Liver MR Elastography Technique and Image Interpretation: Pearls and Pitfalls

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Abbreviations: LSM = liver stiffness measurement, PACS = picture archiving and communication system, QIBA = Quantitative Imaging Biomarkers Alliance, ROI = region of interest, RSNA = Radiological Society of North America, TE = echo time

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SA-CME LEARNING OBJECTIVES

After completing this journal-based SA-CME activity, participants will be able to:

- Describe the important technical parameters that can be used to optimize MR elastography technique and thus aid in performing consistently high-quality examinations.
- Recognize and potentially correct a low-quality or nondiagnostic MR elastogram.
- Interpret MR elastography findings for accurate and reliable LSMs, and include elastography results in the radiology report.

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Liver MR elastography is an imaging technique used to measure liver stiffness in the evaluation for possible fibrosis or cirrhosis. Liver stiffness measurement (LSM) is useful for predicting the stage of liver fibrosis. However, obtaining and reporting accurate and reliable LSMs with MR elastography requires an understanding of the three core components of liver MR elastography: optimization of imaging technique, prompt quality control of images, and proper interpretation and reporting of elastogram findings. When performing MR elastography, six important technical parameters that should be optimized are patient fasting before the examination, proper passive driver placement, proper MR elastography section positioning over the largest area of the liver, use of MR elastography–related sequences at end expiration, choosing the best timing of the MR elastography sequence, and optimization of several essential pulse sequence parameters. As soon as the MR elastography examination is performed, the elastograms should be reviewed to ensure that they are of diagnostic quality so that corrective steps can be taken, if needed, and MR elastography can be repeated before the diagnostic portion of the examination concludes. Finally, the interpreting radiologist needs to understand and be able to perform the proper technique for LSMs, including determining which areas of the liver to include or avoid in the measurements; knowing which conditions, other than fibrosis or cirrhosis, can increase liver stiffness; and understanding how to report elastography results. This article reviews the proper technique for performing liver MR elastography and subsequent quality control assessment, as well as the principles for interpreting and reporting studies. This review may be helpful for implementing and operating a clinical liver MR elastography service.

Online supplemental material is available for this article.

Introduction

Chronic liver disease, including hepatitis B and hepatitis C virus infections, nonalcoholic fatty liver disease, and alcoholic liver disease, is a major cause of morbidity and mortality worldwide (1). Chronic liver disease can lead to liver fibrosis, and if left untreated, can progress to cirrhosis. Hepatic fibrosis is a dynamic process with the potential to be reversed with treatment, especially during the earlier stages (2–7). Thus, identifying and staging fibrosis before cirrhosis develops is an important part of managing chronic liver disease (8).

TEACHING POINTS

- The liver stiffness in healthy subjects does not change significantly with food intake. However, in persons with chronic liver disease, liver stiffness may increase for a short time after a meal. For this reason, patient fasting for 4–6 hours before the MR elastography examination is recommended. Patients should also fast for 4–6 hours before undergoing follow-up MR elastography so that LSMs will be reproducible and measurement changes can be meaningfully interpreted.
- In routine clinical practice, the frequency is generally set at 60 Hz and should not be changed. This is because most of the LSM references and thresholds for staging liver fibrosis cited in the literature are based on imaging at 60 Hz.
- When performing MR elastography, the goal is to acquire elastograms of high quality, with a large area of the liver not covered by the 95% confidence map so that a large portion of the liver can be measured.
- LSMs are obtained in the largest measurable portion of the liver on each of the four elastograms. On each image, a mean LSM, in kilopascals, along with the ROI size, in square centimeters, is obtained. Then, the overall mean liver stiffness is obtained by calculating the weighted arithmetic mean, which reflects the relative contribution of the area of the liver measured on each image.
- On the magnitude images, which provide the best anatomic detail of the liver, it is important to avoid the liver edge (≥1 cm from liver edge), nonhepatic tissues, fissures, gallbladder fossa, and large blood vessels. The left hepatic lobe can have significant motion artifact due to cardiac pulsations and thus should be avoided as well, unless no motion artifact is identified. On the wave images, areas of poor wave propagation, wave distortion, and low-amplitude waves should be avoided. On the gray-scale and color elastograms, the crosshatched regions on the superimposed 95% confidence map must be excluded from measurements. Finally, on the color elastogram, hot spots need to be recognized and excluded from measurements.

Although liver biopsy has been the reference standard for detecting liver fibrosis, many factors limit the clinical use of this procedure. These factors include patient reluctance, potential complications (9–12), sampling error due to liver fibrosis heterogeneity and a small biopsy specimen size, and interobserver variability in interpretation (13,14). As a result of these limitations, noninvasive techniques for liver fibrosis evaluation have been developed. These techniques include various liver stiffness measurement (LSM) procedures such as vibration-controlled transient elastography, shear wave elastography, acoustic radiation force impulse imaging, and MR elastography (15–22). Among these techniques, MR elastography is the most accurate noninvasive imaging examination available for the identification and staging of liver fibrosis (23–25). It is a robust technique, with liver iron overload, its main limitation, potentially resulting in nondiagnostic studies (25,26).

With MR elastography, as compared to any US LSM technique, larger portions of the liver are sampled. It is usually performed in conjunction with liver fat and iron quantification and can be combined with diagnostic MRI to provide the most comprehensive liver imaging examination available (27,28).

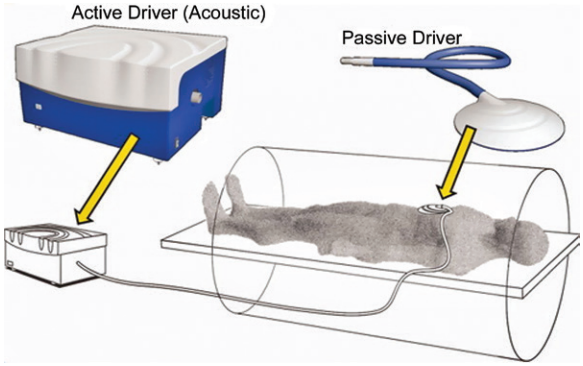


Figure 1. Drawing illustrates a typical liver MR elastography configuration. The patient is positioned supine in the MRI unit, and a passive driver is secured onto the abdominal wall over the liver. A plastic connecting tube connects the passive driver to the active driver, which is located behind a wall outside the imaging room. (Reprinted, with permission, from reference 27.)

