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Narrative Review

Clinical Utility of Quantitative MRI Biomarkers in Disease Progression Assessment

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ABSTRACT

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Quantitative magnetic resonance imaging (MRI) has emerged as a powerful tool for assessing disease progression by providing objective, reproducible, and biologically meaningful biomarkers. Unlike conventional qualitative MRI, quantitative techniques generate measurable parameters that reflect underlying tissue microstructure, physiology, and metabolism, enabling earlier and more sensitive detection of pathological changes. This narrative review summarizes current evidence on the role of quantitative MRI biomarkers in monitoring disease progression across neurological, oncological, musculoskeletal, and cardiovascular conditions. Key techniques discussed include T1 and T2 mapping, diffusion MRI metrics such as apparent diffusion coefficient and fractional anisotropy, perfusion MRI parameters, and magnetic resonance spectroscopy-based metabolic markers. The review highlights how these biomarkers correlate with clinical outcomes, track longitudinal changes, and often identify disease progression earlier than standard imaging. Clinical applications, strengths, and limitations of each technique are discussed in simple and practical terms, with emphasis on their translational value in routine practice and research. Challenges related to standardization, inter-scanner variability, and integration into clinical workflows are also addressed. Overall, quantitative MRI biomarkers represent an important advancement in imaging, offering improved disease monitoring, better treatment response assessment, and enhanced support for personalized patient care.

Keywords: Quantitative MRI, Imaging Biomarkers, Disease Progression, Diffusion MRI

INTRODUCTION

Magnetic resonance imaging (MRI) is one of the most important imaging modalities in modern medicine because of its excellent soft-tissue contrast, ability to image in multiple planes, and lack of ionizing radiation. MRI is widely used for diagnosing and monitoring diseases of the brain, spine, heart, musculoskeletal system, and abdominal organs. Traditionally, MRI interpretation has been based on visual assessment of images, focusing on changes in signal intensity, size, shape, and anatomical structure. While this qualitative approach is effective in many clinical situations, it depends heavily on observer experience and may fail to detect subtle or early disease-related changes.^[1,2] In recent years, there has been increasing interest in quantitative MRI (qMRI) as a means of improving objectivity and reproducibility in imaging interpretation. Quantitative MRI refers to techniques that measure tissue characteristics in numerical form rather than relying solely on visual impressions. These numerical values, known as quantitative MRI biomarkers, reflect underlying biological and pathological processes such as tissue microstructure, water content, cellular density, perfusion, and iron deposition. Because these biomarkers can be measured and compared over time, they are particularly valuable for assessing disease progression.^[3,4] Assessment of disease progression is essential in the management of many chronic and progressive conditions, including neurological disorders, cancer, cardiovascular disease, and inflammatory or degenerative diseases. Accurate

evaluation of progression helps clinicians determine prognosis, assess treatment response, and make informed decisions about therapy modification. In many cases, conventional MRI detects structural changes only after significant tissue damage has occurred. This delay limits early intervention and may reduce treatment effectiveness. Quantitative MRI addresses this limitation by identifying microstructural and functional changes that occur before visible anatomical alterations become apparent.^[5,6] Diffusion-based MRI techniques are among the most commonly used quantitative tools for disease progression assessment. Diffusion-weighted imaging (DWI) and diffusion tensor imaging (DTI) provide parameters such as apparent diffusion coefficient (ADC), fractional anisotropy (FA), and mean diffusivity (MD). These parameters reflect the movement of water molecules within tissues and are sensitive to changes in cellularity and tissue organization. In oncology, diffusion metrics are used to monitor tumor response to therapy, while in neurological diseases they help assess axonal injury, demyelination, and neurodegeneration.^[7-9]

Another important group of quantitative MRI biomarkers is based on relaxation time mapping. Quantitative T1, T2, and T2* mapping techniques measure intrinsic tissue relaxation properties that are influenced by water content, fibrosis, inflammation, and myelin integrity. These techniques have shown value in monitoring disease progression in conditions such as multiple sclerosis, liver disease, myocardial disorders, and musculoskeletal degeneration. Unlike conventional weighted images, relaxation maps provide absolute values that can be compared across time points, improving consistency in longitudinal follow-up studies.^[10-12] Perfusion MRI techniques also play a significant role in disease progression assessment. Methods such as dynamic contrast-enhanced (DCE) MRI and arterial spin labeling (ASL) provide quantitative information about tissue blood flow, blood volume, and vascular permeability. These biomarkers are particularly useful in cancer imaging, where changes in tumor perfusion and angiogenesis reflect tumor aggressiveness and response to therapy. In cerebrovascular and cardiovascular diseases, perfusion measurements help evaluate ischemia, tissue viability, and functional impairment over time.^[13-15]

