REVIEW PAPER

Imaging in Non-Alcoholic Fatty Liver Disease (NAFLD): Current Advances, Quantitative Biomarkers, and Future Directions.

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ABSTRACT

Background: The most common chronic liver illness in the world is non-alcoholic fatty liver disease (NAFLD), which was recently renamed metabolic dysfunction–associated steatotic liver disease (MASLD). Early detection and risk assessment are crucial since progressive illness can result in cirrhosis, severe fibrosis, and hepatocellular cancer. Non-invasive imaging methods have taken centre stage in the assessment of diseases due to the limitations of liver biopsy. **Objective:** To comprehensively review current and emerging imaging modalities in NAFLD/MASLD, highlighting quantitative magnetic resonance techniques and artificial intelligence–based advancements.

Methodology: Ultrasonography remains the primary screening modality due to its accessibility and cost-effectiveness, though it is limited by qualitative assessment and reduced sensitivity for mild steatosis. Computed tomography provides objective attenuation measurements but is constrained by radiation exposure and limited early-stage sensitivity. Ultrasound-based elastography enhances non-invasive fibrosis assessment; however, technical variability persists, particularly in obese individuals. Magnetic resonance imaging techniques, including proton density fat fraction (PDFF) and magnetic resonance elastography (MRE), offer highly accurate, reproducible, and quantitative biomarkers for steatosis and fibrosis evaluation. Multiparametric MRI enables comprehensive whole-liver phenotyping and is increasingly incorporated into clinical trials. Emerging artificial intelligence and radiomics applications demonstrate promise for automated quantification and risk stratification, although further multicenter validation is required.**Conclusion:** Imaging has evolved from a supportive diagnostic tool to a cornerstone of non-invasive NAFLD/MASLD evaluation. Advances in quantitative MRI and AI-driven analytics are poised to enhance precision-based disease assessment and may substantially reduce reliance on invasive liver biopsy.

Keywords: - Non-alcoholic fatty liver disease (NAFLD); Metabolic dysfunction–associated steatotic liver disease (MASLD); Magnetic resonance imaging; Proton density fat fraction (PDFF); Magnetic resonance elastography (MRE); Liver fibrosis; Elastography; Artificial intelligence; Radiomics; Quantitative imaging biomarkers.

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INTRODUCTION

Diabetes The most prevalent chronic liver disease in the world, metabolic dysfunction-associated steatotic liver disease (MASLD), formerly known as non-alcoholic fatty liver disease (NAFLD), is a rising public health problem. In order to improve disease classification and more precisely characterize the metabolic pathways of

hepatic steatosis, an international multi-society Delphi consensus suggested in 2023 that the name NAFLD be replaced to MASLD.(1) The substantial correlation between the accumulation of hepatic fat and metabolic risk factors such as obesity, insulin resistance, type 2 diabetes, dyslipidemia, and hypertension is highlighted by this new nomenclature.(1,2) NAFLD is thought to affect 25% of the world's population, and its incidence is rising in tandem with that of type 2 diabetes and metabolic syndrome.(3,4) Recent modelling studies predict that the prevalence of advanced fibrosis and non-alcoholic fatty liver disease (NAFLD) will increase dramatically over the next ten years, particularly in developing countries.(5) The prevalence of NAFLD in the Indian population has been reported to range from 9% to 32%, demonstrating significant variance linked to metabolic risk profiles, urbanization, and dietary changes.(6) Due to its strong association with cardiovascular disease and extrahepatic effects, NAFLD is now recognized as a multisystem metabolic condition rather than a single hepatic issue.(2)

The histological spectrum of non-alcoholic steatohepatitis (NASH), progressive fibrosis, cirrhosis, hepatocellular carcinoma, and simple steatosis is all included in NAFLD. The most significant predictor of mortality from liver disease and other causes among these stages has continuously been the degree of fibrosis.(7) Liver biopsy is still the gold standard for diagnosing and staging non-alcoholic fatty liver disease (NAFLD), but its clinical usefulness is constrained by invasiveness, interobserver variability, sampling variability, and possible consequences.(8) A key component of the non-invasive assessment of NAFLD is radiological imaging. Because of its affordability and broad availability, conventional ultrasonography continues to be the preferred imaging modality. Nevertheless, traditional B-mode ultrasonography is qualitative and has a lower sensitivity for identifying mild steatosis, especially when the amount of hepatic fat infiltration is less than 20% to 30%.(8) Quantitative imaging methods have significantly improved radiology's diagnostic capabilities in NAFLD within the last ten years. A highly reliable, repeatable, and non-invasive biomarker for measuring hepatic steatosis, magnetic resonance imaging–proton density fat fraction (MRI-PDFF) is becoming more widely accepted as the imaging reference standard in clinical trials and treatment monitoring.(8,9) When it comes to staging liver fibrosis, magnetic resonance elastography (MRE) has proven to be more accurate than ultrasound-based elastography methods, especially in obese patients.(8,10) In parallel, non-invasive fibrosis assessment and risk stratification have seen a broad clinical adoption of ultrasound-based elastography modalities, including as transient elastography and shear wave elastography.(8)

A systematic review of modern radiological modalities is necessary due to the quick development of elastography-based methods and quantitative imaging biomarkers. The objective of this review is to objectively evaluate both traditional and cutting-edge imaging methods for the diagnosis and staging of NAFLD/MASLD, with a focus on non-invasive fibrosis evaluation, quantitative imaging biomarkers, and new developments in precision liver imaging technology.

