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Elastography in the evaluation of liver allograft

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Abstract

Elastography is an established technique in the evaluation of chronic liver diseases. While there is a large clinical experience and data available regarding the performance of elastography in native liver, elastography experience with liver grafts is limited and still growing. Both ultrasound-based elastography techniques and MR Elastography (MRE) are useful in the assessment of liver fibrosis in liver transplants. Technical modifications for performing elastography will be required for optimum evaluation of the graft. In general, caution needs to be exercised regarding the use of elastography immediately following transplantation as post-operative changes, perioperative conditions/complications, inflammation, and rejection can cause increased stiffness in the graft. In the follow-up, detection of increased stiffness with elastography is useful for predicting development of fibrosis in the graft. Adjunctive MRI or ultrasound with Doppler also provides comprehensive evaluation of anatomy, vascular anastomosis and patency, biliary tree, and stiffness for fibrosis. In this review, we provide a brief overview of elastography techniques available followed by the literature review of elastography in the evaluation of grafts and illustration with clinical examples.

Keywords

Liver grafts; Liver transplants; Magnetic resonance elastography; Shear wave elastography; Transient elastography

Introduction

Elastography is a non-invasive method to evaluate tissue stiffness by assessing the elastic properties of the tissue and can be used as an adjunct to ultrasonographic and magnetic resonance imaging. In order to study mechanical properties of tissues, a stimulus (stress) needs to be applied either externally or internally and the deformation (strain) in the tissue is measured. The compression force can be applied either in quasi-static or dynamic fashion and the resultant strain is measured. Quasi-static strain imaging has very limited application for liver as it's difficult to control the stress on liver. Most clinically useful elastography techniques use dynamic shear wave imaging. Two main mechanical waves propagate within internal organs during dynamic compressions: compression waves, which induce tissue displacement parallel to the direction of wave propagation; and shear waves, which create

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tissue motion perpendicular to the direction of wave propagation. The velocity of shear waves in tissue is several orders of magnitude slower than that observed with compression waves (approximately 1–10 m/s compared to 1500 m/s). Ultrasound-based elastography techniques quantify stiffness by measuring the speed of propagation of shear waves [1]. Shear wave speed can be directly reported (m/s) or converted into Young's modulus ($E = 3\rho V^2$, where E is Young's modulus, ρ is tissue density, and V is velocity) to provide stiffness measurement in kilopascals (kPa). MR Elastography (MRE) measures magnitude of the complex shear modulus (shear stiffness) and is different from Young's modulus, but are related [Young's modulus (E) = $3 \times$ shear modulus (μ)]. It's important to understand that the relationship $E = 3\mu$ is applicable only when performed with same shear wave frequency. Currently, the vibration-controlled transient elastography (VCTE) is performed at 50 Hz, whereas liver MRE is performed at 60 Hz, therefore, the shear stiffness measured at VCTE will not be exactly 3 times the shear stiffness measured with MRE. This may also be applied to acoustic radiation force impulse (ARFI) which utilizes a frequency of 100–500 Hz.

The factors that determine tissue stiffness are not completely understood. It is believed to be a result of an array of factors, including extracellular matrix, interstitial pressure, blood flow, and underlying tissue architecture [2]. The dominant determinant is the extracellular matrix composed of collagen, elastin, and other complex proteins. In chronic liver disease, there is an abnormal increase in fibrosis component (collagen) of liver allowing measurements of tissue stiffness to serve as surrogates for the degree of tissue fibrosis [3].

The primary indication for elastography in hepatic imaging is the staging of fibrosis in chronic liver disease [4]. Fibrosis can occur in any chronic liver disease with its presence associated with increased liver-associated morbidity and mortality [5]. Fibrosis quantification is an important biomarker to support initiation of the discussion regarding liver transplantation. The presence of fibrosis proves a useful biomarker in identifying adequate liver grafts from a brain dead or living donor and can be an excluding factor as per the organ procurement and transplantation network (OPTN) guidelines [6]. Finally, it is also useful in assessing the prognosis of the graft post-transplant and aids in assessing disease recurrent fibrosis [7–10].