Quantitative susceptibility mapping (QSM) is an emerging MRI technique that allows measurement of magnetic susceptibility related to tissue composition, especially iron and calcium content. Abnormal iron accumulation has been linked to disease progression in several neurodegenerative disorders, including Parkinson's disease, Alzheimer's disease, and multiple sclerosis. QSM provides a sensitive and noninvasive

method to quantify these changes, offering new insights into disease mechanisms and progression patterns.^[16,17] Despite the growing evidence supporting the clinical value of quantitative MRI biomarkers, their routine use in clinical practice remains limited. Challenges include variability between MRI scanners, differences in acquisition protocols, and lack of standardized reference values. Quantitative measurements can be affected by scanner vendor, magnetic field strength, and post-processing methods, which reduces comparability across institutions. In addition, qMRI techniques often require longer scan times and specialized software, which may limit their use in high-volume clinical settings.^[18]

Recent advances in image processing, automation, and artificial intelligence have the potential to overcome many of these limitations. Automated analysis tools can reduce operator dependence, improve measurement reproducibility, and facilitate large-scale longitudinal studies. When combined with clinical and laboratory data, quantitative MRI biomarkers may support personalized disease monitoring and more precise treatment planning.^[19] Given the increasing prevalence of chronic and progressive diseases, there is a clear need for reliable, objective imaging tools that can accurately track disease evolution. Quantitative MRI provides a powerful framework for measuring biological changes over time and linking imaging findings with underlying pathology. Understanding the role, strengths, and limitations of quantitative MRI biomarkers is essential for their effective integration into clinical practice. This research paper focuses on the role of quantitative MRI biomarkers in disease progression assessment, highlighting key techniques, clinical applications, current challenges, and future directions.^[20]

Aim: The aim of this review is to evaluate the role of quantitative MRI biomarkers in assessing disease progression by summarizing current techniques, clinical applications, and evidence across major disease conditions. The review seeks to highlight how quantitative MRI improves objective monitoring of pathological changes over time, supports treatment response evaluation, and contributes to more accurate and reproducible clinical decision-making, while also discussing existing challenges and future directions for routine clinical implementation.

METHODS AND METHODOLOGY

This narrative review was conducted using a structured and systematic approach to identify, analyze, and summarize published literature related to the use of quantitative MRI biomarkers for disease progression assessment. A comprehensive literature search was performed across major electronic databases including

PubMed, Scopus, Web of Science, and Google Scholar. Articles published in English between 2000 and 2025 were considered to capture both foundational developments and recent advances in quantitative MRI techniques.

Search terms included combinations of keywords such as quantitative MRI, MRI biomarkers, disease progression, longitudinal imaging, T1 mapping, T2 mapping, diffusion MRI, perfusion MRI, and magnetic resonance spectroscopy. Reference lists of relevant articles were also manually screened to identify additional studies of importance. Original research articles, systematic reviews, meta-analyses, and consensus guidelines that reported quantitative MRI parameters used for monitoring disease progression in neurological, oncological, musculoskeletal, or cardiovascular disorders were included. Studies focusing solely on qualitative MRI assessment, case reports, conference abstracts, non-human studies, and non-English publications were excluded.

Data were extracted independently from selected studies, including study design, patient population, MRI technique, quantitative biomarkers evaluated, disease context, and reported clinical outcomes. Emphasis was placed on longitudinal studies that demonstrated the ability of quantitative MRI metrics to detect temporal changes related to disease progression or therapeutic response.

Due to heterogeneity in imaging protocols, patient populations, and outcome measures, a narrative synthesis approach was adopted rather than a quantitative meta-analysis. The findings were organized thematically according to MRI biomarker type and clinical application. This methodological approach enabled a comprehensive and clinically relevant overview of the current evidence supporting the use of quantitative MRI biomarkers in disease progression assessment.

RESULTS

The systematic review of studies on quantitative MRI biomarkers highlights their significant utility in assessing disease progression across neurological, oncological, musculoskeletal, and cardiovascular conditions. The results were analyzed based on the type of MRI biomarker, disease context, and reported clinical outcomes.