PATHOPHYSIOLOGY

In people with metabolic risk factors and no considerable alcohol consumption, metabolic dysfunction–associated steatotic liver disease (MASLD), formerly known as non-alcoholic fatty liver disease (NAFLD), is characterized by excessive hepatic fat buildup.(1) A major component in encouraging hepatic lipid buildup, insulin resistance is closely associated with the complex pathophysiology of non-alcoholic fatty liver disease (NAFLD).(2) The earlier "two-hit" theory has mostly been supplanted by the "multiple-hit" concept, which maintains that hepatic steatosis is brought on by a complex interaction of insulin resistance, adipokine imbalance, oxidative stress, mitochondrial dysfunction, genetic vulnerability, and alterations in the gut microbiota.(11) Adipose tissue lipolysis is increased by insulin resistance, which raises the flow of free fatty acids to the liver. This leads to increased de novo lipogenesis, decreased export of very-low-density lipoprotein (VLDL), and an accumulation of triglycerides in hepatocytes.(2) A significant percentage of people acquire non-alcoholic steatohepatitis (NASH), which is characterized by lobular inflammation, hepatocellular ballooning, and varying degrees of fibrosis, while some may have stable simple steatosis.(3) Among all histological features, fibrosis stage has consistently been proven to be the most reliable predictor of liver-related and overall mortality in NAFLD.(7) Importantly, fibrosis may be treatable in its early stages, highlighting the significance of early detection and accurate staging. Due to the invasive nature of liver biopsies and associated disadvantages, including sampling variability and procedural risks, non-invasive diagnostic techniques are growing in popularity for disease assessment and surveillance.(8)

Understanding the pathophysiological progression from steatosis to fibrosis is essential for interpreting imaging results, as modern radiological techniques increasingly aim to assess the disease's progression and gauge the degree of fibrosis in addition to identifying hepatic fat.

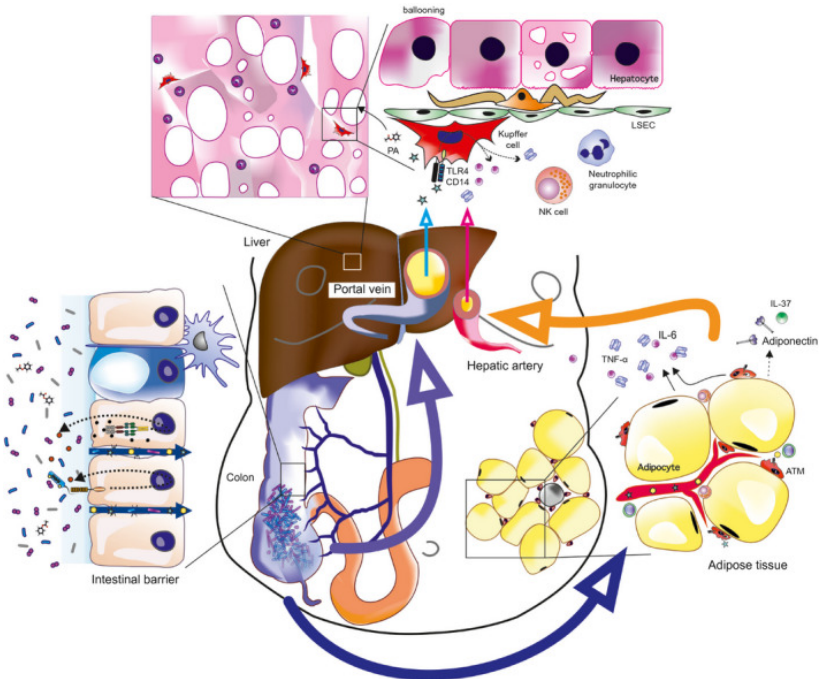

Figure 1Schematic representation of the multiple-hit pathophysiological model of NAFLD/MASLD illustrating the interaction between adipose tissue, gut–liver axis, inflammatory mediators, and hepatic steatosis progression. Reproduced from Buzzetti E, Pinzani M, Tsochatzis EA. Metabolism. 2016;65(8):1038–1048 (Open-access article).(12)

Conventional radiological methods in NAFLD/MASLD:

3.1Conventional B-Mode Ultrasonography

Conventional B-mode ultrasonography (US) is still the most widely used first-line imaging modality for the evaluation of suspected NAFLD/MASLD in healthcare settings due to its accessibility, affordability, and safety record.(13) Qualitative grayscale indicators including posterior beam attenuation, greater hepatic echogenicity in comparison to the renal cortex, blurring of intrahepatic vascular boundaries, and poor diaphragm visibility are used to identify hepatic steatosis sonographically. Hepatocyte internal lipid accumulation, which increases acoustic dispersion, explains these findings. However, because these diagnostic criteria are subjective and operator-dependent, there is heterogeneity in their interpretation.(14) Hernaez et al. (2011) found that the combined sensitivity and specificity for detecting moderate-to-severe steatosis were 84.8% and 93.6%, respectively, in a comprehensive meta-analysis that evaluated 49 studies comparing ultrasonography with histology as the reference standard. However, ultrasound's sensitivity drastically decreases in cases of mild steatosis (<20–30% fat infiltration), limiting its utility in early sickness detection.(14) Importantly, fibrosis cannot be precisely staged by standard ultrasound, nor can simple steatosis be distinguished from steatohepatitis. Additionally, it is unable to provide a numerical assessment of the liver's fat content. Additionally, picture quality may be impacted by the thicker subcutaneous tissue in obese individuals, which would further hinder diagnostic performance. Due to these limitations, which include operator dependence, decreased sensitivity for mild steatosis, and lack of quantitative capabilities, there has been a growing trend toward quantitative ultrasound techniques and elastography-based procedures to increase diagnostic accuracy in NAFLD.(13)

3.2Controlled Attenuation Parameter (CAP)

Crucially, conventional ultrasonography cannot accurately stage fibrosis or differentiate between simple steatosis and steatohepatitis. Furthermore, it cannot give a numerical evaluation of the fat content of the liver. Furthermore, the thicker subcutaneous tissue in obese people may affect image quality, which would further impair diagnostic performance. In order to improve diagnostic accuracy in NAFLD, there has been an increasing tendency toward quantitative ultrasound techniques and elastography-based procedures. These limitations include operator dependence, lower sensitivity for moderate steatosis, and lack of quantitative capabilities.(15) Fast acquisition times, bedside use, and the ability to measure liver stiffness and fibrosis evaluation simultaneously are just a few

advantages of CAP. However, its accuracy may be compromised by obesity, diabetes, and a larger gap between the skin and the liver capsule, particularly in patients who require the XL probe.(13) According to the 2021 EASL Clinical Practice Guidelines on non-invasive diagnostics, CAP is considered a legitimate non-invasive technique for detecting hepatic steatosis in clinical practice, particularly when combined with elastography for fibrosis assessment.(13) However, CAP does not replace magnetic resonance-based techniques when greater quantitative accuracy is required for clinical trials or treatment monitoring.

3.3Ultrasound-Based Elastography for Fibrosis Assessment

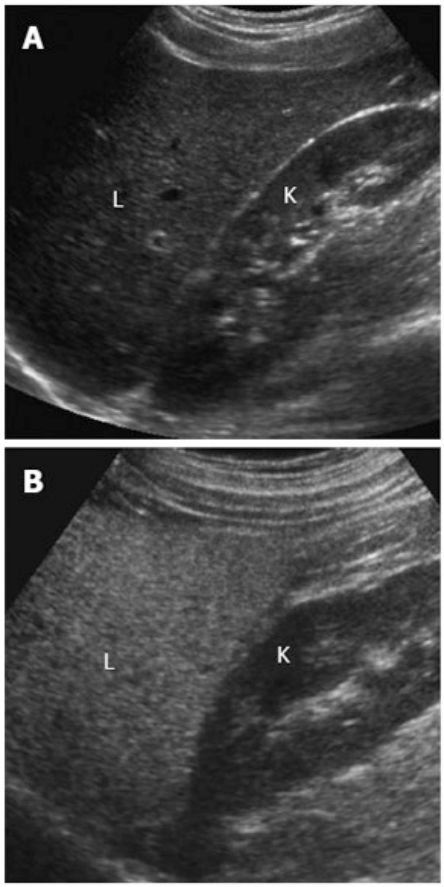

Figure 2Ultrasonographic comparison of normal liver (A) and hepatic steatosis (B). Panel B demonstrates diffusely increased hepatic echogenicity relative to the renal cortex (liver–kidney contrast), consistent with fatty liver disease. Reproduced from Lee SS, Park SH. World J Gastroenterol. 2014;20(23):7392–7402 (15)

Ultrasound-based elastography techniques have become essential non-invasive tools for assessing liver fibrosis in patients with non-alcoholic fatty liver disease. Unlike typical B-mode ultrasonography, which primarily diagnoses steatosis qualitatively, elastography uses liver stiffness as a proxy for the degree of fibrosis. Increased extracellular matrix deposition in fibrotic liver tissue results in decreased elasticity, which can be measured in kilopascals (kPa).(13)

3.3.1 Transient Elastography (TE)

The most thoroughly tested ultrasound-based elastography method is TE, which is sold under the brand name FibroScan®. By tracking the speed at which a mechanically produced shear wave propagates, TE calculates the liver's stiffness. Numerous studies have demonstrated its utility in staging liver fibrosis in NAFLD. According to a thorough study and meta-analysis by Singh et al. (2016), transient elastography shows good diagnostic accuracy for diagnosing advanced fibrosis (≥F3), with pooled AUROC values often above 0.85. However, diagnostic performance declines when identifying intermediate fibrosis phases.(16)

