



Imaging Evaluation for Steatotic Liver Disease

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Metabolic dysfunction-associated steatotic liver disease (MASLD), previously known as nonalcoholic fatty liver disease, is the fastest-growing cause of chronic liver disease worldwide, affecting approximately 30% of the global population. Imaging is vital for detecting, quantifying, and monitoring hepatic steatosis—the defining abnormality of MASLD—and subsequent fibrosis—the key determinant of liver-related outcomes. This review summarizes the principles, clinical usage, efficacy, and advancements in various imaging modalities for the noninvasive assessment of hepatic steatosis and fibrosis, with an emphasis on ultrasound, CT, and MRI. Additionally, this review explores the evolving landscape of MASLD diagnostic approaches, including machine-learning techniques, opportunistic screening, standardized imaging guidelines, and therapies, emphasizing the pivotal role that radiologists can play in shaping these developments.

Keywords: Metabolic dysfunction-associated steatotic liver disease; MASLD; Quantitative ultrasound; Chemical-shift-encoded; CSE-MRI; Proton density fat fraction; PDFF; MR elastography

INTRODUCTION

With the rise in global obesity, metabolic dysfunction-associated steatotic liver disease (MASLD) has increased in prevalence and has become the fastest-growing cause of chronic liver disease worldwide, currently affecting 30% of the global population (Fig. 1) [1]. While MASLD was recognized until recently by prior names, nonalcoholic fatty liver disease (NAFLD) and metabolic associated fatty liver disease, these previous terms were problematic as they emphasized exclusionary rather than defining criteria, and “fatty” was considered colloquial and stigmatizing. In 2023, a multistakeholder effort by hepatology societies introduced

the nomenclature of steatotic liver disease (SLD), which encompasses numerous conditions, including MASLD and metabolic-associated steatohepatitis (MASH, previously known as nonalcoholic steatohepatitis [NASH]) [2].

Recent guidelines from major liver societies, including the European Association for the Study of the Liver, the American Association for the Study of Liver Diseases, and the Korean Association for the Study of the Liver, emphasize the growing role of imaging in the clinical management of MASLD [2-4]. While screening in the general population has not been recommended, the societies recommend noninvasive imaging techniques such as ultrasound (US) and laboratory tests for at-risk populations, including those with elevated liver enzymes or metabolic syndrome markers. Beyond screening, noninvasive imaging has remained the cornerstone of diagnosis and monitoring of MASLD.

The diagnosis of MASLD requires the presence of at least one cardiometabolic risk factor in addition to hepatic steatosis, which can be identified by imaging or histology (Fig. 1). The diagnosis of MASH requires biopsy and is based on a constellation of histologic abnormalities including steatosis, lobular inflammation, and a particular type of hepatocellular damage known as ballooning degeneration;

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it can occur without or with fibrosis. Disease activity is scored based on the sum of individual steatosis, lobular inflammation, and ballooning scores. A subgroup of patients with MASH who also have a NAFLD activity score of ≥ 4 and stage ≥ 2 fibrosis are considered to have at-risk MASH given their elevated risk of liver-related mortality (Fig. 2) [5,6].

Liver steatosis remains a primary criterion for diagnosis and monitoring of MASLD, while liver fibrosis is a primary determinant of liver-related outcomes. With a growing need for scalable approaches to detection and longitudinal follow-up of patients with MASLD/MASH, clinical practice and research trials have focused on potential noninvasive tools for assessing liver steatosis and fibrosis. Noninvasive imaging tests are well positioned to provide quantitative assessment for both detection and longitudinal monitoring of disease severity for MASLD/MASH. This review summarizes currently available imaging modalities for detection and characterization of liver steatosis and fibrosis, emerging technology, and future directions for imaging in the MASLD/MASH landscape.

ASSESSMENT OF HEPATIC STEATOSIS

Hepatic steatosis occurs when excess lipids accumulate within hepatocytes secondary to an imbalance between lipid storage and removal. Three main sources of hepatic fat include: dietary intake, de novo synthesis of fatty acids

(i.e., lipogenesis), and uptake of plasma non-esterified fatty acids originating from the breakdown of adipose tissue [7]. Steatosis is graded histologically on a 4-point ordinal scale (S0, S1, S2, and S3) based on the percentage of hepatocytes containing fat droplets (<5%, 5%–33%, 33%–66%, and >66%, respectively) as assessed at low to medium power microscopy [5]. While liver biopsy has been the reference standard for MASLD, it is observer-dependent and invasive, rendering it unsuitable for longitudinal

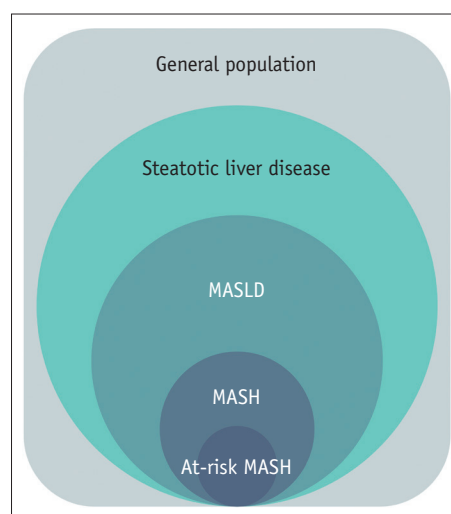


Fig. 2. At-risk MASH is a subset of MASH, which in turn is a subset of MASLD. MASH = metabolic-associated steatohepatitis, MASLD = metabolic dysfunction-associated steatotic liver disease