With MR elastography, a high-quality examination must be performed and the MR elastography findings must be correctly interpreted to obtain accurate results. However, a number of factors can interfere with interpretation. In this article, the pearls and pitfalls of performing MR elastography and interpreting the associated findings are outlined. This includes a review of the six most important technical factors to optimize when performing MR elastography, how to immediately perform a quality control assessment of studies, and five important principles for interpreting and reporting studies. (The original slide presentation for this article from the RSNA Annual Meeting is available online.)

What Is Elastography?

Elastography is an imaging technique used to evaluate the mechanical properties of tissue according to the propagation of mechanical waves. MRI or US is coupled with a device that generates mechanical waves, typically shear waves within the tissue(s) of interest. The shear wave velocity is then measured to calculate quantitative results. The shear wave velocity in tissue is directly related to the stiffness of the tissue (24,29). Propagation of shear waves is faster in stiff or hard tissues and slower in soft tissues (30). Although elastography can be used to evaluate the stiffness in many organs, currently it is most commonly used for liver applications (31).

Liver MR Elastography

In a typical liver MR elastography configuration, an active pneumatic mechanical wave driver is located outside the MR elastography room and

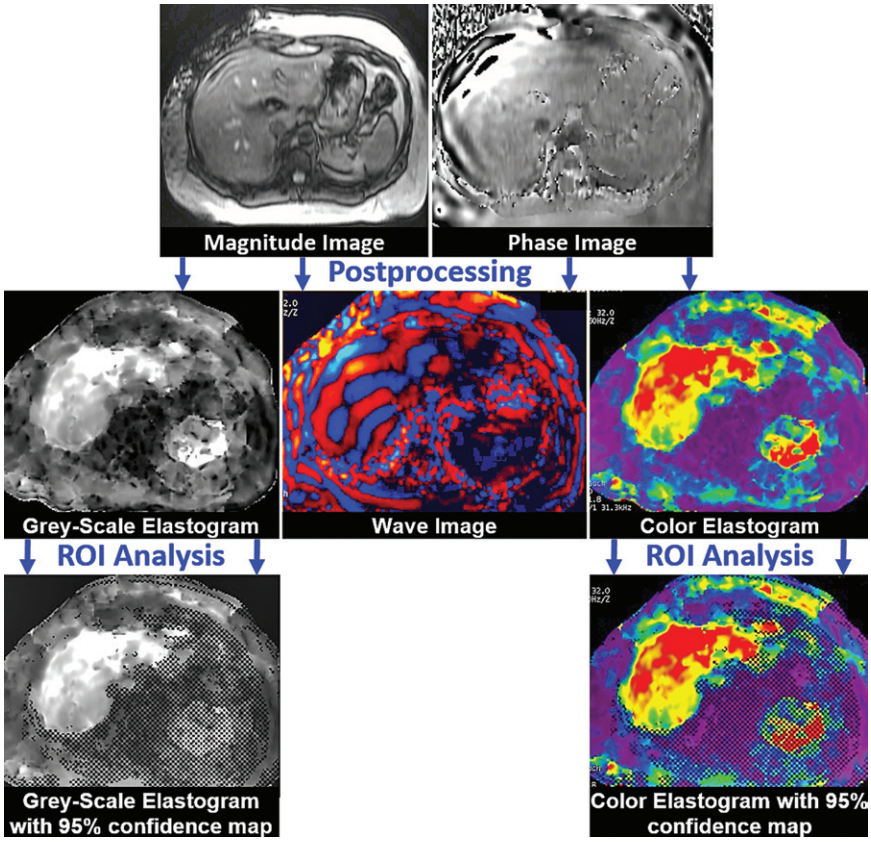


Figure 2. Images acquired during a liver MR elastography examination. Magnitude and phase images yield raw data: The magnitude images provide anatomic information, and the phase images provide wave motion information. With postprocessing, color wave images and stiffness maps, also known as elastograms, are generated. Finally, a confidence map is applied to obtain LSMs. *ROI* = region of interest.

is connected, by way of a flexible 25-ft (7.62-m) polyvinyl chloride tube, to a passive driver that is fastened onto the abdominal wall over the liver (Fig 1) (8,27). The passive driver generates a continuous acoustic vibration that is transmitted through the entire abdomen, including the liver, at a fixed frequency, which is typically 60 Hz.

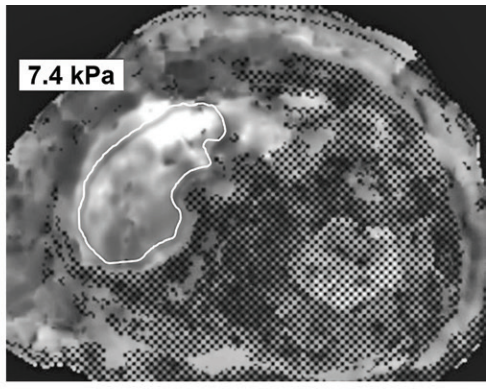
A phase-contrast pulse sequence with motion-encoding gradients is synchronized to the frequency of mechanical waves created by the passive driver. This sequence is then used to image the micron-level cyclic displacements caused by the propagating shear waves to create a magnitude image, which provides anatomic information, and a phase image, which provides wave motion information (Fig 2) (29,32). The most commonly used clinical MR elastography pulse sequence approved by the U.S. Food and Drug Administration is a two-dimensional gradient-recalled-echo MR elastography sequence.

After the magnitude and phase images are created, an inversion algorithm installed in the MRI unit automatically processes these raw data images to create several additional images and maps. The most common output images generated by MRI units from three major vendors are a color wave image depicting the propagation of shear waves through the abdomen, a gray-scale elastogram without a superimposed 95% confidence map, a gray-scale elastogram with a superimposed 95% confidence map, a color elastogram without a superimposed 95% confidence map, and a color elastogram with a superimposed 95% confidence map (Fig 2) (30,33). The confidence map is a statistical derivation used to overlay a "checkerboard" on the stiffness map to exclude regions in the liver that have less reliable (ie, noisy and discontinuous) stiffness data, so that a high-quality LSM can be obtained (8).

Depending on the MRI unit vendor, LSM can be performed on different maps. The gray-scale elastogram is commonly used to obtain quantitative LSMs, in kilopascals. The color elastogram is generally used for qualitative liver stiffness evaluation. However, the color elastograms created by the MRI units from some vendors can also be used to obtain quantitative measurements. The color elastogram used clinically has a stiffness range of 0–8 kPa. A 0–20-kPa color elastogram is also created and is useful for appreciating liver stiffness heterogeneity in livers with advanced fibrosis or cirrhosis; however, this image is rarely required for clinical use (Fig 3) (8).