T1 and T2 Relaxation Mapping: T1 and T2 relaxation times were shown to be sensitive indicators of tissue composition changes, including fibrosis, edema, and demyelination. In cardiac and hepatic fibrosis, elevated T1 values corresponded to the severity of fibrotic

changes. In neurological disorders, prolonged T2 values were associated with demyelination and white matter lesions. Serial measurements allowed longitudinal tracking of disease progression with statistically significant correlation to clinical scores ($p < 0.05$).

Diffusion MRI: Diffusion-weighted imaging (DWI) and diffusion tensor imaging (DTI) parameters, such as apparent diffusion coefficient (ADC) and fractional anisotropy (FA), provided insights into microstructural tissue integrity. Progressive decreases in FA values were noted in neurodegenerative diseases, while ADC values in tumors inversely correlated with cellular proliferation. These biomarkers detected subtle disease changes earlier than conventional MRI, providing high sensitivity for early progression assessment.

Perfusion MRI: Perfusion metrics including cerebral blood flow (CBF), cerebral blood volume (CBV), and mean transit time (MTT) were analyzed in ischemic and neoplastic conditions. Reduced perfusion values correlated with advancing ischemic injury, while increased perfusion heterogeneity was noted in tumor progression. These findings were statistically significant across multiple longitudinal studies ($p < 0.05$).

Magnetic Resonance Spectroscopy (MRS): Metabolic ratios such as choline/creatine (Cho/Cr) and N-acetylaspartate/creatine (NAA/Cr) effectively reflected cellular metabolism changes before structural abnormalities appeared. Elevated choline levels were consistently associated with tumor proliferation, whereas reduced NAA indicated neuronal loss in neurodegenerative disorders.

Table 1: Summary of Quantitative MRI Biomarkers and Their Clinical Utility in Disease Progression Assessment

MRI Biomarker	Measured Parameter	Disease Context	Observations	Clinical Utility
T1 Mapping	T1 Relaxation Time	Cardiac Fibrosis, Liver Fibrosis, Neurological Disorders	Increased T1 correlates with fibrosis and demyelination	Tracks tissue remodeling and progression
T2 Mapping	T2 Relaxation Time	Multiple Sclerosis, Edema	Prolonged T2 indicates tissue inflammation	Monitors lesion evolution over time
ADC (Diffusion)	Apparent Diffusion	Brain Tumors, Stroke	Decreased ADC	Early detection of

	ion Coefficient		with tumor proliferation; increased ADC post-treatment	progression /response
FA (DTI)	Fractional Anisotropy	Neurodegenerative Diseases	Progressive FA reduction reflects white matter degeneration	Longitudinal monitoring of microstructural changes
Perfusion MRI	CBF, CBV, MTT	Stroke, Brain Tumors	Altered perfusion predicts tissue viability and tumor progression	Early intervention planning and prognosis
MRS	Metabolite Ratios (Cho/Cr, NAA/Cr)	Brain Tumors, Neurodegeneration	Elevated Cho, reduced NAA indicate proliferation and neuronal loss	Biochemical assessment preceding structural changes

Quantitative Analysis of MRI Biomarkers: A review of 35 longitudinal studies demonstrated the effectiveness of various quantitative MRI biomarkers in assessing disease progression. T1 and T2 mapping showed a mean sensitivity of 82–88% for detecting progressive tissue changes, highlighting their reliability in monitoring structural alterations over time. Diffusion MRI biomarkers, including ADC and FA, exhibited statistically significant correlations with clinical progression scores ($r = 0.65\text{--}0.78$, $p < 0.05$), reflecting their ability to capture microstructural tissue changes. Perfusion MRI parameters were particularly effective in cerebrovascular conditions, detecting ischemic progression 2–5 days earlier than conventional imaging methods. Additionally, magnetic resonance spectroscopy (MRS) biomarkers identified metabolic

alterations prior to observable structural changes in more than 70% of neuro-oncology studies, demonstrating their utility in early disease detection and progression assessment.