3.3.2 Shear Wave Elastography (SWE)

Shear wave elastography (SWE), which includes point shear wave elastography (pSWE) and two-dimensional shear wave elastography (2D-SWE), is included into conventional ultrasonic systems. By producing acoustic radiation force impulses that result in shear waves, these techniques provide real-time stiffness maps of the liver parenchyma. When compared to transient elastography, SWE may reduce sample variability and offer direct observation of the region of interest. Cassinotto et al. (2016) demonstrated that 2D-SWE performs diagnostically on par with or better than transient elastography in diagnosing advanced fibrosis, with AUROC values consistently exceeding 0.85. Inter-vendor variability and the lack of internationally recognized cut-off values, however, continue to impose limitations.(17) According to EASL (2021), ultrasound-based elastography techniques are recommended as first-line non-invasive procedures for ruling out advanced fibrosis in at-risk groups, especially when paired with serum biomarkers.(13)

In general, ultrasound elastography techniques have significantly reduced the need for diagnostic liver biopsy in NAFLD since they enable non-invasive risk grading. However, their primary objective is to assess fibrosis rather than accurately measure steatosis.

3.4 Computed Tomography (CT) in NAFLD

In the past, computed tomography (CT) has unintentionally revealed hepatic steatosis, particularly in people undergoing abdominal imaging for unrelated purposes. Hepatic fat accumulation results in decreased hepatic attenuation values on non-contrast CT, which are often represented in Hounsfield units (HU).A liver attenuation value that is at least 10 HU lower than the spleen's or an absolute hepatic attenuation of fewer than 40 HU on unenhanced CT are commonly used as diagnostic criteria for moderate-to-severe steatosis.(18)

When it comes to evaluating NAFLD, CT has several serious limitations despite being widely accessible and repeatable. First of all, CT exposes users to ionizing radiation, making it unsuitable for routine screening or long-term disease monitoring, particularly in younger patients.

Second, CT cannot directly assess hepatic inflammation or fibrosis and lacks the sensitivity required for early-stage disease detection. According to the 2021 EASL Clinical Practice Guidelines on non-invasive diagnostics, CT shouldn't be the main diagnostic tool for steatosis assessment when safer and more accurate alternatives like MRI and ultrasound are available.(13)

More recent studies have investigated advanced CT-based techniques, such as dual-energy CT and quantitative CT attenuation mapping, to improve fat estimate. However, these techniques are still not commonly employed in clinical settings as compared to MRI-based proton density fat fraction (PDFF), which provides greater accuracy without radiation exposure.(19)

Because of this, CT is currently only used for incidental detection rather than structured disease staging and has a limited role in the specialized evaluation of NAFLD.

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Magnetic resonance imaging in NAFLD/MASLD: quantitative and advanced techniques

4.1 MRI–Proton Density Fat Fraction (MRI-PDFF)

Magnetic resonance imaging–proton density fat fraction (MRI-PDFF) has emerged as the most accurate and dependable non-invasive imaging biomarker for

assessing hepatic steatosis in NAFLD. Unlike conventional imaging methods, MRI-PDFF provides a direct quantitative evaluation of the liver's fat content, expressed as a percentage of the mobile proton density that could be linked to triglycerides. By accounting for confounding factors such T1 bias, T2* decay, spectral complexity of fat, and noise bias, this technique enables consistent fat estimation across scanners and field strengths.(19,20).

MRI-PDFF is clinically validated against histology, according to numerous studies. Middleton et al. (2017) showed remarkable inter-examination repeatability and a strong correlation between MRI-PDFF and histologic steatosis grade in patients with biopsy-proven NAFLD. Importantly, MRI-PDFF has demonstrated greater sensitivity than CT and ultrasonography in detecting even minute levels of hepatic fat infiltration, making it highly valuable in clinical trial and early sickness detection contexts.(21)

The capacity of MRI-PDFF to assess the complete liver parenchyma rather than just a limited sampling area removes the sampling variability associated with liver biopsy, which is one of its primary advantages. Additionally, MRI-PDFF provides continuous quantitative data that enables accurate tracking of changes in the amount of fat in the liver over time. It is currently utilized as a primary endpoint biomarker in NAFLD-focused therapy trials due to this feature.(19) Reproducibility studies that have shown low inter-scanner and inter-platform variability have validated its use in multicentre trials. MRI-PDFF meets many criteria for a reliable imaging biomarker, including biological validity, repeatability, and reproducibility, according to a position statement from the Radiological Society of North America (RSNA) Quantitative Imaging Biomarkers Alliance.(19)

Despite its advantages, MRI-PDFF has disadvantages. It does not evaluate fibrosis or inflammation directly, and it may be affected if severe iron excess is not treated right once. Additionally, longer acquisition times, cost, and scanner availability may limit routine utilization in large-scale screening populations. However, in radiology-focused practice and research contexts, MRI-PDFF represents a paradigm shift from qualitative to fully quantitative liver imaging.

