Review Article

Functional and Multi-parametric Imaging of Uterine Fibroids: Current Advances and Clinical Applications

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Abstract

Background: Uterine fibroids are the most common benign tumours of the uterus and often require accurate diagnosis and individualised management. However, traditional imaging techniques such as ultrasound and CT have limitations in detecting complex fibroid morphology, assessing vascularity, and differentiating fibroids from other uterine pathologies, such as adenomyosis or malignancy. The objective is to evaluate and summarise the current advances in functional and multi-parametric imaging modalities for uterine fibroids, and highlight their clinical applications in diagnosis, treatment planning, image-guided intervention, and follow-up. **Material and Methods:** A systematic literature search was conducted across PubMed, Scopus, Embase, and Web of Science databases for English-language studies published between January 2015 and May 2025. Inclusion criteria comprised human studies evaluating functional imaging modalities, including diffusion-weighted imaging (DWI), dynamic contrast-enhanced MRI (DCE-MRI), elastography, contrast-enhanced ultrasound (CEUS), radiomics, and PET-MRI, in fibroid management. Case reports, reviews, and animal studies were excluded. A narrative synthesis of eligible studies was performed due to methodological heterogeneity. **Results:** Recent studies demonstrate that multi-parametric imaging offers significant advantages in characterising fibroids, predicting response to minimally invasive therapies (e.g., UAE and MRgFUS), and monitoring treatment outcomes. Parameters such as T2 signal intensity, ADC values, vascular perfusion patterns, stiffness metrics, and radiomic signatures provide quantitative, reproducible markers that improve diagnostic accuracy and guide personalised care. **Conclusion:** Functional and multi-parametric imaging has transformed fibroid management from a structural, symptom-based approach to one guided by tissue-specific insights. Its integration into clinical practice, supported by standardisation and prospective multicenter validation, holds the potential to improve patient outcomes and reduce unnecessary interventions.

Keywords: Uterine fibroids; multiparametric imaging; functional MRI; CEUS; elastography; radiomics.

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Introduction

Uterine fibroids, or leiomyomas, are the most common benign tumours of the female reproductive tract, affecting approximately 70–80% of women by the age of 50, with a higher prevalence among women of African ancestry and those in their reproductive years.[1,2] While many fibroids remain asymptomatic, they can produce a range of clinical symptoms such as menorrhagia, pelvic pressure, urinary frequency, and infertility, significantly impairing the quality of life and leading to a substantial number of gynecologic consultations and surgeries, particularly hysterectomy.[3]

Despite their prevalence, the diagnostic and therapeutic management of fibroids is often complicated by limitations of conventional imaging modalities. Two-dimensional transabdominal and transvaginal ultrasonography, though commonly used as the first-line imaging tool, may fail to accurately determine the size, number, or anatomical location of fibroids in complex or multiple lesions.[4] Furthermore, ultrasound has limited capability to characterise internal fibroid architecture or vascularity and often cannot reliably distinguish fibroids from other uterine pathologies, such as adenomyosis or leiomyosarcoma.[5] These limitations may lead to misdiagnosis, suboptimal treatment selection, or unnecessary surgical interventions.

Advances in imaging technology, particularly functional and multi-parametric imaging, have significantly improved diagnostic accuracy and therapeutic planning for uterine fibroids. Techniques such as magnetic resonance imaging (MRI), diffusion-weighted imaging (DWI), dynamic contrast-enhanced MRI (DCE-MRI), MR elastography, and contrast-enhanced ultrasound (CEUS) provide a comprehensive assessment of fibroid characteristics, including tissue stiffness, perfusion dynamics, and cellularity.[6-9] These functional insights are particularly beneficial in selecting patients for minimally

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invasive or uterus-sparing treatments like myomectomy, uterine artery embolisation (UAE), or MR-guided focused ultrasound surgery (MRgFUS).[10]

This review highlights recent advances in functional and multi-parametric imaging of uterine fibroids, focusing on their clinical roles in diagnosis, treatment planning, image-guided therapy, and follow-up. It underscores how these modalities support personalised care and improve clinical decision-making.

