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Review

A to Z of Imaging Modalities for the Diagnosis and Quantification of Hepatic Steatosis

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Abstract

Steatotic liver disease (SLD), marked by triglyceride accumulation in over 5% of hepatocytes, affects around a quarter of the global population. A key subtype, Metabolic dysfunction-associated steatotic liver disease (MASLD), is closely associated with obesity, type 2 diabetes, and metabolic syndrome, with rising prevalence worldwide. MASLD can lead to severe hepatic complications such as cirrhosis, liver failure, and hepatocellular carcinoma if left untreated. While liver biopsy remains the diagnostic gold standard for assessing hepatic steatosis, its invasive nature and sampling variability underscore the need for reliable non-invasive alternatives. Advances in imaging have enabled the development of modalities such as ultrasonography (US), computed tomography, and magnetic resonance imaging (MRI) for non-invasive steatosis assessment. Conventional US, though widely used, is limited by observer dependency and poor sensitivity for detecting mild steatosis. Quantitative US techniques, particularly attenuation coefficient-based algorithms, have shown improved diagnostic accuracy. The controlled attenuation parameter, often used with transient elastography, offers quick and cost-effective assessment, albeit with reduced sensitivity in obese individuals and limited grading accuracy. CT enables steatosis evaluation via liver attenuation values and liver-spleen attenuation ratios. Dual-energy CT enhances tissue differentiation and correlates moderately well with magnetic resonance imaging proton density fat fraction (MRI-PDFF) and histopathology but is constrained by radiation exposure and limited sensitivity for mild steatosis. MRI techniques—especially PDFF-based imaging—provide superior accuracy and reproducibility in liver fat quantification. PDFF allows for non-invasive, radiation-free measurement across the full steatosis spectrum, with established diagnostic thresholds. Additionally, MR spectroscopy offers the most precise quantification but remains primarily research-based due to logistical constraints. In summary, non-invasive imaging modalities, particularly MRI-PDFF, are increasingly favored for diagnosing and monitoring hepatic steatosis. Future research should focus on optimizing and standardizing these techniques to enhance clinical integration and management of SLD.

Keywords: Steatosis, Liver, Ultrasonography, Computed tomography, Magnetic resonance imaging

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Steatotic liver disease, which is characterised by the accumulation of >5% triglycerides in hepatocytes, is a common liver disease affecting approximately 25% of the world's population.[1] This condition encompasses a wide range of conditions, from simple fatty liver disease (metabolic dysfunction-associated steatotic liver disease, MASLD) to alcoholic, drug-induced and monogenic disease-related hepatic steatosis and steatohepatitis, the latter of which is characterised by more severe inflammation and hepatocyte damage.[2] MASLD is strongly associated with obesity, type 2 diabetes and metabolic syndrome, and its prevalence is increasing worldwide.[3] If left untreated, MASLD can lead to serious liver-related complications such as cirrhosis, liver failure and hepatocellular carcinoma. Cirrhosis due to MASLD is

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the second most common reason for liver transplantation after hepatitis.[4] Therefore, early diagnosis and accurate quantification of hepatic steatosis are critical to preventing disease progression and determining appropriate treatment strategies.

A liver biopsy has long been considered the gold standard for diagnosing and grading hepatic steatosis. Histologically, the percentage of fat in hepatocytes is categorised as follows: <5% (normal); 5%–33% (mild); 34%–66% (moderate); and >66% (severe).[5] However, a biopsy is an invasive procedure with significant disadvantages, including sampling error, variability in interpretation, cost and morbidity.[6] Furthermore, the infrequent need for repeat biopsies to monitor treatment responses has increased the demand for non-invasive methods. In recent years, advances in imaging technologies have enabled the development of various methods for non-invasively detecting and quantifying hepatic steatosis. Table 1 summarizes the diagnostic features of hepatic steatosis across imaging modalities. This review aims to provide a comprehensive examination of the major imaging modalities used in the diagnosis and quantification of hepatic steatosis: ultrasound, computed tomography and magnetic resonance imaging. It discusses their respective advantages and limitations, as well as their clinical applications. It also discusses recent developments and future trends in this field.