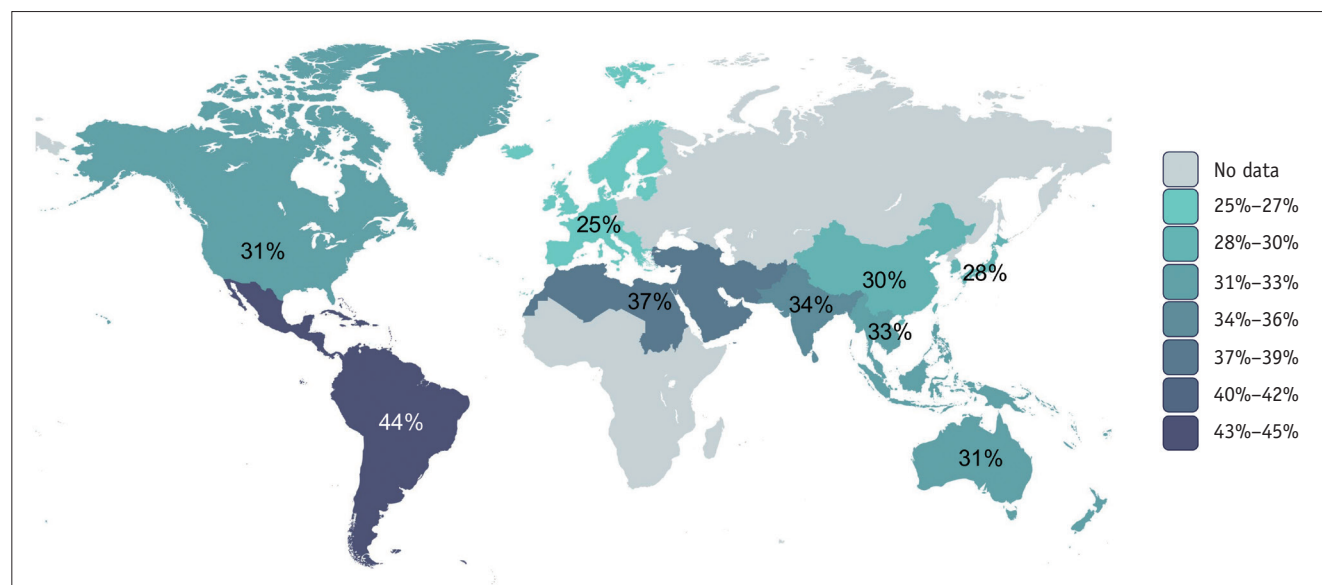


Fig. 1. MASLD prevalence worldwide. The global prevalence of MASLD is estimated to be approximately 30%, with ranges from 25% to 44%. Adapted from Younossi et al., *Hepatology* 2023;77:1335–1347 [1], under a CC BY-NC-ND license. Map created with www.mapchart.net. MASLD = metabolic dysfunction-associated steatotic liver disease

assessment [8]. Given that hepatic steatosis may be heterogeneous, biopsy is also subject to sampling bias [8,9]. Thus, noninvasive methods to enable accurate detection, monitoring and grading of hepatic steatosis over the whole liver are needed (Table 1).

Conventional US

The US does not directly measure liver fat but assesses acoustic properties related to liver fat content. In conventional US, high-frequency sound waves are emitted from a transducer and then reflect off and scatter from

internal structures, such as hepatocytes, generating echoes of variable amplitude based on tissue composition which are displayed in gray scale on B-mode images. Liver parenchyma is normally similar or slightly higher echogenicity compared to the spleen and kidney. In steatosis, fat droplets within hepatocytes act as additional scatterers of the US beam, resulting in greater return of signal to the probe. Fat droplets also attenuate the beam, which decreases penetration into the tissue. These factors result in increased echogenicity of the liver when there is steatosis, especially in the near field, as well as greater

Table 1. Imaging methods for evaluating hepatic steatosis and fibrosis

Modality	Description	Advantages	Limitations
Hepatic steatosis			
Conventional US	Uses sound waves to generate B-mode US images of the liver	• Accessible and cost effective • Non-invasive	• Only provides qualitative assessment • Operator-dependent
Quantitative US	Advanced US technique that quantifies fat content based on quantitative parameters of sound wave propagation	• Allows for quantification • Non-invasive	• May be limited in patients with high BMI • Can be confounded by fibrosis • Operator-dependent
CT	Uses X-rays to create high resolution cross-sectional imaging	• High spatial resolution and ability to detect anatomic abnormalities	• Requires ionizing radiation • Limited in detection of mild steatosis
PDFF	Quantifies liver fat content using confounder-corrected chemical shift imaging	• Highly accurate and reproducible for quantifying steatosis • No radiation	• Cost • Requires a specialized MRI sequence
IP/OP	Detects fat through the differences in fat and water proton frequencies	• Commonly acquired as part of routine MRI protocols • Sensitive to small fat deposits	• Does not correct for confounding effects such as iron overload • Less accurate and precise than PDFF
Hepatic fibrosis			
Vibration-controlled transient elastography	Uses a probe to apply a mechanical pulse and measures how fast a shear wave propagates through the liver	• Cost-effective • Portable • Available in clinic settings	• Lack of anatomic images
Point shear-wave elastography	Uses focused US pulses to measure tissue stiffness at a specific region of interest	• Provides localized mapping	• Operator dependent • Limited to point-based assessments
2D shear-wave elastography	Measures stiffness over a 2D area	• Provides spatial map of stiffness • Can be used in obese patients	• Operator dependent • Cost
2D MRE	Measures propagation of shear waves through hepatic tissue by encoding motion in one direction and allowing analysis in one 2D plane orthogonal to the motion encoding direction	• Less expensive than 3D MRE • Well-established and readily used in clinical practice	• Lower spatial resolution compared to 3D MRE • Prone to technical failure in hepatic iron overload • May not capture subtle regional stiffness variations
3D MRE	Provides 3D analysis of wave propagation	• Superior reproducibility compared to 2D MRE	• Still largely investigational and not readily available in clinical settings

US = ultrasound, BMI = body mass index, PDFF = proton density fat fraction, IP = in-phase, OP = out-of-phase, MRE = MR elastography

blurring/less visualization of deeper structures within the liver (such as the blood vessels) or diaphragm outside the liver (Fig. 3). Certain regions of the liver such as the gallbladder fossa, periportal areas, and near the falciform ligament may harbor focal fat deposition or sparing, likely due to variant vascular in/outflow to these regions. Conventional US can support the diagnosis of SLD when it is suspected clinically based on elevated transaminases and other factors. This modality is also useful in incidentally diagnosing SLD on imaging performed for other indications. However, conventional US is operator and reader dependent and lacks objectivity. Additionally, larger body habitus and overlying adipose tissue may attenuate the beam and confound assessment. Lastly, other chronic liver diseases, such as fibrosis or cirrhosis, may increase parenchymal echogenicity and cause echotexture coarsening, which can confound the interpretation and lead to diagnostic and management errors [10].