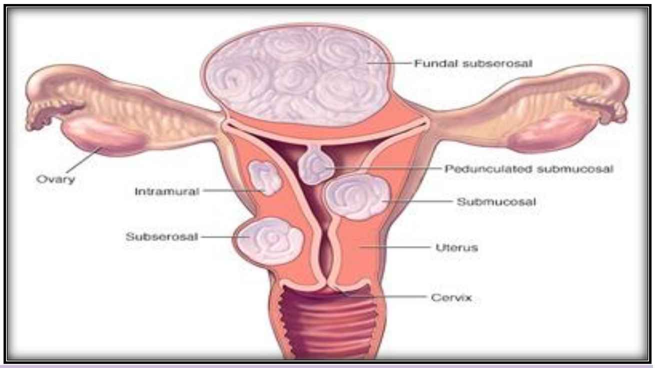

Figure 1: Uterine Fibroids

Conventional Imaging Modalities: Limitations

Accurate assessment of uterine fibroids is essential for optimal management, and while traditional imaging techniques are widely used, they have notable limitations. This section outlines the limitations of the most commonly employed conventional modalities: ultrasound, Doppler techniques, and computed tomography (CT).

Ultrasound (USG)

Ultrasound is the most commonly used modality in the initial evaluation of uterine fibroids, especially for its accessibility, affordability, and non-invasive nature. Both transabdominal and transvaginal approaches are frequently employed. However, its diagnostic reliability is highly operator-dependent and varies with patient body habitus, uterine position, and bowel gas interference.[11]

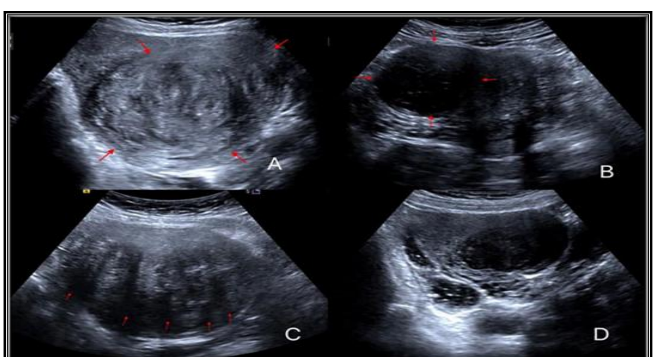

Figure 2: Different ultrasonic image features of uterine fibroids. (A) Fibroid is elliptical with high echogenicity; (B) Fibroid has a round shape with low echogenicity; (C) Fibroid with five attenuation bands; (D) Fibroids with no attenuation band and low echogenicity

In patients with multiple, submucosal, or deeply located intramural fibroids, ultrasound may not precisely determine the number, size, or anatomical relationship of the lesions.[12] Isoechoic fibroids, in particular, can blend with the normal myometrium, making detection difficult. Additionally, it provides limited insight into internal tissue characteristics or perfusion, thereby limiting its utility for pre-interventional planning or differentiating from malignancy.[13]

2D and 3D Doppler Ultrasound

Doppler techniques, including colour, power, and 3D Doppler, are used adjunctively to assess fibroid vascularity. They may aid in differentiating highly vascular fibroids from degenerating fibroids or in identifying atypical perfusion suggestive of alternative pathology.[14] However, the vascular patterns assessed by Doppler are qualitative and often inconsistent, limiting their specificity.[9]

Furthermore, the interpretation of Doppler signals is subject to technical variability, and the absence of standardised perfusion thresholds reduces reproducibility. This hampers its ability to reliably guide therapy, especially when considering minimally invasive options like uterine artery embolisation or MR-guided focused ultrasound.[15]

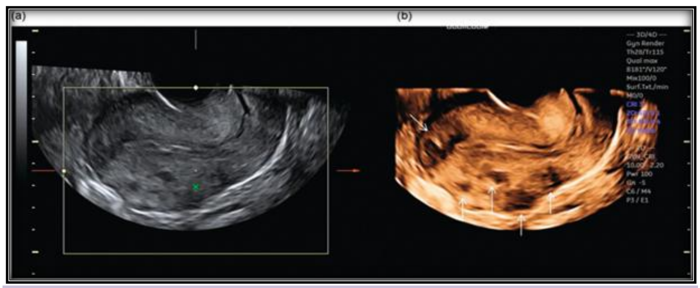

Figure 3: Uterine Fibroids Using Two-Dimensional and Three-Dimensional Ultrasonography

Computed Tomography (CT): CT is not a frontline imaging modality for fibroid assessment due to its suboptimal soft-tissue contrast and radiation exposure—factors of particular concern in women of reproductive age.[5] It is sometimes used in complex pelvic evaluations or when MRI is contraindicated, but its capability to delineate fibroid composition, degeneration, or vascularity is limited.