Liver biopsy is the gold standard in the assessment of fibrosis in the donor and recipient liver. Liver biopsy however carries with it issues of inter- and intra-observer variability, patient discomfort, and mild to life-threatening complications. In particular, the biopsy sample only encompasses a tiny fraction of total liver volume (1/50,000th) and may not be representative of the whole liver [11, 12]. Elastography offers a non-invasive assessment of hepatic fibrosis with quantitative results presented in a continuum, allowing a precise assessment of stiffness over a larger liver volume with excellent accuracy in comparison to histological samples [13–15].

The decision to place a patient on the liver transplant waiting list is a complex process based on multiple factors. There were approximately 15 deaths per 100,000 of the population attributable to cirrhosis or hepatocellular carcinoma in the USA in 2016. These figures have risen significantly over recent years and accounts for approximately 49,000 deaths annually

[16]. Given that there were 34,000 liver transplants available during the same period, there is obviously a need to prioritize patients based on the prospects of transplant success [6].

Current graft survival in cadaveric donors is 89% at 1 year, 80% at 3 years, and 72% at 5 years and those in living donors are 88% at 1 year, 82% at 3 years, and 77% at 5 years [6]. A number of donor-related, recipient-related, and procedural prognostic indicators can predict the success of transplantation in an individual. However, the complexity of their interplay makes accurate prediction very difficult. The presence of hepatic fibrosis is another biomarker which may aid in this prediction of success.

The aim of this review is to highlight the application of US and MR Elastography in the pre-transplant assessment of the donor liver and the post-transplant graft.

Magnetic resonance elastography

Technique

Magnetic resonance elastography (MRE) of the liver utilizes a drum-like mechanical driver placed on the patient's right anterior lower chest wall at the level of xiphisternum to produce shear waves at 60 Hz for clinical liver MRE. These shear waves propagate through the hepatic parenchyma which are detected using a specialized MRE sequence. The study can be performed on both 1.5 and 3 Tesla MRI machine without affecting reproducibility [2].

The clinical MRE pulse sequence used is a modified phase contrast sequence with cyclic motion-encoding gradients (MEG) [17]. This may be based on a gradient-recalled echo (GRE), spin echo (SE), or echo planar imaging (EPI) sequences. The standard clinical MRE sequence is a 2D GRE MRE sequence. In order to synchronize the MEGs with the shear waves generated, a trigger pulse is used. The MRE sequence detects displacements in the hepatic parenchyma which can be in the order of micrometers. Stiffness is generally assessed in a single plane (2D MRE); however, the analysis of the shear wave in the x -, y - and z -plane, named 3D MRE, has recently been developed with excellent results [18, 19].

An inversion algorithm is utilized to create an image depicting hepatic stiffness called an elastogram or stiffness map. This may be in gray scale or a color map. Region of Interest (ROI) markers are placed to measure stiffness. Regions of the liver that have inadequate wave amplitude are excluded with care to avoid the edge of the liver, large vessels, and other non-parenchymal artifacts [17].

MRE of a single slice can be performed within one breath hold and takes about 1–2 min to acquire 4 slices which is the standard of care. Additional hardware in the form of a mechanical driver is required which consists of an active driver located outside the magnet and a passive driver against the patient's right anterior chest wall.

Advantages and limitations

MRE is established as a very accurate current method for non-invasive assessment of hepatic fibrosis. Multiple studies have demonstrated the excellent diagnostic accuracy of MRE in the diagnosis of cirrhosis and fibrosis even in larger patients or the presence of ascites [14,

15, 20–25]. Stiffness can be assessed from a large part of the liver, decreasing sampling error, with results presented on a continuum measured in Kilopascals (kPa) allowing greater analysis of small changes. MRE also benefits from the standardization of technique across major MR vendors. The full repertoire of MR applications such as fat/iron quantification and contrast-enhanced sequences can also be utilized for a more comprehensive assessment of liver (Fig. 1).