Quantitative US

Several quantitative US (QUS) techniques have been developed to provide a more objective estimation of liver fat content. As the speed of sound in soft tissues is slightly greater than that in fat, measuring the liver's speed of sound could serve as a reliable method for assessing hepatic steatosis.

One quantitative measurement is the hepatorenal index (HRI), computing the ratio of liver to kidney echogenicity in arbitrary units [11]. While there is no universal cut-off score, several studies have proposed certain values corresponding to different grades of steatosis. For example, one study demonstrated strong correlation between HRI and percentage of fat ($r = 0.71$), with HRI of 1.28 or greater having a 100% sensitivity for identifying greater than 5% steatosis [11]. The HRI approach has limitations, including the requirement of a normal kidney with sufficient cortical thickness for comparison. Additionally, this technique is subject to user experience and is prone to errors caused by anisotropy, which occurs when a fibrillar structure such as the renal cortex reflects the US beam in different directions [12].

More sophisticated quantitative pulse-echo methods use US radiofrequency data to measure acoustic parameters, such as the attenuation coefficient (AC) and the backscatter coefficient (BSC) (Fig. 4) [13-15]. The AC quantifies acoustic energy loss as US waves travel through a medium at a specific frequency. The AC, or loss of energy, increases as the degree of steatosis increases [16]. The BSC quantifies the degree of US reflection and scattering, i.e., the energy returning to the probe, and provides a quantitative measure of tissue echogenicity. Since fat droplets in hepatocytes scatter the US beam, the BSC increases as the degree of steatosis increase [17]. Although both the AC and the BSC

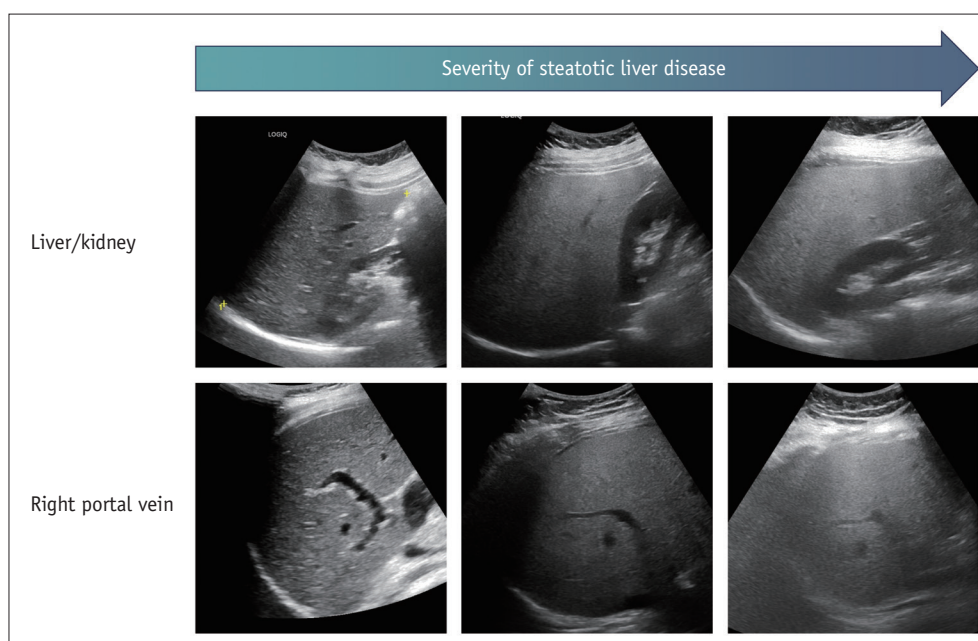


Fig. 3. Three different pediatric patients with varying severity of steatotic liver disease by conventional ultrasound. Note the increasing liver parenchymal echogenicity, blurring of vessels, and increased beam attenuation with increased severity of steatosis.

increase with steatosis, the two parameters are not identical and may provide complementary information. Hence, composite parameters computed by combining multiple QUS parameters have also shown promise [18,19]. For instance, US-derived fat fraction is a composite parameter that combines AC and BSC to estimate fat content as a percentage [19]. In addition, liver fat content can be estimated by applying a deep neural network directly to the US radiofrequency data [20].

QUS is accurate for classifying patients as having or not having steatosis and so is useful for screening and diagnosis. QUS is less accurate for measuring fat content in the high fat range, because the AC and BSC of the liver exhibit a saturation effect, so that further increases in fat content are less perceptible and more difficult to measure. In one study, a saturation effect was noted at a fat fraction of 34% [18].

Quantitative parameters such as AC and BSC have shown good repeatability [21] and inter-sonographer reproducibility [22]. The inter-system reproducibility is good when the same algorithm is used to process the data from different vendors [23], but can be poor when vendor-proprietary algorithms are used [24].

The substantial variability among commercial US vendors in measuring and estimating what should be the same underlying physical property is a barrier to the clinical adoption of these US-based quantitative biomarkers [24]. The source of variability is incompletely understood, but differences between vendors in proprietary acquisition and processing are likely contributory. As QUS computes parameters associated with steatosis but does not measure fat content directly, it can be confounded by other factors,

including assumptions built into the vendor-designed algorithms. Fundamentally, until the vendors adopt a standardized approach, commercial QUS should be used with caution for diagnosis, longitudinal monitoring, or therapeutic response assessment. It may be necessary to use vendor-specific cutoffs for the diagnosis of steatosis and to ensure that follow-up exams are performed on the same system.