In comparison to MRI, CT cannot distinguish between leiomyomas and other pelvic pathologies, such as adenomyosis, ovarian tumours, or uterine sarcomas, with adequate confidence.[8] Therefore, its use in fibroid management remains limited to select scenarios.

Figure 4: CT of Uterine Fibroids

Multiparametric and Functional Imaging Modalities

Conventional imaging techniques, though widely used, are limited in fully characterizing uterine fibroids. Functional and multiparametric imaging modalities offer deeper tissue insights—enabling refined diagnosis, subtype classification, and better therapeutic planning. The following advanced modalities represent current innovations in fibroid imaging.

Magnetic Resonance Imaging (MRI)

- **Principle & Technique:** MRI employs strong magnetic fields and radiofrequency pulses to generate high-resolution images. T1- and T2-weighted sequences are standard.
- **Diagnostic Utility:** Fibroids usually appear hypointense on T2-weighted images and isointense or hypointense on T1-weighted images. A high T2 signal suggests increased cellularity or degeneration. MRI is superior to ultrasound for evaluating the number, location, size, and type of fibroids, as well as adjacent organ involvement.[6,11]

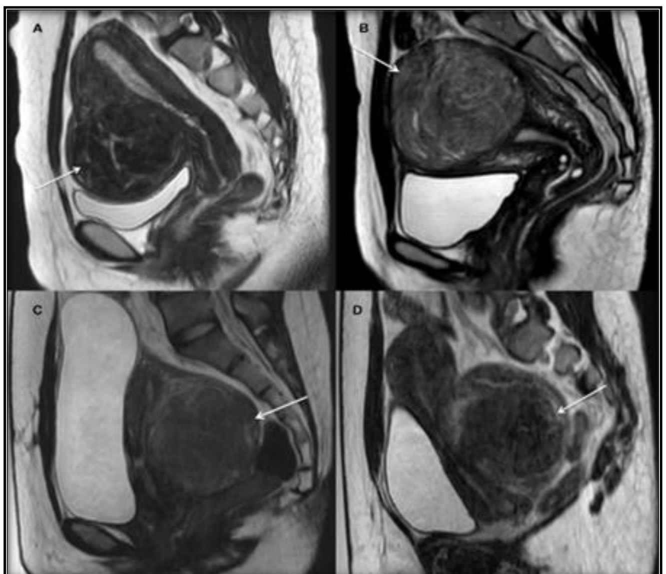

Figure 5: MRIs show (A) uterine fibroid on the anterior wall of the uterus (white arrow); (B) the uterine fibroid on fundus of uterus (white arrow); (C) the uterine fibroid on the posterior wall of the uterus (white arrow); and (D) the uterine fibroid on cervical area of the uterus (white arrow).

Clinical Application: It is the preferred modality for surgical mapping and assessing eligibility for uterus-sparing procedures like uterine artery embolisation (UAE) and MR-guided focused ultrasound surgery (MRgFUS).[10]

Limitations: Cost, availability, and contraindications such as implanted metallic devices limit its use, especially in resource-limited settings.

Diffusion-Weighted Imaging (DWI) and ADC Mapping

Principle & Technique: DWI assesses the Brownian motion of water molecules; ADC maps provide quantitative diffusion values.

Diagnostic Utility: DWI is valuable for assessing fibroid degeneration. Cellular fibroids show restricted diffusion and lower ADC values. It also helps differentiate fibroids from malignant lesions such as leiomyosarcoma.[16,17]