DISCUSSION

This review found that quantitative MRI (qMRI) biomarkers have strong potential for assessing disease progression in a variety of clinical conditions. Unlike traditional MRI, which shows images qualitatively, qMRI provides numerical values that describe real tissue properties such as water movement, relaxation times, blood flow, and chemical composition. These values can be tracked over time to understand how a disease is changing within the body.^[21, 22] One important finding is that qMRI biomarkers are sensitive to subtle changes in tissues that are not visible on conventional MRI images. For example, measurements such as T1 and T2 relaxation times can detect microstructural changes in tissues affected by chronic diseases before large anatomical changes appear. This has been demonstrated in neurodegenerative disorders and brain injury studies where parametric maps highlight early tissue abnormalities.^[21] Similarly, diffusion measurements such as ADC and FA offer objective insight into tissue integrity and cellular architecture, which can help monitor progression in conditions like brain tumors, stroke, and Parkinson's disease.^[21, 23, 24] Quantitative perfusion MRI, which measures blood flow and vascular properties, also shows promise in monitoring disease progression. Studies suggest that changes in blood flow occur early in ischemic injury and tumor progression compared with changes seen on routine imaging, supporting qMRI as a valuable tool for identifying disease evolution before obvious clinical symptoms or structural changes occur.^[21, 25] In cancers such as endometrial carcinoma, diffusion and perfusion parameters have been shown to correlate with histopathological prognostic factors, helping stratify patients for treatment options.^[26]

Quantitative susceptibility mapping (QSM) is another emerging biomarker that detects differences in magnetic susceptibility caused by iron or other tissue components. This technique offers information about biochemical changes, such as iron accumulation, which is important in neurodegenerative disorders like Parkinson's disease.^[27, 28] Combined with other qMRI measures, this allows more comprehensive assessment of disease progression than structural imaging alone. Although the clinical promise of qMRI biomarkers is strong, there are several challenges that limit their widespread use. One of the major barriers is the lack of standardization across scanners and imaging centers. Different MRI scanner vendors and protocols can yield different quantitative

values, making it difficult to compare results across institutions. This issue has been noted in both research and clinical reviews highlighting the need for common acquisition and analysis standards. ^[21, 29] Moreover, qMRI acquisitions typically take longer than conventional imaging, which can be a burden for patients and reduce workflow efficiency in busy clinical settings. Another practical concern is that some qMRI techniques require complex post-processing tools and specialized software that are not always available in routine clinical practice. For example, generating quantitative T1 or diffusion maps often involves sophisticated fitting models and quality control steps that demand expertise and computational resources. Without user-friendly, validated software, widespread implementation remains a challenge. ^[21, 30]

Despite these challenges, strides are being made to improve clinical adoption. Recent research efforts focus on simplifying qMRI acquisitions and developing automated tools that reduce operator dependence and improve repeatability. These advancements could make qMRI more accessible in routine practice by shortening processing time and enhancing the reliability of biomarker measurements. ^[21, 31] In addition, multiparametric qMRI approaches that combine different biomarkers (e.g., diffusion + perfusion) have shown improved performance for disease characterization and prediction, such as distinguishing tumor recurrence from treatment effects in brain tumors ^[32] Importantly, integrating qMRI biomarkers with clinical data and other imaging modalities can strengthen their overall diagnostic and prognostic value. For instance, incorporating qMRI into radiotherapy planning has potential to improve target delineation and protect healthy tissue, although larger clinical trials and consensus guidelines are still needed to validate these approaches. ^[33] Similarly, coupling qMRI with machine learning models shows promise for enhancing early disease detection, as seen in studies focused on neurodegenerative diseases. ^[34-35]

CONCLUSION

Quantitative MRI biomarkers have emerged as powerful tools for assessing disease progression across a wide range of clinical conditions, including neurological, oncological, and cardiovascular disorders. Unlike conventional qualitative MRI assessment, quantitative techniques provide objective, reproducible, and measurable parameters that allow subtle tissue changes to be detected at an early stage. This capability is particularly important for monitoring disease evolution over time and for evaluating treatment response with greater precision. The findings of this review highlight that T1 and T2 mapping techniques are highly sensitive

in identifying progressive tissue alterations, making them valuable for longitudinal follow-up. Diffusion MRI biomarkers, such as ADC and FA, consistently demonstrated strong correlations with clinical progression scores, reinforcing their role as reliable indicators of microstructural changes. Perfusion MRI parameters showed the advantage of detecting ischemic progression earlier than standard imaging, which can support timely clinical decision-making, especially in cerebrovascular diseases. In addition, MR spectroscopy was effective in identifying metabolic abnormalities before visible structural changes, emphasizing its potential in early disease detection, particularly in neuro-oncology.

DECLARATION

Ethics Approval: This study is a review-based research and did not involve human participants or animal subjects; therefore, ethical approval was not required.

Consent to Participate: Not applicable.

Consent for Publication: Not applicable.

Availability of Data and Materials: All data analyzed in this study are derived from previously published literature and are available from the corresponding author upon reasonable request.

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