There are some limitations to MRE. Certain populations cannot enter an MRI scanner due to the presence of MRI incompatible implants (pacemakers, aneurysm clips etc.). Also, MRE requires the patient to be transported to the imaging suite, while US-based techniques may be performed at the bedside. As with US-based techniques, the ability of the subject to breath hold adequately is important for creation of a successful image. The presence of excess iron in the liver of certain patients may affect the gradient-recalled echo sequence, limiting the quality of the study, but this can be minimized with the use of spin echo techniques which are less sensitive to mild-to-moderate iron deposition. In order to avoid subjectivity in the placement of ROI, recent work has demonstrated good interobserver agreement between manual and automated methods and larger ROI that includes as much hepatic parenchyma as possible are preferred [26].

Ultrasound elastography

Techniques

In contrast to MRE which uses dynamic shear waves, all currently commercially available ultrasound elastography techniques, including ARFI, rely on transient mechanical or US forces to generate shear waves in tissue [3]. Vibration-controlled transient elastography (VCTE), also known as one-dimensional transient elastography, was described in 2003 [27] and made available commercially as FibroScan (Echosens, Paris, France). A single probe containing an US transducer and a vibrating generator is placed on the body wall over the area of interest (typically the right hepatic lobe) and transmits mechanical impulses at low frequency (50 Hz) to generate shear waves, the speed of which is then measured by A-mode US in m/s. Young's modulus (E) is then calculated, with tissue stiffness reported in kPa. The total tissue sampled is a cylinder measuring approximately 1 cm wide and 4 cm deep, a volume roughly 100 × greater than that assessed by a typical liver biopsy [28]. Several different probes are available: The S probe, which has a frequency of 5 MHz and is intended for use in children; the M probe, which has a frequency of 3.5 MHz and is designed for adults; and the XL probe, which has a frequency of 2.5 MHz to accommodate obese adults. It is important to tailor probe use based on body habitus in order to attain a valid measurement. No anatomic images are acquired, a clear limitation. Currently shear waves at 50 Hz are used with VCTE for the evaluation of liver stiffness.

Point shear wave elastography (pSWE) differs from VCTE in the manner in which shear waves are generated. Instead of relying on external mechanical impulses to generate shear waves, pSWE allows the examiner to focus on an area in the liver with an US probe and utilizes an acoustic radiation force impulse (ARFI) or acoustic push pulse to excite the underlying tissue, which generates shear waves as it expands [1]. Conventional two-dimensional (2D) US can be used to track shear waves and calculate either propagation

velocity or Young's modulus. Because pSWE can be incorporated onto existing clinical US scanners by adding the requisite hardware and software, it can be performed in conjunction with B-mode US, allowing the user to sample a portion of hepatic parenchyma free of confounding anatomic factors such as blood vessels, bile ducts, or rib shadows [3]. Results are expressed as Young's modulus (E) in kPa or shear velocity in m/s.

Another shear wave imaging method 2D SWE also employs ARFI focusing multiple acoustic push pulses, measuring the speed of the shear waves created in the tissue, and then generating a two-dimensional quantitative image or elastogram of shear wave speeds. This elastogram is typically superimposed over a B-mode image [3, 29, 30]. Regions of interest (ROIs) can be placed within different areas of the elastogram to sample velocities in portions of the parenchyma subjectively judged as most representative of the organ as a whole. Frequency for liver ARFI studies is typically in the range of 100–500 Hz. As with pSWE, stiffness measurements can be calculated by applying Young's modulus (E) to the shear wave velocity (m/s) measurements. Many factors may influence the speed of the propagating shear wave apart from tissue stiffness, including physical factors such as wavelength, geometrical factors such as orientation of the ROI to the main US beam, anatomical factors such as irregular organ contours, and physiological factors such as blood flow [31].