Optimizing the MR Elastography Technique

To generate consistently high-quality elastograms at liver MR elastography, many technical factors need to be considered. The six most important parameters that should be optimized are patient



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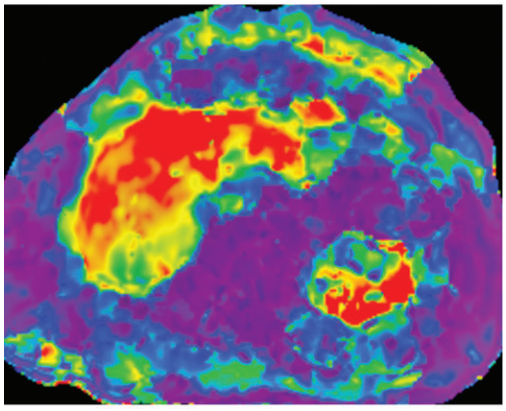

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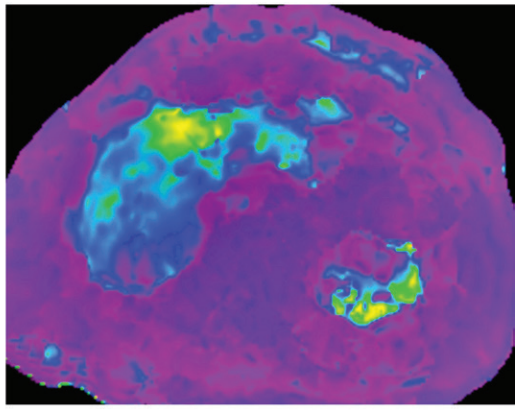

c.

Figure 3. Elastogram images acquired during a liver MR elastography examination. **(a)** Gray-scale elastogram with the 95% confidence map superimposed shows a freehand ROI measurement of an area (outlined) with a mean liver stiffness of 7.4 kPa. **(b)** Color elastogram with a 0–8-kPa scale shows the stiffness distribution in organs for qualitative evaluation. Orange or red regions have higher stiffness values, and blue and purple regions have lower stiffness values. **(c)** Color elastogram with a 0–20-kPa scale. Although color elastograms with this scale are not commonly used clinically, they are helpful for evaluating liver heterogeneity, especially in livers with advanced fibrosis or cirrhosis.

preparation, passive driver placement, MR elastography section positioning, breathing technique, pulse sequence timing, and pulse sequence parameters.

Patient Preparation

The patient preparation for MR elastography is similar to that for a standard liver MRI examination. The liver stiffness in healthy subjects does not change significantly with food intake. However, in persons with chronic liver disease, liver stiffness may increase for a short time after a meal. For this reason, patient fasting for 4–6 hours before the MR elastography examination is recommended (34–39). Patients should also fast for 4–6 hours before undergoing follow-up MR elastography so that LSMs will be reproducible and measurement changes can be meaningfully interpreted.

Passive Driver Placement

The passive driver should be placed over the right hepatic lobe, which is usually the largest portion of the liver, as an LSM obtained from a larger volume of tissue is the most representative of liver stiffness. To localize the right lobe, in most patients, the xiphoid process of the sternum is used for the superior-inferior position, and the right midclavicular line is used for the right-left position (Fig 4). Alternatively, the passive driver can be placed along the right lateral abdominal wall in patients who have a chest wall deformity or have undergone prior surgery, or if the patient cannot lie supine. For patients who have undergone hepatic resection or have liver malposition, the passive driver can be placed over

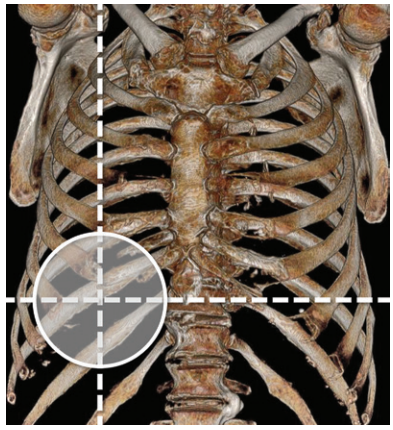

Figure 4. Coronal three-dimensional CT image shows proper placement of the passive driver over the liver. The xyphoid process of the sternum (horizontal dashed line) is used for the superior-inferior position, and the right midclavicular line (vertical dashed line) is used for the right-left position.

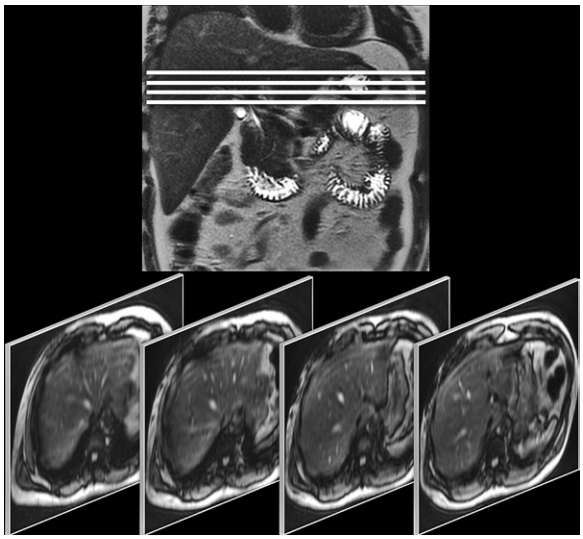

Figure 5. MR elastography section positioning. Top: Coronal T2-weighted MR image shows the sites (four lines) where the four MR elastography magnitude image sections at the bottom were obtained. Bottom: Magnitude image sections include the largest portion of the liver, with the liver dome and inferior aspect of the liver excluded.

a different site if this location approximates the largest portion of the liver.

The passive driver is held in place by an elastic strap and placed on the chest or abdominal wall beneath a torso phased-array coil (17,40,41). When the passive driver is applied, it should be fastened snugly, with the patient holding his or her breath at end expiration (discussed later, in the "Breathing Technique" section). Maintaining adequate contact between the passive driver and anterior abdominal wall improves the delivery of mechanical waves into the liver.

Section Positioning

In a typical MR elastography examination, four elastograms are obtained, and each should include the largest portion of the liver, avoiding the liver dome and inferior portion of the liver (Fig 5). Images obtained too high over the liver dome can yield falsely elevated liver stiffness values owing to oblique waves propagating through the liver (discussed later, in the "Hot Spots" section), while images obtained too low can create chaotic waves resulting in inaccurate or nondiagnostic liver stiffness values.