Computed Tomography

Like conventional US, CT does not measure liver fat directly but instead measures X-ray attenuation, a parameter related to liver fat content. The attenuation of fat is lower than that of normal liver tissue, thus the liver causes less X-ray attenuation when fat is present in the hepatocytes, and the parenchyma appears more hypoattenuating than usual (Fig. 5). There is no established CT threshold for the diagnosis of steatosis, although 40 Hounsfield units (HU) has been widely used as the threshold for hepatic steatosis or liver HU less than 10 HU compared with the spleen [25,26]. In prior studies, a threshold of 48 HU or below on unenhanced CT provided 57% sensitivity and 88% specificity. For steatosis >25% on liver biopsy, the sensitivity and specificity increased to 72% and 95% respectively [27,28]. The diagnosis of SLD can also be made when liver to spleen attenuation ratio is <0.9:1, with sensitivity and specificity of 79% and 97%, respectively [29,30]. Limitations of this approach include the requirement for a normal spleen and confounding effects of iron overload on hepatic and/or splenic attenuation.

Evaluation of liver fat is more complicated when intravenous contrast is delivered due to differences in liver enhancement based on contrast timing and the interaction

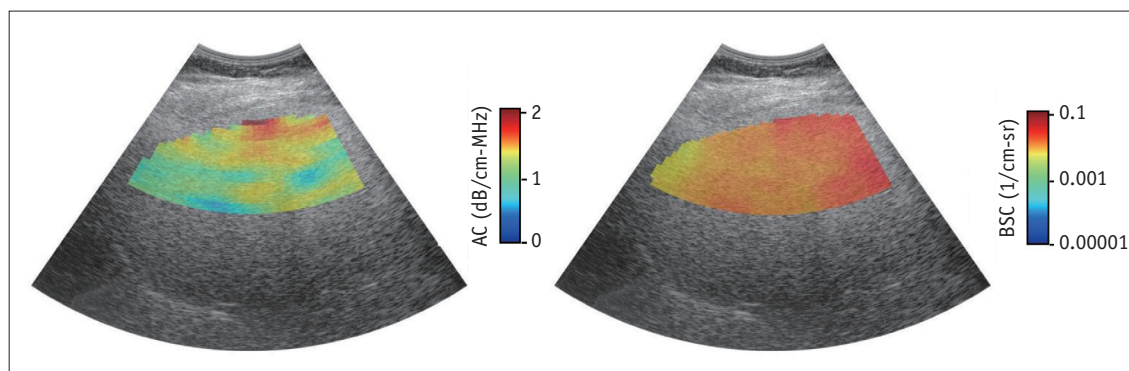


Fig. 4. Steatotic liver disease on qualitative ultrasound. Qualitative ultrasound examination of a 52-year-old woman with biopsy-proven steatotic liver disease demonstrates an elevated AC of 1.15 dB/cm-MHz and a BSC of 0.0042 1/cm-sr. The image was reconstructed using the radiofrequency data acquired from an ultrasound system (Siemens ACUSON S3000; Siemens Healthineers) with a 4C1 (1–4 MHz nominal) transducer. AC = attenuation coefficient, BSC = backscatter coefficient

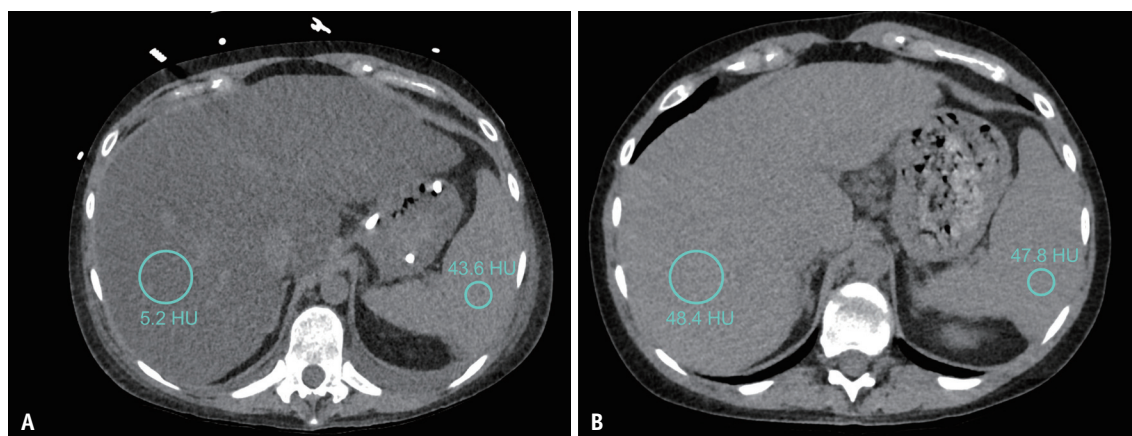


Fig. 5. Steatotic liver disease on non-contrast CT. **A, B:** Axial non-contrast CT images of a 28-year-old woman with alcohol-associated liver disease before **(A)** and after **(B)** 3 months of abstinence. Note that the attenuation of the liver is <40 HU in image **(A)** while it is >40 HU in image **(B)**. HU = Hounsfield units

of contrast with other liver conditions, such as fibrosis. Many researchers have explored whether post-contrast CT can be used to assess liver fat with at least one study showing reasonable performance for detecting moderate steatosis based on post-contrast liver attenuation. In this study, patients with at least moderate steatosis had a mean postcontrast liver attenuation of 67 ± 19 HU ($P < 0.001$); a threshold of <80 HU had 78% sensitivity and 93% specificity while a threshold of <90 HU had 91% sensitivity and 78% specificity [31]. Since the majority of abdominal CTs for a variety of clinical indications are performed with contrast, validation and implementation of post-contrast thresholds may enable earlier detection through incidental detection and opportunistic screening. Dual-energy CT (DECT) has also been explored, particularly in the presence of ionizing contrast, whereby steatosis can be estimated through material decomposition algorithms. Virtual noncontrast imaging has been shown to correlate with liver fat content, with a specificity >90% of hepatic steatosis [32]. Due to ionizing radiation, CT is not recommended for the sole purpose of detecting or monitoring steatosis but can be used for these purposes if CT is acquired for other indications.