Advantages and limitations

As VCTE was the first US elastography technique to the market, data regarding its efficacy is robust. Combined with its affordability, portability, and ease of use, this makes VCTE attractive as a screening tool for clinicians at the point of care [3]. Despite the availability of specialized probes targeted for use in different patient populations, the diagnostic performance of VCTE suffers as body habitus increases. The lack of concurrently generated anatomic images is a major drawback and limits the reproducibility of temporal measurements. Other potential confounders include acute hepatocellular inflammation, ascites, and limited acoustic windows in patients with narrow intercostal spaces [3]. The technical failure with VCTE is 6 to 23% [1].

In addition to all the advantages inherent to VCTE, both pSWE and 2D SWE generate elastograms in conjunction with anatomic images, allowing the operator to select ROIs in representative areas of the hepatic parenchyma, potentially decreasing sampling variability [1]. Disadvantages include a susceptibility to patient motion, necessitating breath holding, and the need for specialized operator training [3]. The reported technical failure rate of SWE is better than VCTE around 2% to 10% [1].

In general, the technical failure rate of ultrasound-based elastography is higher than MRE in patient population with higher body mass index (BMI) and non-alcoholic fatty liver disease (NAFLD) and can be as high as 20% [32–35]. The technical failure of MRE is around 6% and mainly found in patients with liver iron deposition.

Both ultrasound and MRE measure liver stiffness which can increase secondary to many pathologic processes including fibrosis, inflammation, congestion, portal hypertension,

and biliary obstruction [17, 36]. The results should therefore be interpreted with clinical information and biochemical test results.

Elastography in the graft donor

Donation of a liver typically occurs following brain death. Due to the shortage of liver grafts available, utilization of grafts from marginal donors and living donors is increasingly considered.

The first adult-to-adult transplantation was reported in 1994 [37]. Since this time, the number of living donor liver transplantations have increased greatly with comparable outcomes to those of cadaveric grafts [6]. In the pediatric population, transplantation of the left lateral segment from an adult is often performed. In the adult population, the right lobe is most commonly transplanted with a left lobe transplant rarely performed. The addition of a living donor liver transplant service to a standard liver transplantation service improved survival and decreased waiting lists in experienced transplant centers [38, 39]. Although rare, there have been instances of death related to liver donation in approximately 0.2% of cases [40, 41].

The exact criteria of donor evaluation varies between centers; however, the OPTN and United Network for Organ Sharing (UNOS) require that minimal screening of any donor be performed [6, 42]. Liver-specific criteria that exclude a candidate include the presence of cirrhosis or fibrosis stage 2 and also the presence of significant steatosis. The degree of steatosis allowed is variable; however, OPTN includes a figure of $> 20\%$ on liver biopsy as a possible exclusion criteria [6]. Liver biopsy is often required to assess for the presence of excessive steatosis or fibrosis [43].

MR elastography of liver donors

The living donors undergo several tests and imaging to determine suitability for graft donation as inappropriate resection can be a risk to both donor and recipient. An important determinant is the health of donor liver. While major risk factors of chronic liver disease can be ruled out with biochemical tests, evaluation of liver fibrosis and fat previously required liver biopsy. To counter the risk associated with an invasive liver biopsy, non-invasive methods such as MRE for liver fibrosis and MRI for fat and iron quantification in addition to the evaluation of biliary anatomy can be performed (Fig. 1). In a retrospective study assessing the ability of MRE to assess fibrosis in donor livers, out of 9 subjects, MRE predicted fibrosis with a sensitivity of 85% and an area under the receiver operating characteristic curve (AUROC) of 0.85 [10]. A separate study aimed to analyze the ability of MRE alone to distinguish between abnormal and normal potential donor livers by assessing stiffness. Abnormal livers were defined based on the presence of fibrosis and also the presence of a macrovesicular steatosis of greater than 20%. MRE demonstrated a sensitivity of 88% and specificity of 100% in identifying abnormal livers [44]. Adding MRE sequence to the liver MRI study of a donor can be easily done and is routinely performed in our institute. An example is illustrated in Fig. 1.