Breathing Technique

The acquisition of each of the four image sections at MR elastography with the two-dimensional gradient-recalled-echo sequence requires a breath hold of about 16 seconds. Because it is a breath-hold sequence, MR elastography is ideally performed at end expiration to minimize positional changes between individual sections (34). To best accomplish this, the passive driver needs to be fastened snugly to the abdominal wall when it is applied, with the patient holding his or her breath at end expiration. Then, all subsequent sequences, including the elastography scout images, parallel imaging calibration images (if required), and elastogram, should also be performed at end expiration to match the passive driver location and match the technique with which the passive driver was applied. Finally, although use of the end-expiration breath-hold method whenever possible should be encouraged, MR elastography can be performed at end inspiration if necessary.

Pulse Sequence Timing

Liver MR elastography can be performed before or after the intravenous injection of gadolinium-based contrast material. The advantage of performing MR elastography before injecting the gadolinium-based agent is the ability to correct elastography-related quality control issues, should they occur, and repeat the MR elastography examination before or after the diagnostic portion of the MRI examination is performed. The advantage of performing MR elastography after injecting gadolinium-based contrast material is the increased signal intensity of the liver caused by the injected agent. We have found that this increased signal intensity can result in higher-quality elastograms.

Study results (42,43) have shown that the administration of gadolinium-based contrast material has no effect on liver stiffness, and thus there is no substantial difference between the liver stiffness measured before and that measured after intravenous injection of a gadolinium-based contrast agent. Finally, the liver fat and iron quantification usually performed with MR elastography still should be performed before contrast agent administration to avoid the effects of gadolinium on these measurements (Fig 6).

Pulse Sequence Parameters

Typical parameters used to perform MR elastography on a 1.5-T MRI system are as follows: section thickness, 8–10 mm; intersection gap, 2–5 mm; number of sections, four; repetition time msec/echo time (TE) msec, 50/18 per section; flip angle, 30°; and bandwidth, 31.25 Hz (24,27,33,44). However, the parameters used to perform MR elastography vary among MRI unit vendors and according to different magnetic field strengths. The parameters recommended by numerous MRI unit vendors are available in the profile for liver MR elastography developed by the Radiological Society of North America (RSNA) Quantitative Imaging Biomarkers Alliance (QIBA) (44). Although the parameters for using different magnets vary, there are several

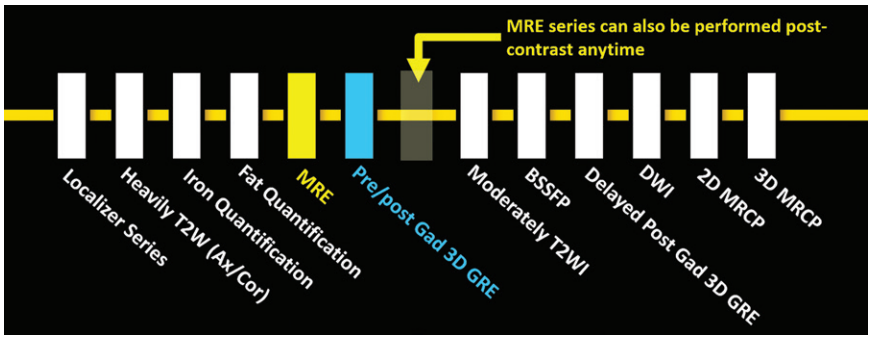

Figure 6. Pulse sequence timing. Diagram shows the timeline for performing an abdominal MRI examination, including MR elastography *(MRE)* and liver fat and liver iron quantification; later sequences are toward the right. In a typical MR elastography examination, the elastogram series can be obtained before the injection of gadolinium-based contrast material *(Gad)*. Alternatively, the elastogram series can be performed any time after the injection to increase the signal intensity of the liver. *Ax/Cor* = axial and coronal, *BSSFP* = balanced steady-state free precession, *DWI* = diffusion-weighted imaging, *GRE* = gradient-recalled echo, *MRCP* = MR cholangiopancreatography, 3D = three-dimensional, *2D* = two-dimensional, *T2W* and *T2WI* = T2-weighted imaging.

common parameters that must be understood to improve the reliability of MR elastography results, including passive driver frequency, passive driver amplitude, and pulse sequence TE.

Passive Driver Frequency.—LSMs are frequency dependent, with larger measurements obtained as the shear wave frequency increases (45). Study investigators have evaluated frequencies between 40 Hz and 200 Hz for liver MR elastography (45), as well as multifrequency MR elastography (46). However, in routine clinical practice, the frequency is generally set at 60 Hz and should not be changed (24,33). This is because most of the LSM references and thresholds for staging liver fibrosis cited in the literature are based on imaging at 60 Hz (8,24). It is also important to perform the follow-up examination at the same 60-Hz frequency to ensure measurement consistency.

Passive Driver Amplitude.—The driver amplitude, or power output, setting determines the intensity of the vibrations that are produced in the passive driver on the abdominal wall. Choosing an ideal driver amplitude is helpful for obtaining a high-quality elastogram. An appropriate default setting for the passive driver amplitude is 50% for an average-sized patient. However, this can be increased or decreased according to the patient's size and comfort level (ie, an amplitude of 75% for larger patients and 25% for thin patients). If the driver amplitude is set too low, the wave amplitude may be unacceptably low and result in a low-quality elastogram. If this value is set too high, the patient may be uncomfortable and distorted waves may be produced, leading to inaccurate LSMs owing to "hot spots" created on the elastogram (discussed later, in the "Hot Spots" section).

Pulse Sequence TE.—According to the RSNA QIBA profile for liver MR elastography (44), the ideal TE for an MR elastography pulse sequence is an in-phase TE, which varies depending on the MRI unit vendor and magnetic field strength. Suggested TEs are provided in the online RSNA QIBA profile document (44). Setting the TE to an in-phase value can improve image quality by minimizing the signal loss that can occur owing to a fatty liver. This is important to know because when MR elastography hardware is first installed on an MRI unit, the default TE may not be set to an in-phase value and thus may need to be changed by an MRI application specialist during or after the installation. MR elastograms can still be acquired at TEs other than an in-phase TE, although the resulting liver signal intensity may be lower.

MR Elastography Quality Control

When liver MR elastography is first performed, each image should be evaluated immediately to ensure its quality so that corrective steps, if needed, can be taken before the examination concludes. The MR technologist and interpreting radiologist should be able to perform these important quality control steps, which are outlined in the next section.

Step 1: Review the Magnitude Images

The first step in the quality control process is to review the magnitude images for a signal void in the subcutaneous tissues of the abdominal wall to confirm that the mechanical waves have been applied (Fig 7a, 7c; Movies 1 and 3, respectively) (33). If there is no signal void, corrective steps must be taken to determine the cause and solution (discussed later, in the "Causes of Nondiagnostic Elastograms" section).

