight into biochemical alterations within the lesion (15). The integration of these complementary imaging modalities significantly improves lesion characterization and diagnostic confidence compared with conventional MRI alone (4,11).

4.1 Diffusion-Weighted Imaging (DWI)

Diffusion-weighted imaging evaluates the microscopic movement of water molecules within tissues and provides information regarding cellular density and membrane integrity (3). Highly cellular tumors often demonstrate restricted diffusion with low apparent diffusion coefficient (ADC) values, whereas necrotic or cystic lesions generally exhibit increased diffusion (15). However, diffusion characteristics alone may not reliably distinguish neoplastic from non-neoplastic lesions because considerable overlap exists among various pathological conditions (11).

MR spectroscopy complements DWI by providing metabolic information that cannot be obtained from diffusion imaging alone (12,15). The combined assessment of diffusion characteristics and metabolite profiles improves differentiation between high-grade tumors, abscesses, demyelinating lesions, and radiation-induced changes, thereby increasing diagnostic accuracy (12,15).

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4.2 Perfusion-Weighted Imaging (PWI)

Perfusion-weighted imaging evaluates tissue vascularity by measuring parameters such as relative cerebral blood volume (rCBV), cerebral blood flow (CBF), and vascular permeability (11). Increased perfusion is commonly associated with high-grade tumors because of tumor-induced angiogenesis, whereas non-neoplastic lesions generally demonstrate lower perfusion values (15).

When combined with MR spectroscopy, perfusion imaging provides complementary information regarding both vascular and metabolic characteristics of brain lesions (2). Several studies have demonstrated that the combined interpretation of elevated rCBV with increased choline significantly improves differentiation between recurrent tumor and radiation necrosis as well as between neoplastic and non-neoplastic lesions (10,15).

4.3 Multiparametric MRI

Multiparametric MRI combines conventional MRI with advanced techniques such as MRS, DWI, and PWI to provide comprehensive anatomical, metabolic, and physiological information (2). This integrated approach enables more accurate characterization of brain lesions by simultaneously assessing tissue metabolism, cellularity, and vascularity (4).

Numerous studies have demonstrated that multiparametric MRI achieves greater diagnostic accuracy than any individual imaging technique alone, particularly in differentiating neoplastic from non-neoplastic lesions, grading gliomas, and distinguishing tumor recurrence from treatment-related changes (1,15). Consequently, the combined use of MRS with diffusion and perfusion imaging is increasingly recommended in routine neuro-oncological imaging to improve diagnostic confidence and support appropriate clinical management (1,2).

5. CLINICAL APPLICATIONS OF MR SPECTROSCOPY

Magnetic resonance spectroscopy (MRS) has evolved from a research technique into a valuable clinical adjunct that complements conventional MRI by providing non-invasive metabolic information about brain lesions (4). The assessment of characteristic metabolite patterns improves lesion characterization, supports treatment planning, evaluates therapeutic response, and facilitates long-term follow-up in patients with intracranial pathologies (1,8).

5.1 Diagnosis and Characterization of Brain Lesions

One of the principal clinical applications of MRS is the characterization of focal brain lesions when conventional MRI findings are inconclusive (4). Metabolite ratios such as Cho/NAA, Cho/Cr, and NAA/Cr assist in differentiating neoplastic from non-neoplastic lesions and improve diagnostic confidence by providing biochemical information beyond anatomical imaging (1,8).

5.2 Tumor Grading and Prognostic Assessment

MRS contributes to glioma grading by identifying metabolic changes associated with tumor aggressiveness (14). Increased choline together with reduced NAA and the presence of lipid or lactate peaks are commonly associated with high-grade tumors, whereas lower-grade gliomas generally demonstrate less pronounced metabolic abnormalities (4,5).

5.3 Treatment Planning and Biopsy Guidance

Brain tumors frequently demonstrate considerable metabolic heterogeneity that may not be apparent on conventional MRI (4). MRS helps identify the most metabolically active regions within a lesion, thereby improving biopsy targeting and assisting clinicians in selecting appropriate treatment strategies (5).

5.4 Assessment of Treatment Response

Monitoring therapeutic response following surgery, chemotherapy, or radiotherapy is another important application of MRS (4). Changes in metabolite ratios during follow-up may indicate tumor progression, treatment response, or post-treatment effects before structural changes become apparent on conventional MRI (10,15).

5.5 Follow-up and Long-Term Surveillance

MRS is increasingly incorporated into the long-term surveillance of patients with treated brain tumors because it provides metabolic information that complements conventional MRI (12). Serial spectroscopic examinations assist in differentiating recurrent disease from treatment-related changes and may reduce unnecessary invasive procedures by improving diagnostic confidence during follow-up (4,10).