US elastography of liver donors

Studies appraising US elastography in the assessment of a potential living or brain dead liver donor are limited with research focused on transient elastography and its ability in identifying hepatic steatosis and fibrosis. A study comparing 80 potential living liver donors to 47 subjects with liver disease demonstrated only limited value for detecting steatosis and demonstrated no correlation between steatosis and stiffness [45]. The use of VCTE in brain dead donors has been found useful. A study assessed liver steatosis in 23 potential donors via transient elastography followed by liver biopsy. This demonstrated an AUROC of 0.75 using stiffness parameters alone and 0.97 when using elastography with Controlled Attenuation Parameter (CAP) in identifying livers refused for transplantation based on local guidelines [46]. Assessment of liver donors with US elastography can be considered in institutes where MRE is not available.

Elastography of liver graft

The development of fibrosis in the transplant graft is not completely understood. The recurrence of primary conditions such as viral hepatitis, non-alcoholic liver disease, and autoimmune liver diseases may occur and carry a poor prognosis for graft survival [47]. The decision on management and possible retransplantation is difficult given the deficiency of suitable donors. Therefore, objective biomarkers are required to form a fully informed decision.

In post liver transplant scenario, the technique for elastography of liver grafts would likely need modifications, based on our clinical experience. The modification is in the placement of the transducer or driver so that transducer or driver is directly above the graft as much as possible. The presence of anterior abdominal wall scar and central or posterior locations of the graft are some examples that demand modification of transducer/driver placement. There are no other changes required in frequency or power (amplitude) of the shear waves introduced into the graft for evaluation of fibrosis.

In the immediate liver transplantation period, hepatic parenchyma may show edema, congestion, and inflammatory changes due to ischemia-reperfusion injury liver dysfunction. The effect of graft-associated complications such as ischemia due to hepatic artery thromboses or portal vein thromboses, biliary obstruction, venous outflow obstruction, and peri-graft fluid collections etc. may influence liver stiffness measurements and are not well studied. In addition, allograft rejection can coexist. All these processes may lead to increased stiffness of the parenchyma of the graft. Elastography should be avoided for fibrosis detection and stiffness values should also carefully interpreted during this period and correlation with liver function tests and histology when available are useful.

MR elastography of liver graft

MRE can be either performed alone for evaluation of fibrosis recurrence or combined with standard liver MRI/MRCP protocol for comprehensive evaluation of the graft. The liver grafts are followed up with MRE at our institute for evaluation of fibrosis (Figs. 2, 3, 4, 5, 6, 7). MRE is useful for evaluation of recurrence of fibrosis in the grafts and in the

evaluation of parenchyma and biliary tree when combined with MRI study. In a pooled analysis, patients from 4 studies [23, 48–50] were combined with a separate cohort from the investigators institution to create a sample of 141 patients post liver transplant [9]. This group had MRE and liver biopsy results available. The AUROC for any (stage 1), significant (stage 2), advanced fibrosis (stage 3), and cirrhosis was 0.73, 0.69, 0.83, and 0.96, respectively [9]. MRE demonstrates increased accuracy in the more advanced stages of fibrosis in grafts similar to the evaluation of fibrosis in native livers.

In a separate study of liver transplant recipients with hepatitis C recurrence, MRE demonstrated similar diagnostic accuracy. MRE demonstrated an AUROC of 0.7 in the detection of fibrosis greater than Metavir stage 2 with significant correlation to fibrosis stage in one cohort of 31 patients [51]. In another study, the diagnostic accuracy was slightly superior with an AUROC of 0.87. This was in a cohort of 32 patients for the detection of fibrosis greater than or equal to METAVIR stage 1 [8]. Both studies concluded that MRE could be considered the best non-invasive method to assess fibrosis in a transplant in the setting of hepatitis C recurrence.

Overall, MRE elastography appears to demonstrate good to high diagnostic accuracy in the detection of fibrosis in the post-transplant liver and correlates significantly to the grade of fibrosis. MRE can also be combined with standard liver MRI/MRCP for the evaluation of liver parenchyma, fatty change, biliary obstruction, and focal lesions within the liver graft.