Ultrasonography

Ultrasonography (US) is generally the primary imaging technique used to evaluate hepatic steatosis.[7] It is widely used because it is non-invasive, widely available and capable of real-time imaging, as well as being relatively low cost. Liver steatosis is graded on US based on liver echogenicity compared to surrounding organs (such as the kidneys or diaphragm) and the visibility of vascular structures. Mild (Grade 1): There is a slight increase in liver echogenicity and the vascular structures and diaphragm are still clearly visible. Moderate (Grade 2): A marked increase in liver echogenicity and slight obscuration of vascular structures and the diaphragm. Severe (Grade 3): A very marked increase in liver echogenicity; the vascular structures and diaphragm are barely or completely obscured.[8] Ultrasound (US) is effective in detecting moderate to severe fatty infiltration and may be suitable as a screening method for abnormal liver morphology.[9] However, conventional ultrasound has some limitations. These include a lack of interobserver and intraobserver reliability and reproducibility, subjective and operator-dependent inter-

Table 1. Comparison of imaging modalities for the detection and quantification of hepatic steatosis.[38,40-44]

Modality	Sub-techniques	Steatosis Threshold	Sensitivity (%)	Specificity (%)	Advantages	Limitations	Clinical Use
Conventional Ultrasound (B-mode US)	- B-mode - Echogenicity grading	Moderate–severe (≥30%). Mild (≥5%)	84–94 50–65	85–95 60–85	Widely available, inexpensive, bedside tool	Operator-dependent, limited accuracy in mild steatosis and obesity	First-line screening tool
Quantitative Ultrasound	-Attenuation coefficient based -Elastography	Mild (≥5%) Moderate–severe (≥15–30%)	80–90 92–97	80–92 85–95	Objective, quantifiable, improved reproducibility, simultaneous fibrosis evaluation	Requires compatible equipment and trained personnel	Diagnosis, staging, treatment monitoring
Controlled Attenuation Parameter (CAP)	-CAP via FibroScan -Elastography	Mild steatosis (≥5%)	70–89	80–95	Quantitative, rapid, simultaneous fibrosis evaluation	Decreased accuracy in obese or ascitic patients, limited spatial resolution	Screening, diagnosis, and longitudinal follow-up
Computed Tomography (CT)	- Non-contrast CT - Dual-energy CT	Moderate–severe (≥30%)	43–77	88–100	Rapid, objective attenuation (HU) measurement, often incidental	Ionizing radiation, poor sensitivity for mild steatosis	Opportunistic diagnosis during unrelated imaging
Magnetic Resonance Imaging (MRI)	- In-phase/Out-of-phase (Chemical shift) - PDFF (Proton Density Fat Fraction) - MR Spectroscopy (MRS) -MR Elastography	Mild (≥5%), All stages	PDFF: 90–98 MRS: 95–99	PDFF: 90–95 MRS: 90–98	Gold standard for noninvasive fat quantification; excellent for both steatosis and fibrosis assessment	High cost, limited availability, MRS requires expertise	Diagnostic reference standard, research and follow-up

pretation, low accuracy in detecting mild hepatic steatosis and an inability to quantify liver fat.[10]

Recently developed quantitative ultrasound-based imaging techniques show significant promise in transforming the qualitative assessment of hepatic steatosis with conventional ultrasound into objective, quantitative measurements.[11] This new technology is based on the premise that fatty liver disease may accelerate US energy loss, which is associated with increased sound attenuation. Among the various commercially available algorithms, attenuation coefficient (AC) algorithms are the most widely used.[12] This method has yielded good to excellent results in the detection and grading of hepatic steatosis.[13] Additionally, it can be used in conjunction with elastography to simultaneously assess fibrosis. In addition to having similar advantages to traditional US, they are less operator-dependent.[14] Nevertheless, the variability observed across different imaging platforms necessitates the use of vendor-specific cutoff thresholds for accurate fat quantification, which are still under refinement and standardization. Figures 1 shows examples of conventional grey-scale and quantitative US.