6. ADVANTAGES OF MR SPECTROSCOPY

6.1 Improved Tissue Characterization

Unlike conventional MRI, which primarily depicts structural abnormalities, MRS evaluates tissue metabolism by measuring endogenous metabolites such as NAA, choline, creatine, lactate, and lipids (5). These metabolic alterations improve differentiation between neoplastic and non-neoplastic lesions, thereby increasing diagnostic confidence in challenging clinical cases (4).

6.2 Non-Invasive Assessment

MRS provides biochemical information without the need for ionizing radiation or intravenous contrast administration (4). This makes it particularly useful for repeated examinations, pediatric patients, and individuals in whom invasive diagnostic procedures are undesirable or contraindicated (1).

6.3 Improved Diagnostic Accuracy

Several studies have demonstrated that combining MRS with conventional MRI improves the differentiation of neoplastic and non-neoplastic lesions compared with structural imaging alone (7). The integration of metabolite analysis with diffusion and perfusion imaging further enhances diagnostic performance and supports more accurate clinical decision-making (2,11).

6.4 Guidance for Treatment Planning and Follow-up

MRS assists clinicians by identifying metabolically active tumor regions for biopsy, monitoring treatment response, and differentiating tumor recurrence from post-treatment changes during follow-up (4,10). These applications support individualized patient management and may reduce unnecessary invasive procedures (15).

7. LIMITATIONS AND CHALLENGES

7.1 Technical Limitations

The quality of MR spectra is highly dependent on adequate magnetic field homogeneity, appropriate voxel positioning, and effective water suppression (5). Motion artifacts, susceptibility effects near the skull base, and poor signal-to-noise ratio may degrade spectral quality and reduce diagnostic reliability, particularly in small or deeply located lesions (4).

7.2 Overlapping Metabolic Patterns

Although characteristic metabolite profiles assist in lesion differentiation, considerable overlap exists among neoplastic, inflammatory, infectious, and treatment-related lesions (1). Elevated choline or reduced NAA may be observed in several pathological conditions, limiting the specificity of MRS when interpreted in isolation (3).

7.3 Lack of Standardization

Variations in scanner manufacturers, magnetic field strength, acquisition parameters, pulse sequences, and post-processing methods may produce differences in metabolite measurements between institutions (4). The absence of universally standardized protocols remains a major challenge for the reproducibility and broader clinical implementation of MRS (1).

7.4 Limited Availability and Expertise

The successful clinical application of MRS requires specialized software, optimized imaging protocols, and experienced radiologists for accurate spectrum interpretation (4). Limited availability of advanced spectroscopy techniques and variability in operator expertise continue to restrict its routine use in many healthcare centers (5).

8. FUTURE PERSPECTIVES

8.1 High-Field MR Spectroscopy

The increasing availability of high-field MRI systems, particularly 3 Tesla (3T) and 7 Tesla (7T) scanners, has substantially improved the quality of MR spectroscopic imaging (5). Higher magnetic field strengths provide better signal-to-noise ratio and spectral resolution, enabling more accurate detection and quantification of brain metabolites, especially those present at low concentrations (4).

8.2 Artificial Intelligence and Radiomics

Artificial intelligence (AI) and radiomics are increasingly being integrated with MR spectroscopy to facilitate automated spectrum analysis and improve lesion classification (4). Machine-learning algorithms can analyze complex metabolic patterns, reduce observer variability, and support more accurate differentiation of brain lesions, thereby enhancing clinical decision-making (1).

8.3 Quantitative Imaging Biomarkers and Precision Medicine

The development of quantitative metabolic biomarkers is expected to strengthen the role of MRS in personalized medicine (4). Standardized metabolite measurements may improve disease characterization, predict treatment response, and facilitate individualized therapeutic strategies in patients with brain tumors and other neurological disorders (1,5).

9. CONCLUSION

Magnetic resonance spectroscopy has emerged as a valuable complementary imaging technique that enhances the diagnostic performance of conventional MRI by providing non-invasive metabolic information about brain lesions. Characteristic metabolite patterns and metabolite ratios improve the differentiation of neoplastic and non-neoplastic lesions, facilitate glioma grading, distinguish tumor recurrence from radiation-induced changes, and support treatment planning and follow-up.

Although technical limitations, variability in acquisition protocols, and overlapping metabolic profiles remain important challenges, integration of MRS with advanced imaging techniques such as diffusion- and perfusion-weighted imaging has significantly improved diagnostic accuracy and clinical confidence. Future developments in high-field MRI, artificial intelligence, radiomics, and quantitative metabolic biomarkers are expected to further expand the clinical utility of MRS and strengthen its role in precision neuroimaging. Consequently, MRS should be considered an important adjunct to conventional MRI for the comprehensive evaluation and management of patients with intracranial lesions.

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