Magnetic Resonance Imaging

MRI measures proton signal at specific resonance frequencies, and therefore MRI, unlike CT or US, can directly measure the presence of fat. MRI can acquire spoiled gradient recalled echo images at two or more echo times with appropriate inter-echo spacing to enable fat-water signal separation. As this approach leverages differences

in resonance frequencies between fat and water hydrogens (i.e., chemical shift) to decompose the liver signal into fat and water signal components, it is known as chemical-shift-encoded (CSE)-MRI [33]. CSE-MRI methods have evolved over the years. Earlier methods acquired images at two echoes, one when fat and water were nominally in phase (IP) and the other when they were nominally out of phase (OP). This dual-phase (IP and OP) approach enables qualitative assessment of liver fat content but is prone to quantification error due to the presence of confounders.

By correcting for these confounders, advanced CSE-MRI methods enable computation of the proton density fat fraction (PDFF) [34]. A direct measure of hepatic fat content, PDFF is a highly accurate, reproducible, and robust biomarker for the assessment of SLD across field strengths and different vendors [35-38]. Higher PDFF values indicate more severe steatosis; a cutoff value of 5% in patients without predisposing risk factors has been suggested [39]. In another study by Park et al. [39], using chemical shift imaging-based MRI PDFF data and high-speed T2-corrected multi-echo MR spectroscopy PDFF data, the authors suggested cut offs of 3.5% and 4.0% for ruling-in hepatic steatosis.

Accurate PDFF measurement requires addressing multiple confounding factors, including T1 bias, T2* decay, the multi-peak fat spectral model, noise bias, and eddy currents [33,40]. This requires a specialized sequence with low flip angle to minimize T1 bias and multiple echoes at appropriately spaced echo times to permit simultaneous fat-water signal separation and correction for T2* decay (Fig. 6). This sequence is not available at every institution or may not be run on all imaging protocols. At the authors'

institution, this sequence is part of the diffuse liver disease protocol, but not part of the routine abdomen MRI protocol. protocol [41]. The optimal echo spacing depends on whether the PDFF estimation is based on magnitude or complex data [33,34,42]. The Quantitative Imaging Biomarkers Alliance (QIBA) develops standardized imaging protocols, known as “Profiles,” to enhance the reproducibility and clinical utility of quantitative imaging biomarkers across imaging modalities. There is QIBA PDFF profile which addresses the clinical application of CSE MRI for the use of PDFF as a quantitative biomarker for hepatic fat content, and imaging centers and radiologists are encouraged to adopt the profile for their clinical implementation of PDFF [43].

PDFF strongly correlates with histopathologic findings of hepatic steatosis (i.e., the percentage of cells containing intracellular fat droplets), although it is noted they are not equivalent measures. PDFF is also highly accurate compared to MR spectroscopy, and may be more sensitive [44-46]. In a meta-analysis including 1,679 participants, PDFF was demonstrated to have excellent linearity, bias, and precision, even across different manufacturers and reconstruction methods [47]. This enables PDFF to detect even small longitudinal changes in hepatic fat content, making it an ideal endpoint in clinical trials [48], especially in trials of anti-steatogenic drugs, and suitable

for longitudinal monitoring and therapeutic response assessment in clinical care.

Routinely acquired Dixon-based fat-suppressed imaging in abdominal MR protocols can allow for the computation of fat-signal fraction [49]. However, without correction for various confounders, the fat-signal fraction is less accurate and less reproducible than PDFF. Deep learning (DL) has shown promise in inferring PDFF from conventional in-phase and out-of-phase images (Fig. 7) [50] without the acquisition of a dedicated sequence, which could facilitate opportunistic screening for SLD on MR exams that were performed for other clinical indications.

ASSESSMENT OF HEPATIC FIBROSIS

Liver fibrosis results from chronic liver injury and is characterized by the accumulation of extracellular matrix proteins, predominantly collagen. In MASLD, these are deposited initially in the pericellular spaces. As fibrosis progresses, it extends to the central veins and portal tracts, eventually leading to bridging, nodule formation, architectural distortion and impaired liver function. Multiple histologic scoring systems exist and include the Knodell score/Histological Activity Index and the Kleiner score. The Kleiner score ranges from 0 to 4, with 0 indicating no

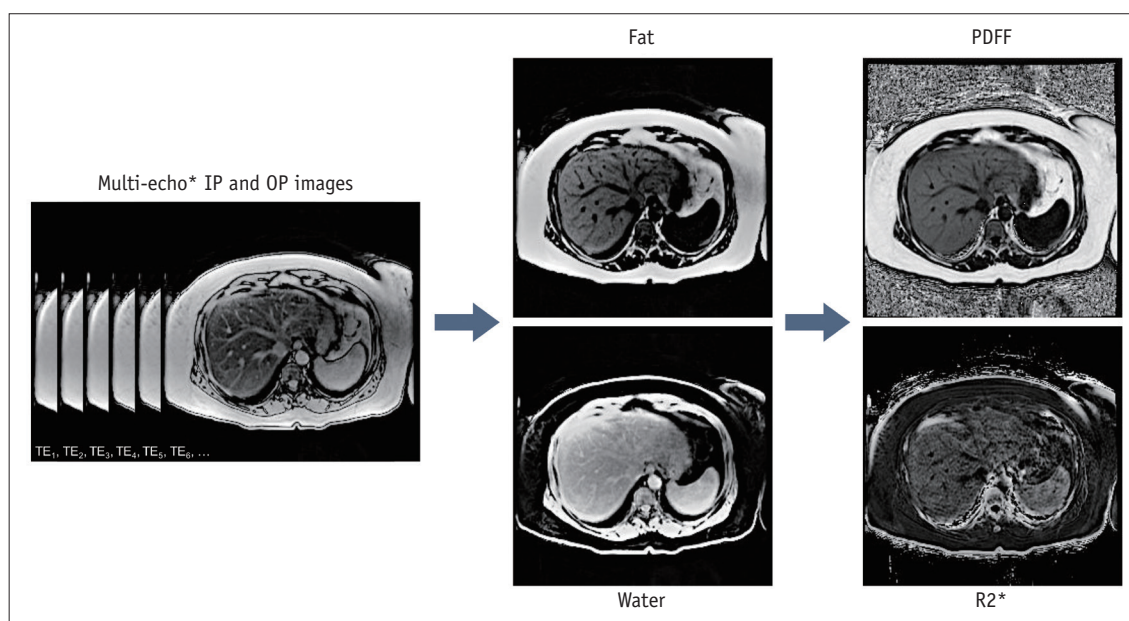


Fig. 6. Steatotic liver disease on MRI-PDFF. Axial non-contrast MRI of a 48-year-old woman with biopsy-proven steatotic liver disease. Multi-echo MRI is utilized to decompose the liver signal into fat and water signal components, which are utilized to compute the PDFF. *At echo times suitable for chemical-shift-based fat-water signal separation. PDFF = proton density fat fraction, IP = in-phase, OP = out-of-phase