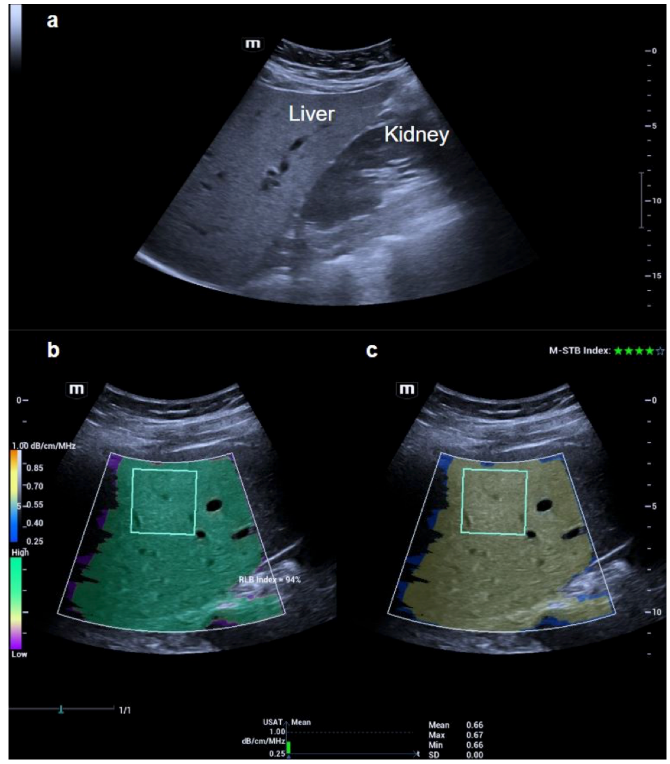

Figure 1. Conventional grayscale ultrasonography **(a)**, increased hepatic echogenicity relative to the renal cortex is observed. Despite this elevation, vascular structures within the liver and the posterior diaphragm remain clearly visualized, which is characteristic of Grade I hepatic steatosis. In quantitative ultrasonography, a reliability map is displayed alongside the B-mode image to evaluate the accuracy of measurements **(b)**. Green areas indicate regions where data was acquired optimally. An attenuation index is also displayed, with values exceeding 90% reliability being recommended for diagnostic confidence. Measurements are taken from the hepatic parenchyma using a region of interest measuring around 3 cm. In this case, the observed mean attenuation value of 0.66 dB/cm/MHz is consistent with Grade I hepatic steatosis **(c)**.

Controlled Attenuation Parameter

The Controlled Attenuation Parameter (CAP) is a widely used method for the rapid, non-invasive assessment of fatty liver that is also cost-effective. It can be used alongside transient elastography to measure fibrosis simultaneously.[15] CAP cut-off values vary between studies, with initial values between 219 and 248 dB/m generally indicating mild steatosis (S1).[16] However, its accuracy may be reduced in obese individuals. Furthermore, CAP is less sensitive than quantitative ultrasound (US) and magnetic resonance imaging (MRI) in detecting and classifying hepatic steatosis. Although current guidelines still recommend CAP, AC-based ultrasound and MRI-PDFF are increasingly favoured for diagnosing steatosis.[11]

Computed Tomography

The diagnosis of hepatic steatosis using computed tomography (CT) is based on the X-ray absorption properties of liver parenchyma. Fat has a lower density than water or tissue, and therefore appears less dense (in Hounsfield units, or HU) on CT images.[17] There are two main methods of estimating hepatic steatosis using CT: measuring liver attenuation alone, or comparing liver attenuation with spleen attenuation.[18] The attenuation of a healthy liver is generally 8–10 HU higher than that of the spleen, at around 50–57 HU. A liver HU value below 40 has been reported to indicate 30% steatosis. A liver-to-spleen HU ratio below 1.0 is another method of suggesting steatosis.[19,20] Figure 2a presents an example of a CT liver steatosis measurement. The linear relationship between HU units on CT and PDFF enables CT-based liver fat content to be expressed as the PDFF equivalent [PDFF(%) = -0.58 x (CT HU) + 38.2].[21] Dual-energy computed tomography (DECT) enables hepatic fat to be quantified by acquiring images at two different energy levels (typically 80 and 140 kVp), allowing tissue components to be distinguished based on their atomic number.[22] In cases of hepatic steatosis, DECT enhances fat detection by amplifying the contrast between lipid-rich and lipid-poor tissues, offering superior sensitivity compared to conventional single-energy CT.[23] Recent studies have found that DECT-derived fat quantification correlates moderately well with MRI-PDFF and histopathology.[24,25]

The main advantages of CT scanning are its widespread availability, short acquisition time and ability to rapidly assess the entire abdomen. CT has made one-stop assessment possible, integrating vascular, parenchymal, volume and steatosis assessment, particularly in the evaluation of liver transplant donors.[17] However, CT has several significant disadvantages when it comes to detecting fatty liver. The most notable of these is the use of ionising radiation, which is particularly concerning in the case of repeated scans or when scanning young patients. Furthermore, CT is less sensitive than more advanced methods (e.g. MRI-PDFF) for detecting mild steatosis; it may miss cases where the liver fat content is below 10–20%. HU values can also be affected by factors such as hepatic iron deposition, glycogen storage diseases or recent contrast medium administration, which makes it difficult to accurately quantify the amount of steatosis.[18]

Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is considered a superior method to ultrasonography and computed tomography (CT) for comprehensively assessing hepatic steatosis.[26,27] The ability of MRI to detect and quantify liver fat is based on the difference in resonance frequencies between hydrogen protons bound to water and triglycerides — a phenomenon known as the chemical shift effect. Some MRI techniques can calculate this frequency difference, which can also be directly observed in the spectrum with MR spectroscopy. Thus, the amount of liver fat can be reliably assessed.[28] The fact that MRI provides detailed data without the need for contrast material enables it to be used safely in children and patients with renal failure.[29] Furthermore, MRI elastography can provide a simultaneous assessment of fibrosis.

Chemical shift imaging (in-phase/opposed-phase MRI) is

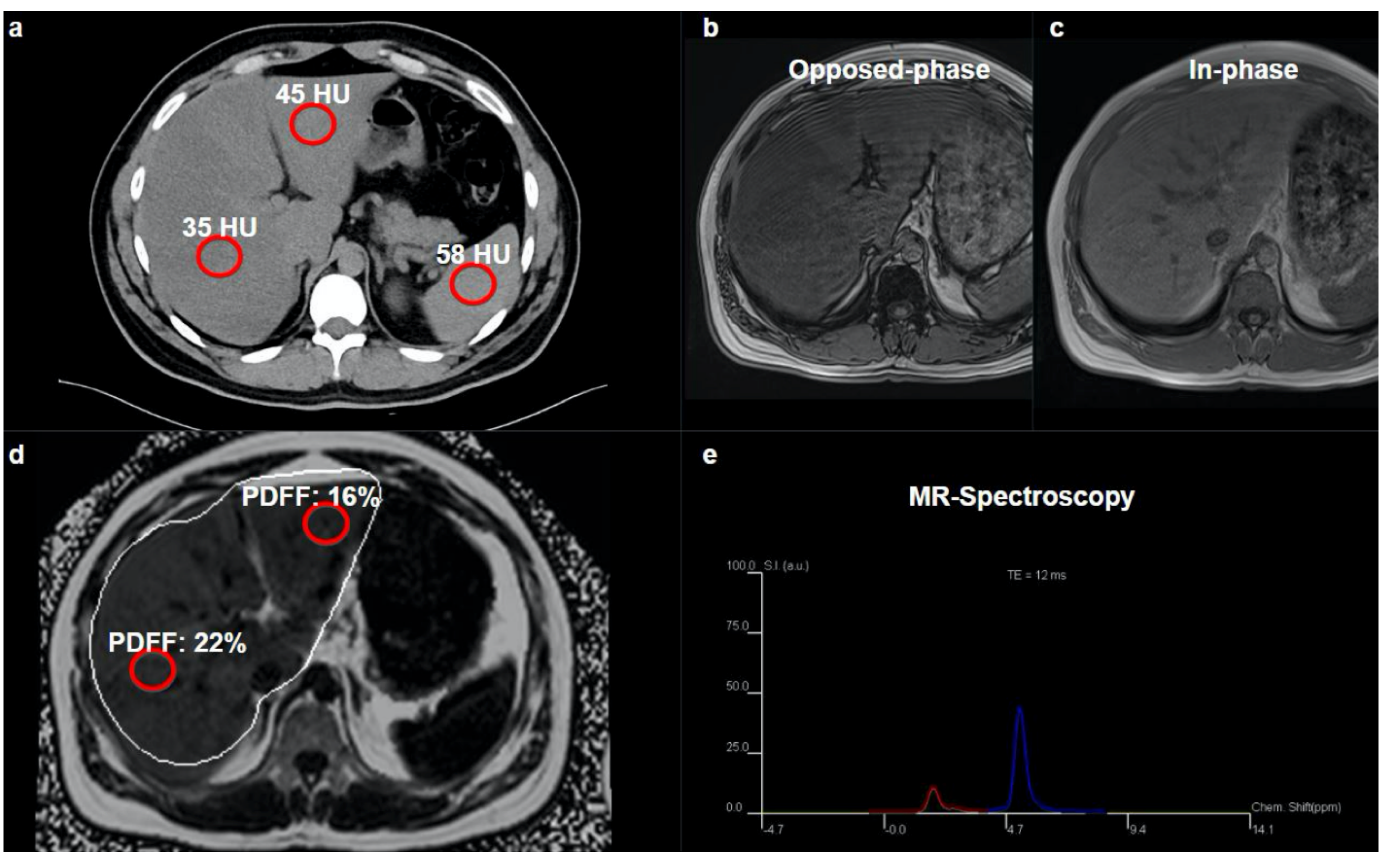

Figure 2. In a 42-year-old male living liver donor candidate, non-contrast computed tomography **(a)** demonstrates hepatic and splenic attenuation values, with lower Hounsfield Unit (HU) measurements in the liver compared to the spleen. Steatosis appears more pronounced in the right hepatic lobe. On magnetic resonance imaging, the opposed-phase images show a marked signal drop compared to in-phase sequences, supporting the visual, qualitative diagnosis of hepatic steatosis. On MRI-PDFF **(d)** images, quantitative fat fraction measurements are displayed for both hepatic lobes using regions of interest, revealing objective fat quantification. Additionally, magnetic resonance spectroscopy **(e)** demonstrates two prominent spectral peaks at 4.7 ppm (water) and 1.3 ppm (fat). The ratio of the signal intensities of the fat peaks to the sum of the fat and water peaks is used to calculate liver fat content. Based on the quantitative assessment, severe steatosis is identified in the right lobe, while the left lobe shows moderate steatosis.

based on the different resonance frequencies of hydrogen protons in water and fat molecules.[30] By using in-phase (IP, water + fat) and opposed-phase (OP, water – fat) sequences, it is possible to observe the tendency for signals from fat and water protons to either sum up or cancel each other out.[31] When there is little or no fat in the liver parenchyma, the signal intensity on in-phase and out-of-phase images is similar. However, when fat accumulates in the liver, the signal intensity decreases on out-of-phase images; this decrease is proportional to the degree of steatosis. A fat signal fraction image can be generated by combining IP and OP images (IP-OP/2IP).[32] Chemical shift imaging is widely used for the qualitative detection of macrovesicular steatosis, and its radiation-free nature and relatively short acquisition time make it valuable in clinical practice.[33] Figure 2b-c present an example of a IP/OP liver steatosis measurement.