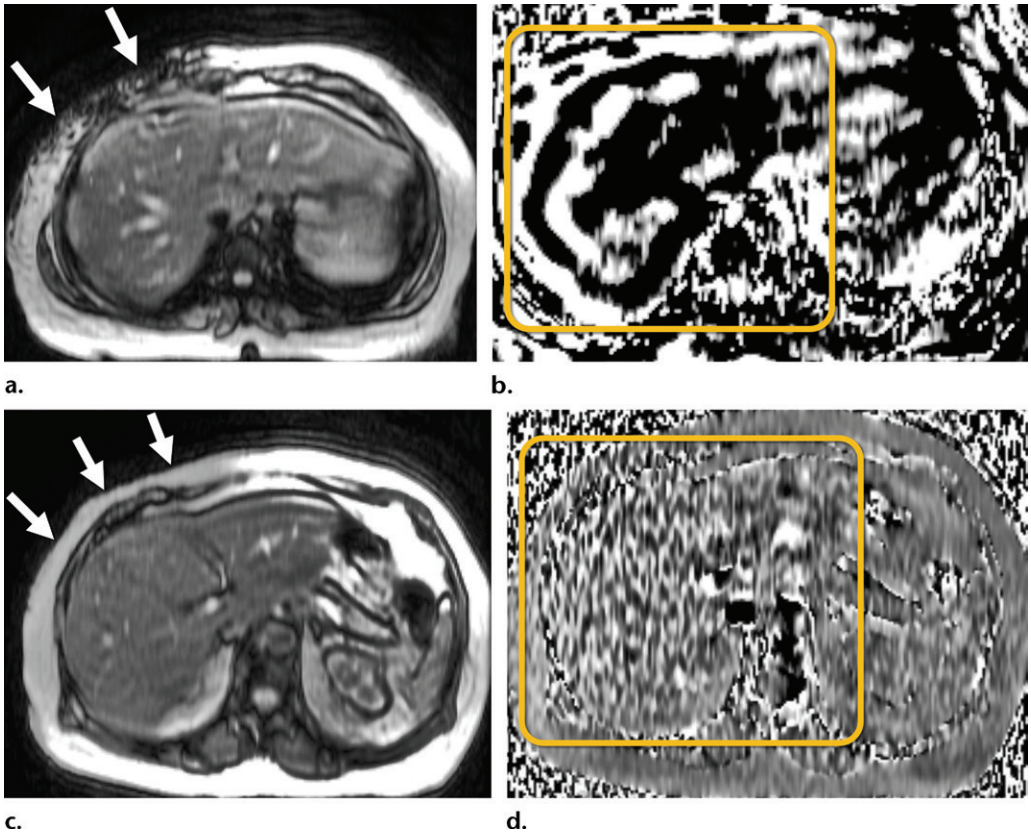

Figure 7. Magnitude and phase image review for quality control in two patients. **(a)** Axial magnitude image obtained at MR elastography shows a diffuse signal void (arrows) in the subcutaneous tissues in the right upper quadrant in the abdominal wall, indicating that the mechanical waves were applied (Movie 1). **(b)** Corresponding phase image shows shear waves (rectangle) moving through the liver; this is an expected finding with a diagnostic MR elastography examination (Movie 2). **(c)** Axial magnitude image in a different patient, whose MR elastography findings were nondiagnostic. There is no signal void in the abdominal wall subcutaneous tissues (arrows) (Movie 3). **(d)** Corresponding phase image shows no shear waves moving through the liver (rectangle) (Movie 4). The cause for this nondiagnostic MR elastography examination was a disconnected tube between the passive driver and active driver.

Step 2: Review the Phase Images

The next quality control step is to review the phase images to determine that shear waves are propagating through the liver (Fig 7b, 7d; Movies 2 and 4, respectively). Usually, when an abdominal wall signal void is seen on the magnitude images, waves moving through the liver will be seen on the phase images, and vice versa.

Step 3: Review the Wave Images

The next quality control step is to review the wave images to exclude areas of poor wave propagation, low-amplitude waves, or wave distortion (Fig 8a–8c; Movies 5–7, respectively). High-quality waves will form parallel to the outer surface of the liver and propagate nearly undisturbed through the liver. In a normal liver, as the waves move centrally, they will tend to lose amplitude (ie, become less bright) because they are attenuated by soft normal liver parenchyma. With poor wave propagation, the waves will not continue to be parallel through the liver and will either lose their parallel orientation or have low amplitude (ie, dark regions). Low-amplitude waves are attenuated (darker) and have a poor signal-to-noise ratio. This is not ideal for postprocessing and can potentially result in an artifactually low LSM. *Wave distortion*, or wave interference, is defined as waves that either do not move parallel through the liver or are disrupted. Wave distortion may lead to an artifactually high or low LSM.

Step 4: Evaluate the Elastogram Quality

In the final quality control step, the elastogram must be evaluated for diagnostic quality. Elastograms can be assigned to one of three categories: high quality, low quality, or nondiagnostic. When performing MR elastography, the goal is to acquire elastograms of high quality, with a large area of the liver not covered by the 95% confidence map so that a large portion of the liver can be measured. On a low-quality elastogram, only a small portion of the liver is not covered by the 95% confidence map. On a nondiagnostic elastogram, all or nearly all of the liver is covered by the 95% confidence map (Fig 9).