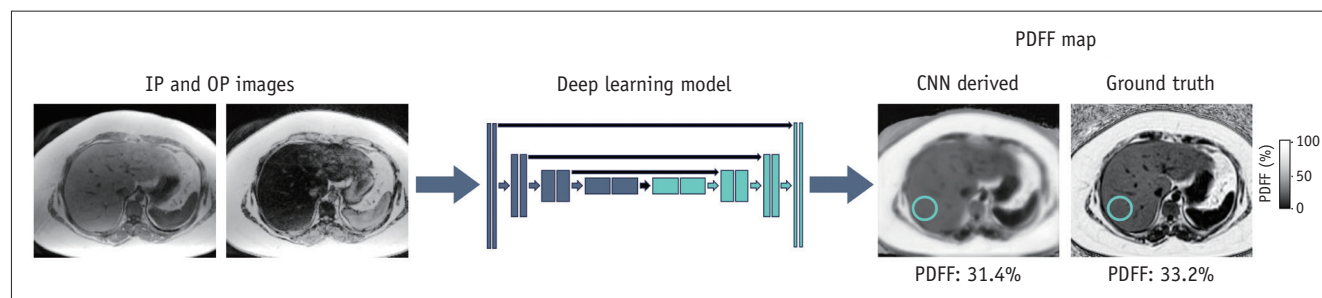


Fig. 7. Artificial intelligence-derived PDFF measurement from conventional IP and OP MR images. PDFF = proton density fat fraction, IP = in-phase, OP = out-of-phase, CNN = convolutional neural network

fibrosis and 4 indicating cirrhosis [5].

Importantly, the assessment of liver fibrosis is commonly carried out through non-invasive imaging methods, such as elastography, which measures liver stiffness as a proxy for fibrosis (Table 1). Of note, while stiffness is related to liver fibrosis, but it is not a direct measure of fibrosis.

US Elastography

US elastography assesses liver stiffness by applying or inducing transient shear waves that propagate through tissues. These shear waves are detected using US, and their speed is estimated. Under simplifying assumptions, the speed of the shear waves can be converted into an estimated stiffness. Three commonly used methods include vibration-controlled transient elastography (VCTE), point shear-wave elastography (pSWE), and two dimensional SWE (2D-SWE) [51-53]. VCTE employs a mechanical external vibration at a fixed, controlled frequency, whereas pSWE and 2D-SWE generate shear waves using an acoustic radiation force impulse, resulting in a frequency that is not externally controlled and varies with tissue response. All US-based methods measure transient shear waves, which reduce interference from longitudinal waves but lower the signal-to-noise ratio (SNR) and necessitate multiple independent acquisitions; stiffness is reported either as Young's modulus (kPa) or as shear wave speed (m/s), reflecting historical conventions in US imaging.

The major advantages of US elastography are portability and relatively low cost [54]. US elastography is suitable for detecting significant or advanced liver fibrosis due to its noninvasive nature and quick execution. Emerging data suggest that US elastography may be useful for assessing disease progression or regression in response to treatment. However, its accuracy and reliability can be impacted by factors such as acute inflammation, meal intake, and cholestasis [55]. Another major challenge is the high rates

of technical failure in patients with obesity, a key risk factor for SLD [56]. Additionally, accuracy is dependent on operator experience and there is only moderate concordance between vendors [54,57]. To improve standardization, the Society of Radiologists in Ultrasound published a consensus statement on interpreting these measurements and the probability of compensated advanced liver disease for given stiffness values [58], with additional guidance by the World Federation of Ultrasound in Medicine and Biology [16].

pSWE focuses on a spherical compression wave on a spot, creating perpendicular shear waves, and shear-wave displacement is recorded using tracking pulses. Unlike VCTE, this approach permits selection of a region-of-interest (ROI) under direct visualization. In comparison, 2D-SWE uses ultrafast imaging to track shear-wave displacement across a 2D field of interest, which enables generation of quantitative elastograms and placement of multiple ROIs in the field of interest. US elastography has been reported to have a 85% sensitivity and 79% specificity for detection of significant fibrosis ($F \geq 2$), and 90% sensitivity and 85% specificity for detection of advanced fibrosis ($F \geq 3$) [59]. pSWE has better different-day, different-operator reproducibility coefficient for measuring shear wave speed (31%) than VCTE (36%) (Fig. 8) [54]. QIBA also has a profile for appropriate pSWE and 2D-SWE technique and reporting [60]; imaging centers and radiologists are encouraged to adopt the profile for their clinical implementation of these methods.