Proton density fat fraction (PDFF), as measured by MRI, provides a quantitative and verifiable measure of liver steatosis and is considered the non-invasive gold standard due to its high correlation with histological fat content.[34] PDFF is obtained using multi-echo gradient echo (GRE) sequences. These sequences capture signals from fat and water at different echo times (TE) and use mathematical models to calculate the percentage fat fraction in the liver. Cut-off values for MRI PDFF liver steatosis grades are <6% for normal (S0), 6–17% for mild (S1), 17–22% for moderate (S2), and >22% for severe (S3) steatosis.[35] PDFF measurements provide high accuracy and reproducibility in fat quantification by correcting for the influence of other biological factors, such as iron accumulation, on the signal (T2* correction). This feature offers a significant advantage in the detection of mild steatosis and sensitive monitoring of treatment response, playing an increasingly important role in clinical research and individualised patient management.[36] Figure 2d presents an example of a MRI-PDFF liver steatosis measurement.

Magnetic resonance spectroscopy (MRS) is an MRI technique that provides highly accurate quantitative measurements of liver steatosis, but it is primarily used for research purposes in clinical practice.[37] By analysing the frequency spectrum of signals from a specific volume (voxel), MRS can quantify individual fat and water protons. This method provides an absolute percentage of fat content with a high level of accuracy and is more resistant to artefacts than other imaging technique.[38] However, MRS has several practical limitations, including long acquisition times, relatively small sample sizes and more complex data processing requirements. Due to these limitations, MRS is generally used as a reference tool for scientific studies and the validation of new imaging methods, rather than in clinical practice.[39] Figure 2e presents an example of a MRS liver steatosis measurement.

Conclusion

Hepatic steatosis is a growing global health problem that requires accurate, non-invasive diagnostic tools for early detection and monitoring. Although liver biopsy remains the reference standard, its invasiveness limits its widespread use. However, advances in imaging modalities, particularly quantitative AC-based US and MRI-PDFF techniques, have significantly improved the noninvasive assessment of liver fat content. MRI techniques offer the highest diagnostic accuracy among imaging modalities and are becoming increasingly important in clinical management. Future research should focus on optimising these methods for broader clinical integration and standardization.

Disclosures

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