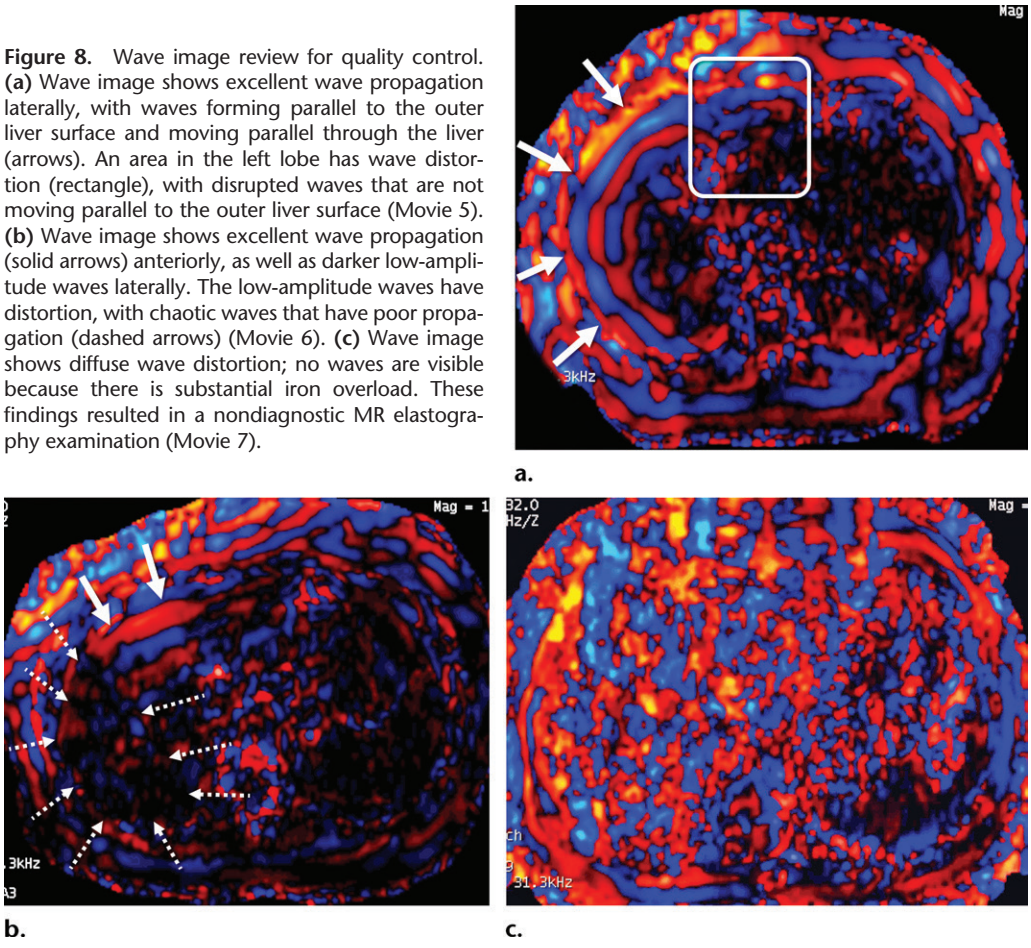

Figure 8. Wave image review for quality control. **(a)** Wave image shows excellent wave propagation laterally, with waves forming parallel to the outer liver surface and moving parallel through the liver (arrows). An area in the left lobe has wave distortion (rectangle), with disrupted waves that are not moving parallel to the outer liver surface (Movie 5). **(b)** Wave image shows excellent wave propagation (solid arrows) anteriorly, as well as darker low-amplitude waves laterally. The low-amplitude waves have distortion, with chaotic waves that have poor propagation (dashed arrows) (Movie 6). **(c)** Wave image shows diffuse wave distortion; no waves are visible because there is substantial iron overload. These findings resulted in a nondiagnostic MR elastography examination (Movie 7).

The minimal amount of liver tissue that needs to be left uncovered by the 95% confidence map for an examination to be considered diagnostic is an ongoing subject of research. However, there is consensus among experienced users that the total ROI that includes the ROIs from all of the sections in an examination should contain at least 700 pixels for an examination to be considered diagnostic (44). Nonetheless, when an MR elastography examination is deemed to be low quality and borderline diagnostic, the priority should be to try to determine the cause of the low-quality examination, with the goal of improving the repeated or subsequently performed examination.

Finally, in a normal liver, as compared with a fibrotic or cirrhotic liver, there tends to be a smaller region that is not covered by the 95% confidence map, as normal liver parenchyma attenuates the shear waves much more than a fibrotic or cirrhotic liver. This attenuation reduces the amplitude of shear waves, particularly in the deeper regions of the liver, resulting in a lower confidence level. Knowledge of this attenuation in normal livers is useful to avoid repeating an MR elastography examination when it is not needed.

Causes of Low-Quality Elastograms.—High-quality elastography is achieved when the liver parenchyma has a high signal-to-noise ratio, there is adequate delivery of shear waves to the liver, and high-quality waves propagate through liver tissue. There are many potential causes for a low-quality elastogram (Table). The most common cause is poor shear wave delivery to the liver, which may be due to several factors. A common cause of poor shear wave delivery is the passive driver improperly secured to the abdominal wall because it loosened after application. Alternatively, the passive driver may have been inadvertently applied during inspiration rather than end expiration. Another reason is that the location of the elastogram section may not match the location of the passive driver, which may be positioned too high or too low. Even if the elastogram section location matches the driver location, the driver still may have been applied too high or too low. Structures interposed over the liver, such as the lung base or colon, also can interfere with shear wave delivery. Finally, a leak in the connecting tube between the active and passive drivers may be the reason for the poor shear wave delivery.

Other causes for low-quality elastograms include a too high or too low active driver

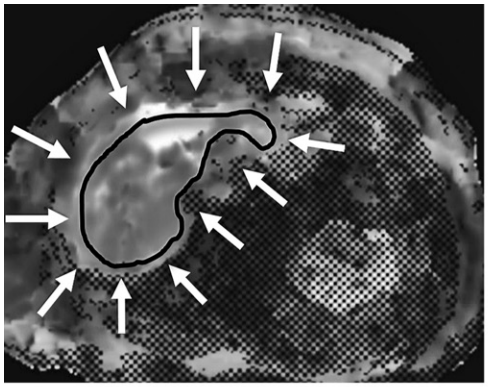

Figure 9. Elastogram evaluation for quality control. **(a)** High-quality gray-scale elastogram shows a large area of the liver (arrows) that is not covered by the 95% confidence map, allowing measurement of a large portion of the liver. **(b)** Low-quality gray-scale elastogram shows a relatively small portion of the liver (arrows) that is not covered by the confidence map, as compared with the large noncovered region in **a.** **(c)** Nondiagnostic gray-scale elastogram shows the entire liver covered by the confidence map, with no liver tissue available for measurement.

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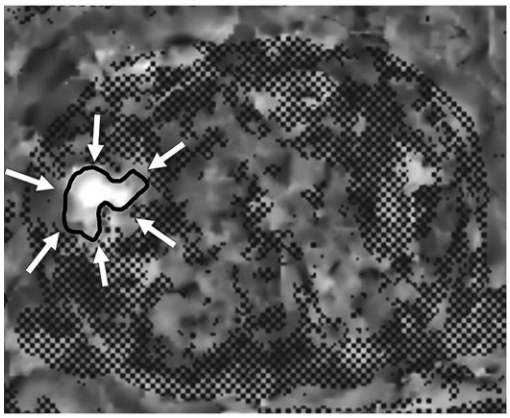

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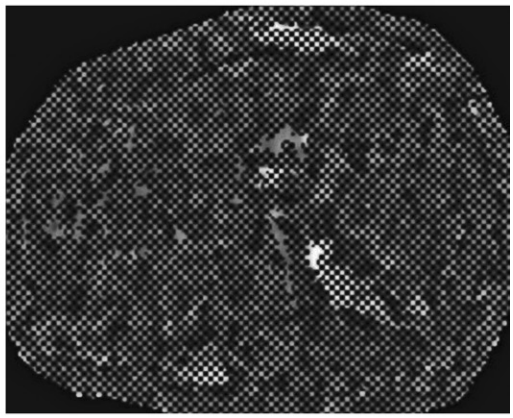


c.