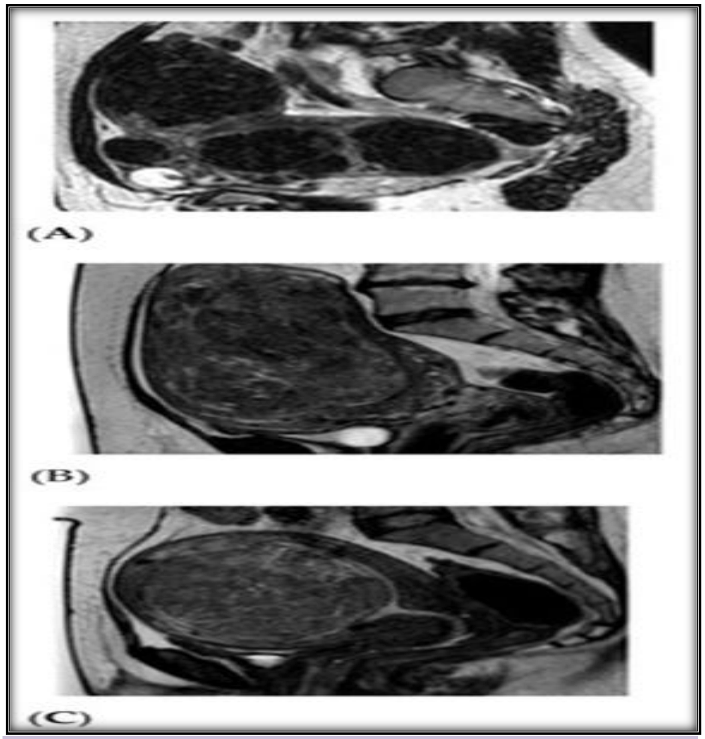

Figure 6: Magnetic resonance imaging (MRI) types of uterine fibroid (UF). (A). Type I presents as a "dark" UF as seen on MRI T2-weighted imaging. (B). Type II has a mixed MRI bright and dark structure. (C). Type III presents in MRI as a "bright" type of UF, usually not suitable for MRI-HIFU (high-intensity ultrasound) treatment.

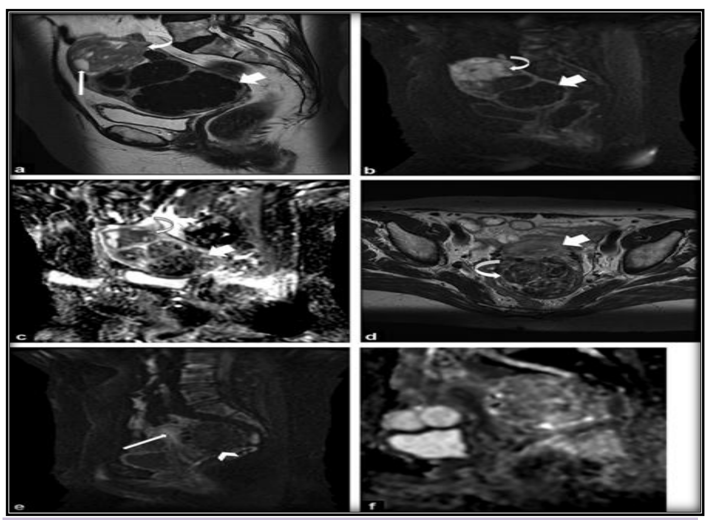

Figure 7: DWI and ADC maps of uterine tumours. (a–c) leiomyosarcoma showing intermediate T2 signal with necrosis (a), high signal on b1000 DWI (b), and restricted diffusion with low ADC (873 × 10^{-3} mm²/s) (c). Coexisting benign leiomyomas show low T2 and DWI signal with lower ADC (796 × 10^{-3} mm²/s). (d–f) A 67-year-old woman with atypical leiomyoma showing heterogeneous low T2 signal (d), no restriction on DWI (e), and high ADC (1661 × 10^{-3} mm²/s) (f). Final diagnosis confirmed post-hysterectomy.

- **Limitations:** There can be overlap in ADC values between cellular fibroids and malignancies, reducing specificity without correlation with other MRI parameters.

Dynamic Contrast-Enhanced MRI (DCE-MRI)

- **Principle & Technique:** DCE-MRI involves serial post-contrast imaging to evaluate perfusion and enhancement kinetics.
- **Diagnostic Utility:** It enables vascular characterization of fibroids, assisting in pre-treatment planning and post-treatment assessment. High perfusion indicates suitability for MRgFUS, while low enhancement may suggest degeneration.[18]
- **Limitations:** Gadolinium-based contrast agents pose risks in renal impairment. The technique requires high temporal resolution and expert interpretation.