VCTE is cost-effective, portable, and well-suited for point-of-care usage in specialized clinics [61]. This modality remains the most commonly used method in clinical practice [62]. Its main technical drawback is the lack of anatomic images, which makes it difficult to ensure that the measurement location is consistent across time points. In one study, the different-day, different-operator reproducibility coefficient of VCTE when measuring shear

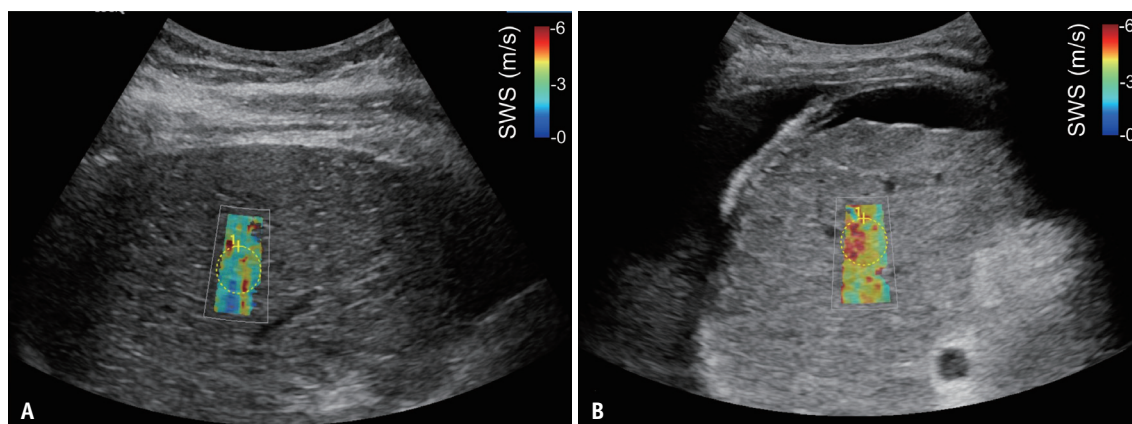


Fig. 8. Hepatic fibrosis on ultrasound elastography. Ultrasound elastography examination in two patients with varying degrees of hepatic fibrosis. **A:** A 67-year-old man with a history of alcohol-associated cirrhosis with a SWS value of 1.93 m/s (4.5 MHz frequency, C1-6 probe, GE LOGIQ E10 system). **B:** A 57-year-old woman with a history of decompensated cirrhosis with a SWS value of 2.8m/s (4.5 MHz frequency, C1-6 probe, GE LOGIQ E10 system). SWS = shear wave stress

wave speed in m/s was 36% [54], suggesting that serial changes in shear wave speed as large as 36% relative to baseline might reflect measurement variability rather than true change. Another important drawback is that, while it is available in the ambulatory hepatology setting, it is not typically available in the community or primary care setting, and thus accessibility issues remain.

MR Elastography

MR elastography (MRE) uses a driver to generate continuous oscillatory mechanical waves in the patient while acquiring a phase-contrast multiphase sequence with motion-encoding gradients [51]. Like US elastography, MRE is noninvasive and avoids ionizing radiation. Compared to US elastography, MRE holds several advantages, including substantially greater liver coverage and better agreement between vendors. MRE is accurate [63], and has better repeatability than US-based methods with a meta-analytic repeatability coefficient of 20% [64,65]. One pooled analysis demonstrated that MRE can accurately detect fibrosis across all stages, independent of body mass index [66]. A range of cutoff values has been proposed, spanning from 2.4 to 2.93 kPa in the literature, likely dependent on various risk factors and etiology of liver disease [67].

MRE can be performed as a 2D gradient-recalled echo-based sequence or a 2D spin-echo-based echo-planar imaging sequence [53]. The protocol also includes T1 and T2 weighted sequences for anatomic localization and evaluation. Post-contrast evaluation can also be included for evaluation of liver lesions. The SE-EPI is less susceptible to technical failure in cases of hepatic iron overload due to

its decreased sensitivity to T2* relaxation. The raw images are post-processed to generate wave images, elastograms, and confidence maps (Fig. 9). In MRE, liver stiffness is quantified as the magnitude of the complex shear modulus.

Another emerging technique, while still investigational, is 3D MRE. 3D MRE enhances traditional MRE by providing 3D analysis of wave propagation to enable a more comprehensive and accurate estimate of liver stiffness considering increased tissue heterogeneity with disease progression [68]. While 2D MRE encodes motion in one direction (z) and allows for analysis of wave motion in one 2D plane orthogonal to the motion encoding direction (x, y), 3D MRE encodes motion in three directions (x, y, z) and allows for analysis of wave motion in a 3D volume. The major advantage of 3D MRE compared to 2D MRE is superior repeatability: 3D MRE has an estimated repeatability coefficient of 11% [69-71], better than that of 2D MRE (20%) [69-71]. 3D MRE and 2D MRE are comparable in terms of discriminating $\geq F1$, $\geq F2$, $\geq F3$, and F4 fibrosis [72]. Hence, while 2D and 3D MRE have similar diagnostic performance, 3D MRE is likely to be superior for longitudinal monitoring. 3D MRE also permits assessment of viscoelastic parameters beyond stiffness, including the loss modulus, which has been proposed as a marker of inflammation as mentioned briefly below.

The use of MRE to assess hepatic fibrosis can be confounded by factors such as inflammation, cholestasis, postprandial state, and hepatic venous congestion [51]. Notably, MRE is not affected by hepatic steatosis [73,74]. The Society of Abdominal Radiology and QIBA have provided guidance on how to acquire, interpret and report MRE [75,76]. While MRE is accurate and reproducible, it