4.2 Magnetic Resonance Elastography (MRE)

Magnetic Resonance Elastography (MRE) has emerged as one of the most dependable non-invasive imaging techniques for staging liver fibrosis in NAFLD patients. In MRE, the shear waves created by low-frequency mechanical vibrations that go through the liver parenchyma are imaged using phase-contrast MRI sequences. A quantitative evaluation of liver stiffness in kilopascals (kPa) is made possible by the close correlation between the propagation velocity of these shear waves and tissue stiffness.(10)

MRE outperforms ultrasound-based elastography techniques in terms of diagnostic accuracy, particularly in obese individuals—a population that is more prevalent in NAFLD. According to Singh et al. (2016), MRE was very good in detecting advanced fibrosis (≥F3), with pooled AUROC values frequently exceeding 0.90. Importantly, transient elastography may fail due to acoustic limitations, although MRE maintains excellent technical success rates even in people with high body mass index.(22)

Because MRE can assess a large volume of liver tissue, which reduces sampling variability, it has a major benefit over biopsy and region-limited ultrasonography methods. Additionally, steatosis (using PDFF), fibrosis (using stiffness mapping), and other hepatic abnormalities can be assessed simultaneously in a single comprehensive examination by integrating MRE into routine liver MRI procedures.(19) In an attempt to improve the identification of early fibrotic changes and inflammatory activity, multiparametric MRI approaches that integrate MRE with T1 and T2 mapping have also been studied recently. These quantitative approaches demonstrate a shift toward imaging-based NAFLD phenotyping, which is in line with precision medicine strategies.(13)

4.3 Magnetic Resonance Spectroscopy (^{1}H-MRS)

Proton magnetic resonance spectroscopy (^{1}H-MRS) was one of the first non-invasive techniques to quantify hepatic steatosis. By assessing the relative signal strength of water and lipid proton resonances within a localized voxel of liver tissue, ^{1}H-MRS enables the direct biochemical evaluation of intrahepatic triglyceride level, in contrast to conventional MRI sequences that provide anatomical pictures.(23) After several validation studies shown a high degree of agreement between the fat percentage generated by MRS and the outcomes of liver biopsies, MRS established itself as a non-invasive reference method for fat quantification in research settings. Despite its high accuracy, ^{1}H-MRS has considerable limitations. Because it only samples a small, restricted voxel of liver parenchyma, it might not adequately reflect the varied distribution of fat in the liver. Furthermore, the technical limitations for capture and post-processing of MRS restrict its normal clinical utility. Longer acquisition

times and motion sensitivity further restrict widespread use.(19)

Since the development of multi-echo chemical shift-encoded MRI techniques, MRI-PDFF has essentially replaced MRS in clinical practice because to its improved reproducibility and faster acquisition times for whole-liver fat maps. However, ^{1}H-MRS continues to be a validation reference standard in studies evaluating new fat-quantification techniques.(20)
In the context of NAFLD, MRS represents a major turning point in the development of quantitative liver imaging and laid the foundation for modern MRI-based biomarkers.

4.4 Multiparametric MRI and Quantitative T1 Mapping (cT1)

In order to provide a comprehensive evaluation of hepatic steatosis, inflammation, and fibrosis, a sophisticated imaging method called multiparametric MRI (MP MRI) combines multiple quantitative MRI biomarkers, including proton density fat fraction (PDFF), magnetic resonance elastography (MRE), and T1/T2 mapping. Unlike standard imaging, which evaluates each disease component separately, MP MRI attempts to profile NAFLD by concurrently evaluating tissue stiffness, fibro-inflammatory activity, and fat content.(24)

Iron-corrected T1 mapping (cT1) is one of MP MRI's most promising features. When fibrosis and inflammation are present, the native T1 relaxation duration increases due to changes in tissue composition and extracellular fluid expansion. However, hepatic iron buildup can abnormally shorten T1 values. Consequently, corrected T1 (cT1), which takes into consideration T2* effects from iron overload, provides a more precise biomarker of fibro-inflammatory activity. Multiparametric MRI revealed a significant correlation between cT1 levels and histological indicators of inflammation and fibrosis in people with chronic liver disease, including NAFLD, according to a prospective study by Pavlides et al. (2017).
Significantly, cT1 showed promise in distinguishing between simple steatosis and steatohepatitis, addressing a significant limitation of conventional imaging modalities that cannot do so non-invasively.(24)

Further validation study has highlighted the use of MP MRI in risk assessment and long-term disease tracking. Banerjee et al. (2014) reported that when T1 mapping was combined with PDFF and T2* rectification, liver tissue composition could be accurately represented utilizing a single acquisition technique.(25)

From a radiology perspective, multiparametric MRI represents a paradigm shift toward quantitative, reproducible imaging biomarkers that go beyond fat quantification alone. Steatosis (PDFF), fibrosis (MRE), and inflammatory activity (cT1) are all included in MP MRI, which is consistent with precision medicine methods and is increasingly being used in clinical studies evaluating novel NASH drugs. Even with its potential, MP MRI is currently limited by cost, the need for consistent acquisition methods, and the availability of post-processing software. However, if quantitative imaging biomarkers continue to develop, multiparametric MRI may be crucial for non-invasive phenotyping and therapy monitoring in metabolic liver disease.