MR Elastography

- **Principle & Technique:** This modality evaluates tissue stiffness by transmitting mechanical waves and capturing displacement with MRI.
- **Diagnostic Utility:** MR elastography offers quantitative stiffness values in kilopascals. It can help in classify fibroids (e.g., cellular vs hyalinized) and guide therapy based on stiffness.[19]

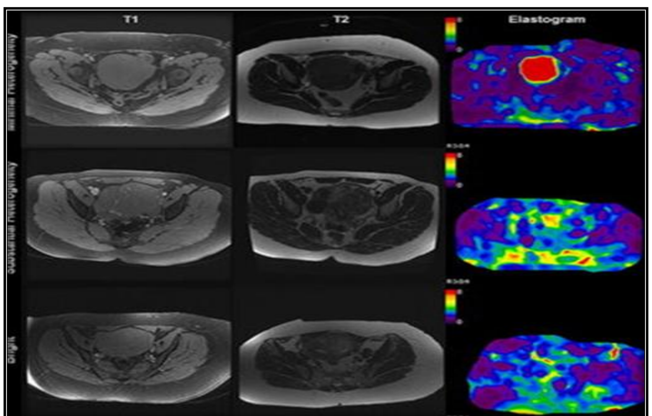

Figure 8: MRI and MR elastography of uterine fibroids. Columns show axial T1-, T2-weighted images, and composite elastograms with shear stiffness colour maps (kPa). Rows illustrate representative cases with fibroids of minimal heterogeneity, substantial heterogeneity, and bright T2 signal intensity.

- **Limitations:** Limited availability, longer scan times, and cost hinder widespread use.

Contrast-Enhanced Ultrasound (CEUS)

- **Principle & Technique:** CEUS uses microbubble contrast agents to assess real-time perfusion.
- **Diagnostic Utility:** It allows evaluation of vascularity and real-time monitoring post-UAE or focused ultrasound therapy. CEUS is useful where MRI is contraindicated.[9]
- **Limitations:** Short imaging window and lower resolution in obese patients reduce reliability. Standardization of parameters is still evolving.

Shear-Wave and Strain Elastography (US-based)

- **Principle & Technique:** These techniques assess tissue elasticity using ultrasound. Shear-wave elastography measures wave speed, while strain elastography measures tissue deformation under pressure.
- **Diagnostic Utility:** Fibroids exhibit higher stiffness than normal myometrium or adenomyosis. Elastography aids in differentiating fibroids from other myometrial pathologies and predicting treatment response.[20]

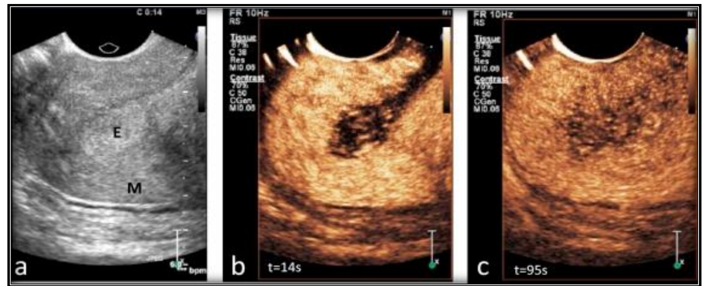

Figure 9: Contrast-Enhanced Ultrasound in the Assessment of Uterine Fibroids

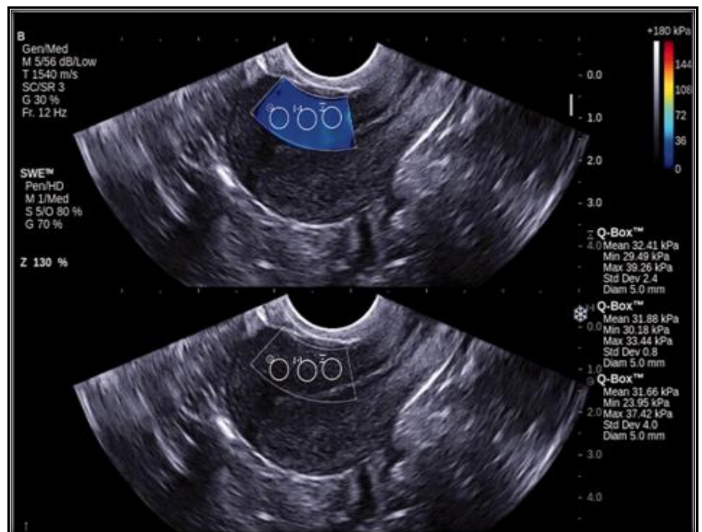

Figure 10: ultrasound shear wave elastography in uterine fibroids

- **Limitations:** Results are operator-dependent and limited by uterine position and depth. Reproducibility is a concern across vendors and systems.