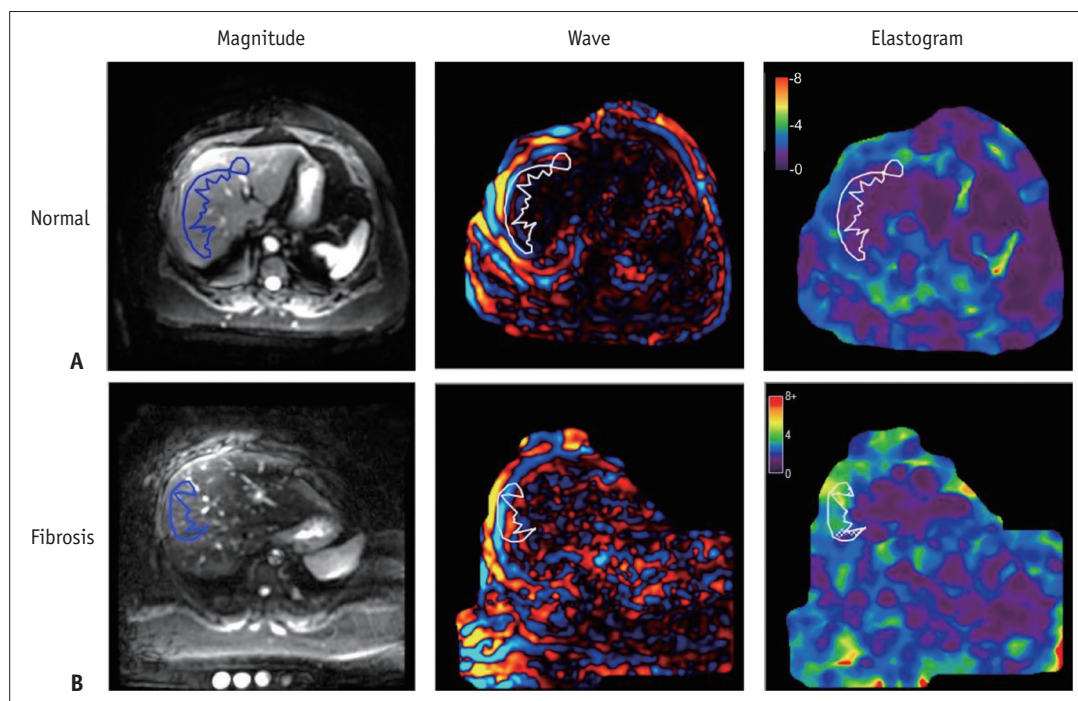


Fig. 9. Hepatic fibrosis on MRE. MRE examination in two patients with varying degrees of hepatic fibrosis. **A:** A 65-year-old woman with a liver biopsy-negative for fibrosis with a stiffness value of 1.54 kPa. **B:** A 49-year-old man with biopsy-proven hepatic fibrosis (stage F2) with a stiffness value of 4.04 kPa. MRE = MR elastography

requires specialized MRI hardware and software that is not always available or acquired. Although MRE takes more time to acquire and costs more upfront, one study suggested that the higher performance of MRE may make it more cost-effective overall for the evaluation of advanced fibrosis [77]. Additionally, MRE is limited to patients who can undergo MRI, and those with implantable devices such as neurostimulation systems, plants, and drug infusion pumps may be ineligible.

EMERGING DIRECTIONS

Emerging directions for noninvasive biometric imaging of MASLD focus on enhancing the accuracy of imaging biomarkers for individual components of MASH—namely, fat, fibrosis and inflammation while also accurately staging the disease as a whole and identifying patients at the highest risk for complication/morbidity and progression.

Corrected T1 (cT1) is an imaging technique that can be used as a noninvasive biomarker for hepatic fibrosis and inflammation and identifying patients with at-risk MASLD [78]. Iron overload can cause technical failure of MRE techniques due to signal loss from susceptibility [79,80]. cT1 accounts for the degree of iron deposition and holds

promise for assessing liver inflammation, a key factor in the progression of liver diseases, and a differentiator between steatosis and steatohepatitis [81]. MRE may also play a role in assessing steatohepatitis, as inflammation can increase interstitial fluid volume and increase the estimated loss modulus, which can be estimated using 3D MRE [82,83].

Multiparametric imaging assessment further allows for the assessment of inflammation and fibrosis, and may be helpful in patients with mixed etiologies, specifically steatohepatitis. One recent study demonstrated multiparametric US method combining attenuation values and laboratory values demonstrated good discrimination values in predicting steatohepatitis in patients with MASLD [84]. Multiparametric MR, which can include mapping of T1 and T2* and spectroscopy, is also sensitive and accurate in quantifying both the inflammatory components and fibrotic components of MASLD in histological comparison [85].

DL has emerged as a promising tool for expanding the capability of MRI for the diagnosis of MASLD, with the potential to automatically detect, quantify, and characterize fat content and fibrosis on an imaging and histological level, as well as aiding in predictive modeling and risk stratification. Guo et al. [86] recently proposed an US-based model that reached an accuracy of about 91%

in classifying normal, mild, moderate, and severe fatty liver. Another machine learning model has been shown to predict liver stiffness on a binary classification (clinically significant, defined as $F \geq 2$) based on reconstructing virtual MRE from conventional MRI with a sensitivity of 80%, specificity of 75%, and accuracy of 78% [87]. As DL becomes more efficient at generating virtual elastography images from conventional MRI and clinical data, this may enable opportunistic screening approaches. The use of DL would enable clinicians to identify early-stage liver disease without additional invasive procedures or dedicated imaging, making it both cost-effective and accessible to larger populations. Machine learning also has the potential to automate workflows to enhance efficiency and reduce operator dependence, particularly in tasks such as ROI placement during image analysis.

FURTHER CONSIDERATIONS AND CONCLUSIONS

The growing prevalence of MASLD underscores the need for accurate, accessible, and non-invasive diagnostic tools for detecting and monitoring liver steatosis and fibrosis. As imaging continues to play a larger role in the diagnosis, longitudinal follow-up, and management of MASLD, radiologists must play an active role in advancing solutions to these challenges.

It is estimated that the vast majority of patients are unaware of their diagnosis of MASLD, and symptoms may only present after progression to advanced liver disease [88]. Several medications show potential to reverse fibrosis, which further emphasizes the importance of early detection of MASLD [89-91]. Resmetirom, the only currently FDA-approved agent shown to improve MASLD-related liver fibrosis by at least one stage, is costly and given the prevalence of MASLD, accurate patient selection is crucial at the healthcare system level [92]. Opportunistic screening is an emerging approach to improving awareness and early diagnosis of MASLD through incidental detection, especially when combined with machine learning techniques. Additionally, the development of imaging guidelines and standardized reporting could enhance the consistency of management recommendations and improve clinical decision-making. Lack of current guidance on how to synthesize diagnostic tests in clinically meaningful ways and lack of standardized reporting guidelines offers a potential space for radiologists contribute meaningfully [93,94]. By actively contributing our expertise in imaging

to the creation of clinical guidelines, radiologists can help ensure that diagnostic practices are not only accurate and reproducible but also cost-effective and accessible to patients to improve the early detection and management of MASLD.

Conflicts of Interest

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