Causes of Low-Quality and Nondiagnostic Elastograms

Low-quality elastograms
Poor shear wave delivery to liver
Too high or too low active driver power output setting
Liver parenchymal causes
Interfering paramagnetic materials
Motion artifact
Nondiagnostic elastograms
Significant iron overload
Nonfunctioning active driver
Disconnected or kinked tube connecting active and passive drivers

power output setting. If this setting is too low, there may not be enough wave amplitude in the liver to generate a high-quality elastogram. If this setting is too high, the waves may be distorted and thus result in a poor-quality study (47).

A poor-quality elastogram may be related to a parenchymal condition such as unrecognized iron overload or severe hepatic steatosis resulting from the use of a non–in-phase TE in the examination. Both of these conditions can lead to a decrease in liver signal intensity that results in a lower-quality elastogram (Fig 10a, 10b). Paramagnetic materials, such as embolization coils, a transjugular intrahepatic portosystemic shunt, or chest wall metallic clips, in or adjacent to the liver can cause interference due to susceptibility artifact resulting in signal loss, which can extend to the liver (Fig 10c, 10d). This is due to the relatively long pulse sequence TE of about 20 msec that is most commonly used in current MR elastography protocols. This TE is extremely sensitive to susceptibility artifact. Finally, since MR elastography is a breath-hold sequence (approximately 16 sec), any motion artifact will decrease the quality of the elastogram.

Causes of Nondiagnostic Elastograms.—There are three main causes of a nondiagnostic elastogram (Table). The most common cause is significant iron overload (Fig 8c) (25). Iron overload results in a lower liver signal-to-noise ratio, which can lead to unreliable measurements (32). When this occurs, repeating the elastography examination with conventional gradient-echo MRI sequences will not correct the problem. More recently available spin-echo MRI sequences that are less affected by iron overload can be used, if they are available (48,49). Another cause for nondiagnostic elastograms is a nonfunctioning active driver, which can be inadvertently turned off or may need to be rebooted. Finally, the connecting tube between the active driver and passive driver may be disconnected or kinked (34) (Fig 11).

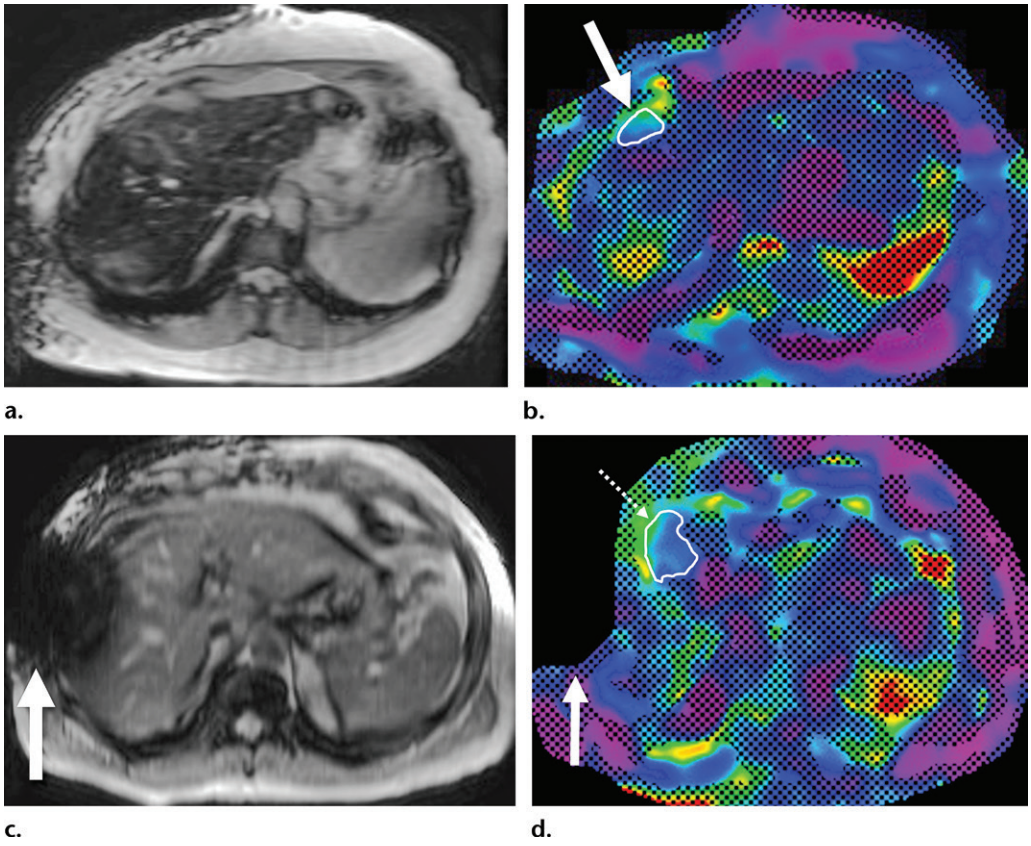


Figure 10. Low-quality elastograms. **(a, b)** Axial magnitude image **(a)** shows relatively decreased liver signal intensity that is due to mild iron overload and results in a low-quality color elastogram **(b)**, with only a small portion of the liver (arrow in **b**) not covered by the 95% confidence map for LSM. **(c)** Axial magnitude image shows a signal void (arrow), caused by an abdominal wall metal clip, along the lateral aspect of the liver. **(d)** Color elastogram shows a signal void (solid arrow) that extends into the liver and results in a low-quality elastogram, with only a small portion of the liver (dashed arrow) not covered by the confidence map for LSM.

MR Elastogram Interpretation and Reporting

After an MR elastography examination is performed, the interpreting radiologist needs to understand how to obtain LSMs, the potential measurement pitfalls, and how to report examination results. These issues are discussed in the next section.

"Gestalt" Assessment

When interpreting MR elastography findings, the first step is to perform an overall "gestalt" assessment to determine whether the elastogram is probably normal or probably depicts elevated liver stiffness. The specific images that need to be reviewed for this assessment include the wave images, 0–8-kPa color elastogram, and gray-scale and color elastograms with the 95% confidence maps.