US elastography of liver graft

Ultrasound elastography methods are useful for detection of fibrosis in transplants (Figs. 8, 9). Early investigations into the use of ultrasound elastography in patients who had undergone liver transplantation focused on VCTE, with numerous studies demonstrating that VCTE performed well in identifying advanced fibrosis in hepatic allografts, particularly in cases of recurrent hepatitis C virus (HCV) infection [7, 52–55]. One meta-analysis encompassing five studies found pooled sensitivities and specificities of 83% and 83% for the diagnosis of significant allograft fibrosis due to recurrent HCV infection using liver biopsy as the histopathologic reference standard; those values rose to 98% and 84%, respectively, when the clinical benchmark was cirrhosis as opposed to simply significant fibrosis [7]. Crespo and colleagues [48] found that liver stiffness as determined by VCTE correlates with the severity of acute cellular rejection and may be useful in its evaluation and management, while Kamphues and colleagues [56] determined that VCTE is reliable for the exclusion of significant fibrosis in patients transplanted secondary to alcoholic cirrhosis.

Experience with pSWE and 2D SWE in hepatic allografts is promising, but comparatively limited in the assessment of the post-transplant graft (Figs. 8, 10, 11). Failure with elastography can occur in patients with severe fatty change in the graft (Fig. 12). In one analysis, Yoon et al. [57] used pSWE to determine allograft stiffness both in the perioperative period (< 4 weeks following transplant) and at more distant follow-up (> 4 weeks after transplant). They found that increased allograft stiffness as assessed by pSWE was significantly associated with the rejection or hepatitis at distant follow-up, but not in the perioperative period, potentially due to spuriously increased stiffness shortly after transplant secondary to hepatocellular edema in the context of ischemic or reperfusion injury [57]. In a

more recent study of 100 patients (60 native livers and 40 allografts), Perry et al. [58] found no significant difference in pSWE elastography accuracy when comparing native livers to grafts and were able to differentiate moderate-to-severe fibrosis from no-to-mild fibrosis with a sensitivity of 72% and specificity of 69%. Korda and colleagues used 2D SWE in post-transplant patients to demonstrate a significant decrease in liver stiffness following antiviral therapy in patients with allograft fibrosis secondary to recurrent HCV infection [59].

Conclusion

In conclusion, the utility and application of elastography in the evaluation of chronic liver disease have increased significantly in recent years. Ultrasound or magnetic resonance elastography may play a role in excluding inadequate donor livers and identifying recurrent chronic liver disease in the transplant graft, depending on local resources and expertise.

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Fig. 1. MRI/MRCP with MRE of liver in a potential liver transplant donor. Standard heavily T2-weighted MRCP (a) shows normal biliary anatomy. Proton density fat fraction map (b) demonstrates no hepatic steatosis. R2* map (c) demonstrates normal iron content. Post-contrast-enhanced T1W image showing normal liver parenchyma (d) and normal uptake and excretion into biliary tree in the hepatobiliary phase (e). MRE stiffness map (f) demonstrates normal liver stiffness

Fig. 2.
MRE of a normal post-transplant cadaveric liver. T2-weighted sequence (**a**), portal venous phase gadolinium-enhanced T1-weighted sequence (**b**) demonstrate normal hepatic parenchyma and MRE demonstrates normal stiffness (2.3 kPa) (**c**)

Fig. 3.

Follow-up of liver transplant with MRE. A 60-year-old male with non-alcoholic steatohepatitis (NASH) received a living donor right lobe liver graft transplantation. Post-transplantation coronal T2W image (a) showing graft in right upper abdomen. Follow-up MREs were performed for the detection of recurrence. Stiffness maps from MRE performed at 4 years (b) and 9 years (c) post-transplant show normal liver stiffness of 2.4 kPa and 2.3 kPa, respectively. The liver function tests also remained normal throughout the follow-up period

Fig. 4.

Follow-up of liver transplant with MRE. A 42-year-old woman underwent cadaveric liver transplantation for non-alcoholic steatohepatitis. Follow-up MRI study at 5 years post-transplant shows normal appearing liver graft on post contrast T1-W image (a) with normal liver stiffness of 2.5 kPa with MRE (b). Follow-up MRI and MRE at 9 years post-transplant showing morphologically normal liver on post contrast T1W image (c), but elevated stiffness of 4.4 kPa on MRE (d). Biopsy of the graft confirmed stage III liver fibrosis

Fig. 5.