ARTIFICIAL INTELLIGENCE AND RADIOMICS IN NAFLD IMAGING

5.1 Rationale for AI Integration in NAFLD Imaging

Recently called metabolic dysfunction–associated steatotic liver disease (MASLD), non-alcoholic fatty liver disease (NAFLD) is a multifaceted condition with various degrees of fibrosis, inflammation, ballooning, and steatosis. Among these, fibrosis stage is still the most accurate predictor of both overall survival and liver-related mortality.(26) Although magnetic resonance imaging–proton density fat fraction (MRI-PDFF) and magnetic resonance elastography (MRE) are known non-invasive quantitative biomarkers for steatosis and fibrosis, respectively, their interpretation has traditionally relied on summary parameters like mean fat fraction or average liver stiffness. These global assessments might not adequately reflect two features of increasing fibrosis: architectural remodeling and regional variability. Artificial intelligence (AI), including machine learning and deep learning methods, offers the ability to extract multidimensional imaging information beyond simple threshold-based measures. This may enhance NAFLD diagnostic performance and risk categorization.

5.2 Deep Learning for Steatosis Detection on Ultrasound

Ultrasound remains the most often used imaging method for the initial evaluation of hepatic steatosis due to its low cost and simplicity of use. However, using standard B-mode ultrasonography to assess moderate steatosis (less than 20–30% fat infiltration) is operator-dependent and qualitative.(27)
To get around these limitations, deep learning techniques for steatosis identification and grading have been developed.

In contrast to conventional texture analysis methods, Byra et al. (2018) demonstrated that convolutional neural network-based transfer learning significantly improved the classification of hepatic steatosis when applied to ultrasound images, achieving area under the curve (AUC) values above 0.80 when validated against reference standards. These findings imply that AI can identify subtle echo texture differences that human viewers cannot reliably identify. These techniques may increase screening effectiveness in high-risk metabolic populations and reduce interobserver variability in community practice settings.(28)

5.3 AI Applications in MRI-Based Steatosis Quantification

Currently regarded as the most reliable non-invasive biomarker for determining liver fat level, MRI-PDFF is widely used in NAFLD clinical trials.(9,29) Even though PDFF analysis is quantitative, it often requires human segmentation or region-of-interest placement. Whole-liver volumetric fat measurement is now feasible because to the advent of AI-based automated liver segmentation algorithms, which also improve reproducibility and lessen sample bias.

In NAFLD cohorts, automated segmentation algorithms have demonstrated a high degree of compatibility with expert manual delineation, enabling its use in comprehensive research studies and long-term therapeutic monitoring.(9) Deep learning algorithms allow for the objective assessment of medication response through standardized whole-organ analysis in NASH pharmacotherapy research, where small changes in fat fraction may have clinical implications.

5.4 Machine Learning for Fibrosis Prediction Using Elastography

The most clinically significant predictive factor in NAFLD is still the fibrosis stage.(26) The good diagnostic accuracy of magnetic resonance elastography for liver fibrosis staging is demonstrated by pooled AUROC values for advanced fibrosis in meta-analyses that have surpassed 0.90.(30)

However, the primary foundation for conventional interpretation is the mean liver stiffness criteria.

Recent machine learning algorithms have attempted to improve fibrosis identification by combining spatial stiffness heterogeneity with multiparametric imaging data. Compared to single-parameter models, research integrating MRE stiffness with other MRI parameters, such as PDFF and T1 mapping, has demonstrated superior advanced fibrosis discrimination.(31) These multiparametric frameworks reflect the complex pathophysiology of NAFLD, where fibrosis, inflammation, and steatosis coexist and interact dynamically.

5.5 Multiparametric and Predictive Modelling Approaches

Machine learning models that integrate imaging biomarkers with clinical and laboratory factors have demonstrated improved prediction performance for advanced fibrosis when compared to independent imaging measurements. Precision medicine's tenets are supported by integrative approaches like this one, which may also aid in customized risk assessment. Moreover, T1 mapping, elastography, and PDFF are examples of multiparametric MRI techniques that have shown promise in predicting the progression of a disease and its response to treatment.(24) While not all of these models specifically use deep neural networks, they do employ computational modeling approaches that form the foundation for future AI-driven predictive systems.

5.6 Current Limitations and Future Directions

Despite promising preliminary results, AI applications in NAFLD imaging are currently in relatively early stages of clinical translation. Small sample sizes and single-center cohorts are used in most studies, which limits generalizability. Variations in scanner suppliers, imaging methods, and patient demographics present further challenges.

Furthermore, regulatory and validation issues must be resolved before AI-based decision-support systems may be included into routine clinical procedures. To provide dependable, repeatable AI tools for NAFLD assessment, standardized acquisition processes and comprehensive multicenter prospective validation studies would be required. As dataset availability rises and harmonization efforts progress, the significance of AI in non-invasive sickness staging and therapy monitoring is expected to expand.

Comparative diagnostic performance of imaging modalities in NAFLD

6.1 Comparative Accuracy for Detection of Hepatic Steatosis

Hepatic steatosis needs to be precisely identified and measured in order to diagnose NAFLD. Due to its affordability, ease of use, and safety record, ultrasonography remains the most widely used first-line imaging technique. However, when hepatic fat infiltration is less than 20% to 30%, classic B-mode ultrasonography is qualitative and less sensitive for detecting mild steatosis.(27) Pooled sensitivity and specificity values for moderate-to-severe steatosis are approximately 84% and 93%, respectively, according to

meta-analyses; however, performance significantly declines in the early stages of the illness.(14) Ultrasound accuracy is also impacted by the operator's experience and the patient's body type, particularly in obese individuals.