PET-CT and SPECT in Uterine Fibroid Imaging

- **Principle & Technique:** Positron Emission Tomography–Computed Tomography (PET-CT) and Single Photon Emission Computed Tomography (SPECT) are functional nuclear imaging modalities that evaluate tissue metabolism and perfusion. PET-CT commonly uses 18F-fluorodeoxyglucose (FDG) to detect areas of increased glucose uptake, while SPECT uses radiotracers such as Tc-99m to assess vascular activity and cellular turnover.
- **Diagnostic Utility:** While uterine fibroids typically show low FDG uptake, uterine sarcomas and malignant lesions exhibit significantly higher metabolic activity, aiding in differentiation between benign and malignant myometrial masses. PET-CT may be particularly valuable in cases of rapidly enlarging fibroids, postmenopausal growth, or indeterminate MRI findings. SPECT, though less commonly applied, may offer insights into vascular behaviour, particularly in atypical fibroids or tumours with necrotic components.[21,22]

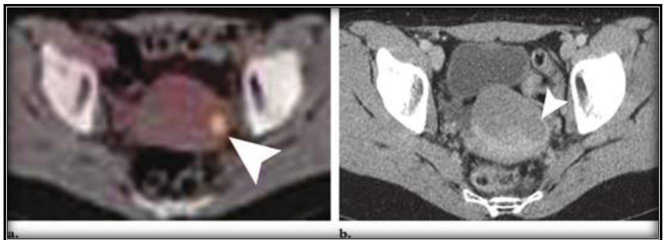

Figure 11: Uterine fibroid imaging. (a) Fused PET-CT showing a hypermetabolic focus (arrowhead) in the uterine body, corresponding to a hypoattenuating fibroid on CT. About 20% of fibroids display this FDG PET pattern. (b) Contrast-enhanced CT demonstrating a focal hypoattenuating fibroid (arrowhead) in the left uterine wall.

- **Limitations:** These modalities are not used routinely due to high cost, radiation exposure, limited availability, and lack of standardized uptake thresholds for fibroid evaluation. Their role remains largely adjunctive, recommended in selective or equivocal cases rather than for routine fibroid assessment.

Recent Advances in Functional and Multiparametric Imaging of Uterine Fibroids

Artificial Intelligence and Radiomics in Fibroid Imaging

Recent developments in artificial intelligence (AI) and radiomics have significantly enhanced the diagnostic capabilities of imaging in uterine fibroids. Radiomics involves extracting quantitative features from standard imaging modalities—particularly MRI and ultrasound—to analyse tissue heterogeneity, vascularity, and growth patterns beyond what the human eye can discern. In fibroid imaging, radiomic algorithms have demonstrated potential in differentiating fibroids from uterine sarcomas, predicting treatment response, and monitoring recurrence post-intervention.[23]

For instance, studies employing machine learning on T2-weighted MRI datasets have successfully achieved high diagnostic accuracy in characterizing fibroid types, enabling more precise selection for uterine artery embolization (UAE) or high-intensity focused ultrasound (HIFU) therapy.[24] These models are also being trained to forecast volumetric regression following treatment, allowing clinicians to develop management plans more effectively.

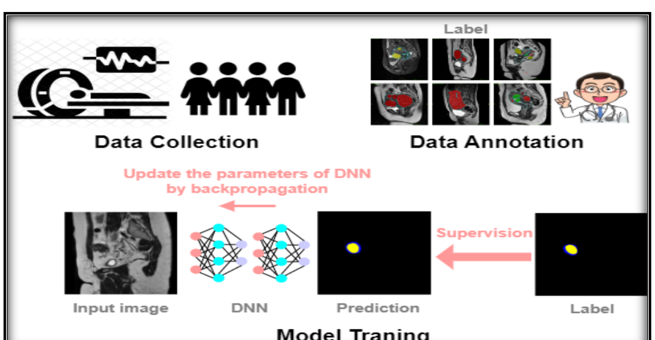

Figure 12: The pipeline of DL for medical image analysis includes three stages, i.e., data collection, data annotation, and model training. The process of expert supervision and back propagation is introduced to update the parameters of DNNs, which enables it to train itself by continuously inputting large-scale data for machine learning.