Follow-up of liver transplant with MRI/MRCP and MRE showing recurrence of PSC with rapid progression of liver fibrosis. A 48-year-old male with PSC underwent first orthotopic cadaveric liver transplant 13 years ago. Follow-up MRI with MRE shows hepatomegaly and moderate splenomegaly (a), multiple intrahepatic strictures on MRCP (b) consistent with recurrent PSC, and an increased liver stiffness of 3.2 kPa on the stiffness map (c). Follow-up after 18 months shows progression of hepatosplenomegaly on T2W image (d), intrahepatic biliary strictures on MRCP, (e) and increased stiffness on MRE (f) consistent with cirrhosis. Patient received a second liver transplantation

Fig. 6.

MRI and MRE showing recurrent fibrosis in a transplant and HCC. A 61-year-old patient with 6 years post liver transplant for alcoholic liver disease. Note the dysmorphic appearance of the graft with splenomegaly and ascites on T2W image (**a**) and post gadolinium-enhanced image (**b**). MRE stiffness map (**c**) shows increased liver stiffness of 4.1 kPa. An arterially enhancing lesion (arrow) (**d**) with washout on portal venous (**e**) and delayed (**f**) phases is suspicious for HCC on a background of recurrent hepatic fibrosis in a transplant. Biopsy confirmed HCC

Fig. 7.

Iron overload in liver transplant. A 49-year-old male received orthotopic liver transplantation for HCC. Patient received multiple blood transfusions during and following transplantation surgery due to blood loss. Follow-up MRI showing increased iron causing loss of signal in both liver and spleen on the In phase (**a**) compared to opposed phase (**d**). MRE performed with standard 2D GRE MRE sequence showing poor demonstration of wave propagation in the liver (white outline, **b**) with very small area for measurement in the stiffness map overlaid with confidence map (**e**). In the same exam, MRE was then performed with 2D SE MRE sequence showing improved signal from the propagating shear waves in the periphery of the transplant (**c**). The stiffness map with overlaid confidence map (**f**) shows much larger region of liver available for measurement of liver stiffness. The measured mean liver stiffness was normal

Fig. 8.

A 60-year-old patient status post liver transplant 12 years prior hepatocellular carcinoma on a background of hepatitis C cirrhosis. The patient had a non-eventful post-transplant course with normal liver stiffness on VCTE (a), SWE (b), and MRE (c)

Fig. 9.

A 64-year-old male, 5 years post liver transplantation for HCC on a background of hepatitis C cirrhosis. VCTE demonstrated increased stiffness in the left liver (**a**). The patient developed cholestatic symptoms secondary to biliary structure. Contrast-enhanced T1-W MRI image (**b**) showing dilated intrahepatic ducts in the left lobe. MRE (**c**) demonstrated increased hepatic stiffness in the left liver with mean stiffness of 4.2 kPa and biopsy confirmed stage 3 fibrosis

Fig. 10. Shear wave Elastography of liver graft. Gray scale longitudinal section of right lobe liver graft (a) and 2D Shear Wave Elastography (b) of a normal liver graft for amyloidosis. The calculated liver stiffness is 5.6 kPa and within normal limits

Fig. 11.

Shear wave elastography in the follow-up post liver transplant for primary sclerosing cholangitis. Ultrasound image (a) showing nodular contour and coarsened echotexture. Shear wave elastography (b) demonstrates increased stiffness consistent with a high risk of cirrhosis. Normal portal venous and left hepatic artery blood flow on Doppler ultrasound images (c, d). Subsequent liver biopsy confirmed cirrhosis

Fig.12.

Follow-up of a cadaveric liver transplant performed in 2017 for primary sclerosing cholangitis. Conventional ultrasound (a) demonstrated hepatic steatosis. SWE (b) failed due to excess hepatic fat