Computed tomography (CT) allows objective attenuation testing using liver-to-spleen attenuation ratios and Hounsfield units. CT's sensitivity for mild steatosis is modest, and its application in long-term surveillance is restricted by ionizing radiation exposure, even though it can reasonably reliably diagnose moderate-to-severe steatosis.(32)

Magnetic resonance imaging–proton density fat fraction (MRI-PDFF), which has demonstrated exceptional diagnostic performance in biopsy-correlated NAFLD cohorts for all steatosis grades, is the most accurate non-invasive imaging biomarker for estimating the amount of fat in the liver.

Tang et al. (2015) found that the MR-estimated PDFF was very accurate in classifying histologic steatosis grades, with AUROC (area under the receiver operating characteristic curve) values reaching 0.90 for distinguishing between ≥5% steatosis. Because of its exceptional consistency and constant quantitative assessment of fat fraction, MRI-PDFF is especially well suited for long-term disease monitoring and treatment trials.(9)

6.2 Comparative Accuracy for Fibrosis Staging

Steatosis is the hallmark of NAFLD, although the stage of fibrosis remains the strongest predictor of liver-related morbidity and mortality.(26) Thus, from a clinical perspective, accurate non-invasive fibrosis staging is essential. Ultrasound-based transient elastography (TE) has gained widespread use in clinical settings due to its portability and ease of use. Meta-analyses have demonstrated good diagnostic performance for advanced fibrosis, with AUROC values in NAFLD populations often falling between 0.85 and 0.88.(16)

Magnetic resonance elastography (MRE) has consistently demonstrated better diagnostic performance when compared to ultrasound-based elastography techniques. According to a meta-analysis by Singh et al. (2016), MRE showed pooled AUROC values of approximately 0.92 for the identification of advanced fibrosis in chronic liver disease, including NAFLD cohorts.

MRE reduces sample variability and enhances repeatability by assessing a larger amount of hepatic parenchyma than ultrasonic elastography. Furthermore, MRE performance is less affected by obesity, a critical feature in individuals with metabolic liver disease.(30)

6.3 Role of Multiparametric MRI in Comprehensive Disease Assessment

Multiparametric MRI approaches explain fibrosis, inflammation, and steatosis in a single scan, going beyond discrete measurements of fat or stiffness. Techniques utilizing PDFF, MRE, and T1 mapping parameters have demonstrated stronger correlations with the degree of histologic activity and fibrosis.(24) This type of comprehensive assessment is particularly useful in distinguishing between simple steatosis and non-alcoholic steatohepatitis (NASH), which has a higher chance of developing.

6.4 Clinical Implications and Modality Selection

The choice of imaging modalities in NAFLD is influenced by the clinical environment, available resources, and intended application. Ultrasound is still appropriate for initial screening in primary care settings. Transient elastography provides a readily available fibrosis risk assessment in outpatient practice. The best environments for MRI-PDFF and MRE are tertiary facilities, research applications, and clinical trials requiring high diagnostic accuracy and consistency. In conclusion, while traditional modalities are still helpful for screening and risk stratification, MRI-based quantitative techniques now have the highest diagnostic accuracy for both fibrosis staging and steatosis quantification in NAFLD Advanced MRI techniques may become more widely available in clinical practice as a result of ongoing technology advancements and cost reductions.

Future trends in imaging of NAFLD/MASLD

7.1Transition Toward Quantitative and Multiparametric MRI

In the future of NAFLD imaging, quantitative, repeatable, and multiparametric magnetic resonance-based techniques capable of performing comprehensive liver phenotyping are becoming increasingly crucial.(25,27) Unlike qualitative ultrasonography or attenuation-based CT assessment, MRI-derived biomarkers provide constant quantitative measures of hepatic fat, fibrosis, and iron deposition.(9,25) Proton density fat fraction (PDFF), a standardized and reproducible biomarker for measuring hepatic steatosis, displays a high correlation with histologic steatosis grading in biopsy-proven NAFLD cohorts.(9,21)

Tang et al. demonstrated a strong correlation between MRI-PDFF and histologic steatosis grades, validating its application as a non-invasive quantitative biomarker.(9) According to Middleton et al., MRI-PDFF evaluations

closely match histologic fat fraction and can detect long-term changes during therapeutic intervention.(21) Because of these findings, phase II and III NASH clinical trials currently commonly use MRI-PDFF as a surrogate endpoint.(9,33)

Thanks to multiparametric MRI techniques that include PDFF, T1 mapping, and T2* mapping, iron overload and fibroinflammatory activity can now be evaluated in a single scan. Banerjee et al. found a correlation between corrected T1 (cT1) values and fibrosis and inflammatory activity, which could be helpful in identifying patients with active steatohepatitis.(25)

7.2Expansion and Technical Evolution of Magnetic Resonance Elastography

Magnetic resonance elastography (MRE) is becoming regarded as the most dependable non-invasive technique for staging liver fibrosis in NAFLD.(10,22) AUROC scores for advanced fibrosis diagnosis above 0.90, outperforming transient elastography in various comparison analyses, according to a thorough review and meta-analysis by Singh et al.(22) Future advancements include improved spatial resolution to more precisely characterize the distribution of heterogeneous fibrosis, three-dimensional MRE acquisition, and higher-frequency vibration techniques.(10,22) Improving MRE-based risk stratification techniques could significantly affect prognostic modelling and patient selection for clinical trials because fibrosis stage is the strongest predictor of liver-related outcomes in non-alcoholic fatty liver disease (NAFLD).(7)