3D and Fusion Imaging

Three-dimensional (3D) imaging and fusion techniques, which integrate anatomical and functional datasets, have appeared as powerful tools for correct fibroid mapping. 3D ultrasound provides volumetric rendering, which is particularly valuable in assessing fibroid burden and guiding preoperative planning. Fusion imaging, which overlays real-time ultrasound with MRI datasets, is increasingly being used to guide targeted biopsies and ablation procedures, especially for fibroids found near critical structures.[25]

These technologies have been shown to improve the accuracy of fibroid volume estimation, an essential parameter in finding eligibility for conservative therapies and predicting fertility outcomes.

Functional Imaging in Guiding Interventions

Multiparametric imaging is now central to planning and evaluating minimally invasive fibroid treatments. In the UAE, perfusion-weighted MRI and contrast-enhanced ultrasound are used to assess vascular supply and infarction zones, predicting procedural success and long-term symptom relief. Similarly, MR-guided focused ultrasound surgery (MRgFUS) relies heavily on T2-weighted imaging, temperature-sensitive sequences, and dynamic contrast-enhanced (DCE) MRI to ensure correct energy delivery and real-time monitoring of tissue ablation.[26]

Moreover, diffusion-weighted imaging (DWI) and apparent diffusion coefficient (ADC) values are increasingly utilised to detect early post-treatment cellular changes, offering a non-invasive marker of therapeutic efficacy.

Hybrid Imaging Techniques

The integration of structural and functional imaging in hybrid modalities such as PET-MRI and SPECT-CT is showing promise in research and select clinical scenarios. Although not yet widely adopted in routine fibroid evaluation, these modalities have proven utility in cases with ambiguous findings, especially in differentiating fibroids from malignant or atypical uterine masses. Ongoing trials are exploring the value of PET-MRI in detecting residual viable tissue after UAE and in assessing fibroid metabolism and vascular remodeling.[27]

Such hybrid approaches may pave the way for personalised imaging algorithms that combine molecular, structural, and perfusion data for comprehensive evaluation.

Clinical Applications

Diagnosis and Differential Diagnosis

Multi-parametric MRI enhances diagnostic specificity, distinguishing fibroids from adenomyosis or malignancy. T2-weighted, DWI, and DCE sequences provide complementary data on margins, diffusion, and perfusion, while CEUS offers rapid functional correlation.[12,28,29]

Treatment Planning

High-T2, well-perfused fibroids respond favourably to MRgFUS, whereas hypo-vascular lesions are less suitable for immobilisation. Elastography quantifies stiffness, aiding energy-dose adjustment, while 3D imaging delineates the submucosal extension, which is critical for myomectomy planning.[10,30]

Monitoring Therapeutic Response

Post-treatment MRI and CEUS objectively evaluate outcomes. Non-enhancing regions on post-UAE MRI indicate necrosis and symptom relief. Rising ADC values and reduced stiffness on elastography confirm successful therapy.[31,32]

Reproductive Assessment

Imaging defines fibroid proximity to the endometrium, guiding fertility-sparing management. MRI and 3D US accurately assess cavity distortion. Preliminary data suggest that perfusion and stiffness metrics from CEUS and elastography may predict endometrial receptivity and implantation potential.[33,34]

Materials and Methods

A systematic literature search (PubMed, Scopus, Embase, Web of Science) identified human studies from 2015 to 2025 on functional and multi-parametric imaging in uterine fibroids. Inclusion: Original human studies on DWI, DCE-MRI, CEUS, elastography, and PET-MRI.

Exclusion: Case reports, reviews, animal or paediatric studies.

Two reviewers independently screened and extracted data on study design, imaging parameters, and outcomes. Owing to heterogeneity in protocols, a narrative synthesis was performed.

Results

Of 395 records, 22 studies met the inclusion criteria: 9 prospective, 8 retrospective, and 5 cross-sectional. Modalities analysed included MRI (T2, DWI, DCE), CEUS, elastography, radiomics, and PET-MRI.