Additionally, research is being done on integrating MRE with PDFF and T1 mapping into composite multiparametric scores in order to improve diagnostic precision and reduce unclear zones.(22,25)

7.3Imaging Biomarkers as Surrogate Endpoints in Clinical Trials

Due to the rapid development of pharmaceutical treatments that target fibrosis, inflammation, and steatosis, imaging biomarkers are being evaluated more often as surrogate endpoints in clinical trials. It has been demonstrated that MRI-PDFF correlates with histologic improvement in steatosis and is sensitive to minor longitudinal changes in the quantity of fat in the liver.(21,33)

A reduction in MRI-PDFF of at least 30% was associated with histologic response in NASH patients, according to Loomba et al., confirming its role as a quantitative response biomarker.(33)

Additionally, MRE has been helpful in monitoring the progression or regression of fibrosis over time, improving its role in the assessment of long-term sickness.(10,22)

7.4 Artificial Intelligence and Radiomics in NAFLD Imaging

Artificial intelligence (AI) and radiomics have the potential to completely transform liver imaging in the future, particularly in the areas of automated detection, segmentation, and fibrosis prediction.(34,35) On CT images, deep learning systems have demonstrated promise in correctly diagnosing hepatic steatosis. A growing number of contemporary frameworks are being adjusted for the evaluation of metabolic liver disease, despite the fact that the original AI applications were developed for more thorough liver lesion characterization.(34)

Radiomics-based texture analysis has shown potential in assessing liver fibrosis by detecting high-dimensional quantitative traits from ultrasonic elastography and MRI data. Wang et al. demonstrated that deep learning-based radiomic analysis significantly improved diagnostic accuracy for fibrosis assessment when compared to standard stiffness metrics alone.(35)

Even with these positive results, most AI research is still limited by retrospective design and the lack of large multicentre validation cohorts.(34,35)

7.5Toward Precision Imaging and Integrated Risk Stratification

The current paradigm for NAFLD imaging is precision medicine models that integrate imaging biomarkers with laboratory, clinical, and genetic data.(7,27) Since fibrosis stage has consistently been shown to be the strongest predictor of liver-related and overall mortality in NAFLD, accurate non-invasive fibrosis assessment is essential.(7) As multiparametric imaging advances, the combination of PDFF, MRE, and T1 mapping may offer personalized risk assessment and therapy distribution.(22,25) Large-scale collaborative efforts are working on the regulatory validation of non-invasive biomarkers for clinical usage, suggesting a move away from diagnostic imaging and toward comprehensive disease phenotyping.(27)

CONCLUSION

Now more commonly referred to as metabolic dysfunction–associated steatotic liver disease, non-alcoholic fatty liver disease is one of the most significant metabolic health problems of the modern era. Its growing range, which encompasses cirrhosis, hepatocellular carcinoma, advanced fibrosis, basic steatosis, and steatohepatitis, need accurate, reproducible, and non-invasive diagnostic methods. As the prevalence of metabolic illnesses continues to rise

worldwide, imaging's role has evolved from a supportive diagnostic tool to a crucial element in sickness detection, staging, and long-term monitoring.

Conventional ultrasonography is still the most widely accessible screening technique, although its qualitative nature and lower sensitivity for early disease restrict its value in a comprehensive assessment. Computed tomography provides objective measurements of attenuation, although radiation exposure limits its sensitivity in moderate steatosis. While ultrasound-based elastography approaches have improved non-invasive fibrosis categorization, technical variability and poor reliability in obese patients remain important considerations.

Magnetic resonance-based techniques are currently the most comprehensive and dependable imaging modality for assessing NAFLD. Quantitative MRI methods allow reliable assessment of fibrosis and precise identification of hepatic fat content without the sampling ambiguity of liver biopsy. Multiparametric MRI techniques provide whole-liver phenotyping, which offers a more complete understanding of disease load.

These advancements have significantly expanded the application of imaging beyond simple diagnosis to risk evaluation and treatment tracking.

The advancement of radiomics and artificial intelligence further highlights the revolutionary potential of imaging in metabolic liver disease. Customized risk assessment may be made possible by predictive modelling, automated segmentation, and quantitative biomarker extraction. Standardization, multicentre validation, and integration into healthcare workflows remain critical prior to widespread implementation.

The entire histopathologic spectrum of fibrosis, inflammation, and steatosis cannot yet be accurately depicted by a single imaging tool, despite enormous progress. Therefore, a multimodal and patient-specific imaging strategy is still needed in contemporary clinical practice. In conclusion, imaging has developed from a screening tool to an essential part of a comprehensive assessment of NAFLD. As quantitative techniques and data-driven strategies advance, imaging is expected to become increasingly important in precision hepatology. This could enable earlier, more customized therapy intervention and reduce reliance on invasive biopsy.

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