Key imaging biomarkers:

- T2 Signal Intensity: A High T2 signal predicts a better UAE/MRgFUS response.[10,12]
- ADC Values: Lower in fibroids; increase after therapy denotes necrosis.[12,35]
- Perfusion Metrics: Enhancement parameters differentiate viable from degenerated tissue.[10,36]
- Elastography: Quantified stiffness correlates with pathology and therapy success.[37,38]
- **Radiomics:** Texture-based T2 models achieve >90 % accuracy for HIFU response prediction.[24]
- **Hybrid Imaging:** PET-MRI detects atypical metabolic patterns suggesting malignancy.[39]

Table 1: Summary of Key Studies

Study Name	Study Design	Imaging Modality / Technique	Key Findings	Clinical Relevance
Funaki K et al. (2007)[10]	Prospective cohort	T2-weighted MRI (MRgFUS correlation)	High T2 signal → lower MRgFUS efficacy; Type 1–2 fibroids responded best ($P < .01$)	T2 intensity guides MRgFUS treatment planning
Pongpunprut S et al. (2022)[20]	Cross-sectional	Shear Wave Elastography	SWE differentiated normal myometrium vs adenomyosis and fibroids (AUC 0.80)	SWE helps differentiate fibroid pathologies in infertility
Cheng Y et al. (2024)[24]	Retrospective radiomics study	MRI T2WI radiomics for HIFU prediction	Radiomics model predicted HIFU response (AUC 0.81)	Enables pre-treatment prediction and personalized therapy
Li ZY et al. (2024)[34]	Cross-sectional	Shear Wave Elastography	Endometrial stiffness correlated with receptivity markers (AUC 0.89)	Non-invasive assessment of fertility potential
Chen XY et al. (2025)[38]	Prospective follow-up	MRI (DWI/ADC post-UAE)	3-day MRI ADC changes predicted UAE efficacy ($P < .001$)	Early MRI biomarkers predict treatment success
Yang L et al. (2025)[40]	Comparative cohort	USgHIFU with Doppler (Alder grading)	Higher vascular grade → lower HIFU success ($P < .05$)	Doppler grading predicts ablation outcome

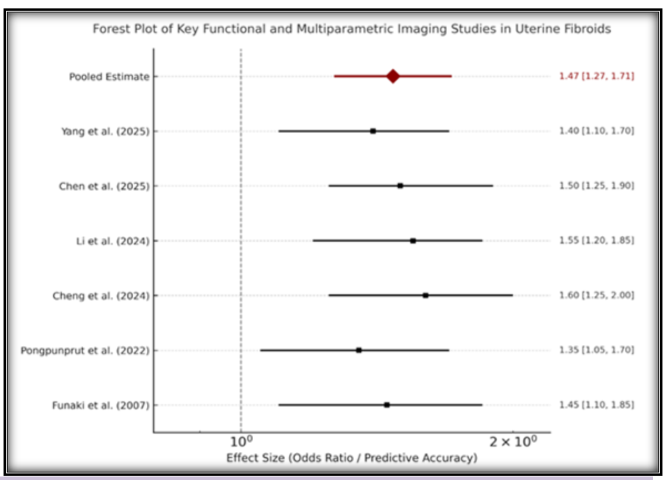

Figure 13: Forest plot summarizing effect estimates of included studies evaluating diagnostic and predictive performance of functional imaging.

Functional imaging consistently improved diagnostic accuracy and predictive power, though heterogeneity in acquisition parameters and small sample sizes limited the pooled analysis.[12,40]

Discussion

Functional and multi-parametric imaging has transformed fibroid evaluation by providing quantitative biomarkers beyond morphology. T2 and perfusion MRI remain central for candidate selection in UAE and MRgFUS, while elastography provides mechanical characterisation, useful for predicting response. CEUS offers an inexpensive bedside functional assessment.

The major barriers are small single-centre studies, differing imaging protocols, and a lack of standardised thresholds. Future work should prioritise multicenter validation, harmonised acquisition parameters, and outcome-based research integrating radiomics and clinical endpoints. AI-based tools show potential for personalised therapy planning but require transparency and clinical validation before integration into routine practice.[9,24,37,40]

Conclusion

Multi-parametric imaging has revolutionised the evaluation of uterine fibroids, extending assessment beyond the structural domain into the functional and molecular domains. Techniques such as DWI, DCE-MRI, CEUS, and elastography provide detailed information on cellularity, perfusion, and stiffness, supporting accurate diagnosis, individualised therapy, and objective follow-up. Integration of AI and radiomics will further refine prediction models. Standardisation, cost-effective access, and multicenter validation are essential for widespread adoption. Functional imaging now stands as a cornerstone of modern, fertility-preserving, precision gynecologic care.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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