Wave images of healthy nonfibrotic livers generally show waves that are thinner and become darker as they move centrally, because they are attenuated by the soft liver parenchyma. On the 0–8-kPa color elastogram, the liver parenchyma will be blue or purple owing to lower normal liver stiffness values. On the gray-scale and color elastograms, only the liver periphery may not be covered by the 95% confidence map owing to wave attenuation by healthy soft liver parenchyma. However, this noncoverage does not indicate a low-quality elastogram (30) (Fig 12a–12c, Movie 8).

In contrast, fibrotic and cirrhotic livers show thicker waves that are not attenuated centrally, as they move more quickly through the stiffer liver parenchyma. On a 0–8-kPa color elastogram, the liver parenchyma will be red or orange owing to higher liver stiffness values. On the gray-scale and color elastograms, most of the liver is not covered by the 95% confidence map because of the lack of attenuation as the waves pass through the stiff liver parenchyma (Fig 12d–12f, Movie 9).

Obtaining LSMs

The next step in the interpretation process is to correlate the gray-scale elastogram findings with the magnitude image (providing anatomic information) findings to determine what portions of the liver are being sampled on the gray-scale elastogram (Fig 13). Note that these two images are created with the same pulse sequence and from the same acquired data; therefore, they reflect the same

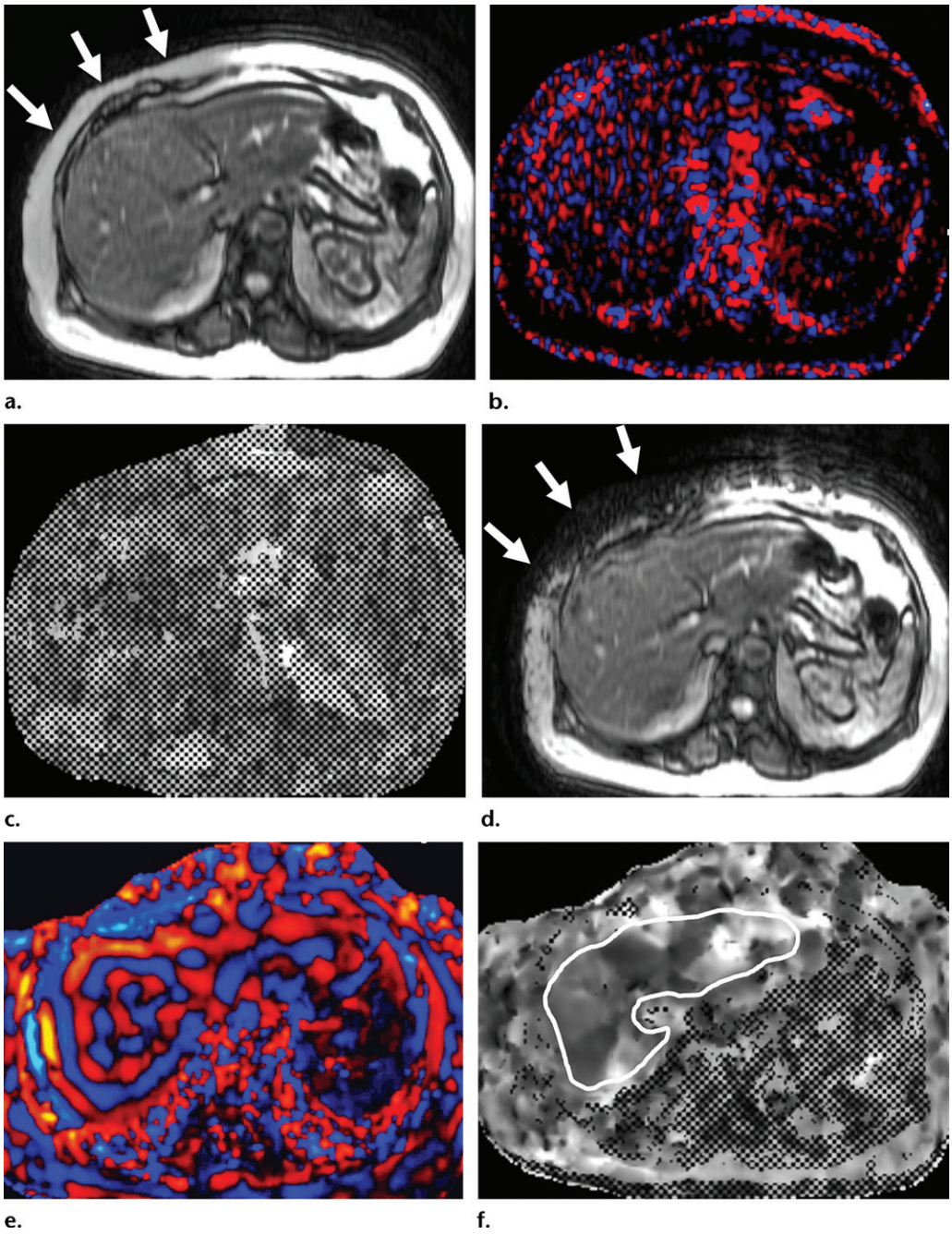


Figure 11. Disconnected tube. **(a–c)** Magnitude image **(a)** shows no subcutaneous signal void in the abdominal wall (arrows). As a result, no waves are present on the wave image **(b)**, and the gray-scale elastogram **(c)** is nondiagnostic, with the entire liver covered by the confidence map. The cause for this nondiagnostic elastogram was disconnected tubing between the active driver and passive driver. **(d–f)** Magnitude image **(d)** obtained at repeat MR elastography a few minutes later, after the tubing was reconnected, shows a signal void (arrows) in the abdominal wall, with excellent waves moving through the liver on the wave image **(e)** and a significant amount of liver tissue (outlined) available to sample on the gray-scale elastogram **(f)**.

anatomy. LSM can be performed manually or by using automated software (50). However, even if the measurements are automated, it is important to understand how they were obtained and to validate their accuracy by obtaining manual measurements. The manual LSM technique and associated pearls and pitfalls are outlined in this section.

LSM can be performed on the MRI unit. However, for convenience and workflow optimization, these measurements usually are obtained on an independent workstation or a picture archiving and communication system (PACS), as long as the obtained values have been validated to match those obtained on the MRI unit. The following text describes how to obtain an LSM by using a commercially available PACS workstation. With this method, the freehand ROI tool is used to obtain measurements. Using the freehand ROI tool, the

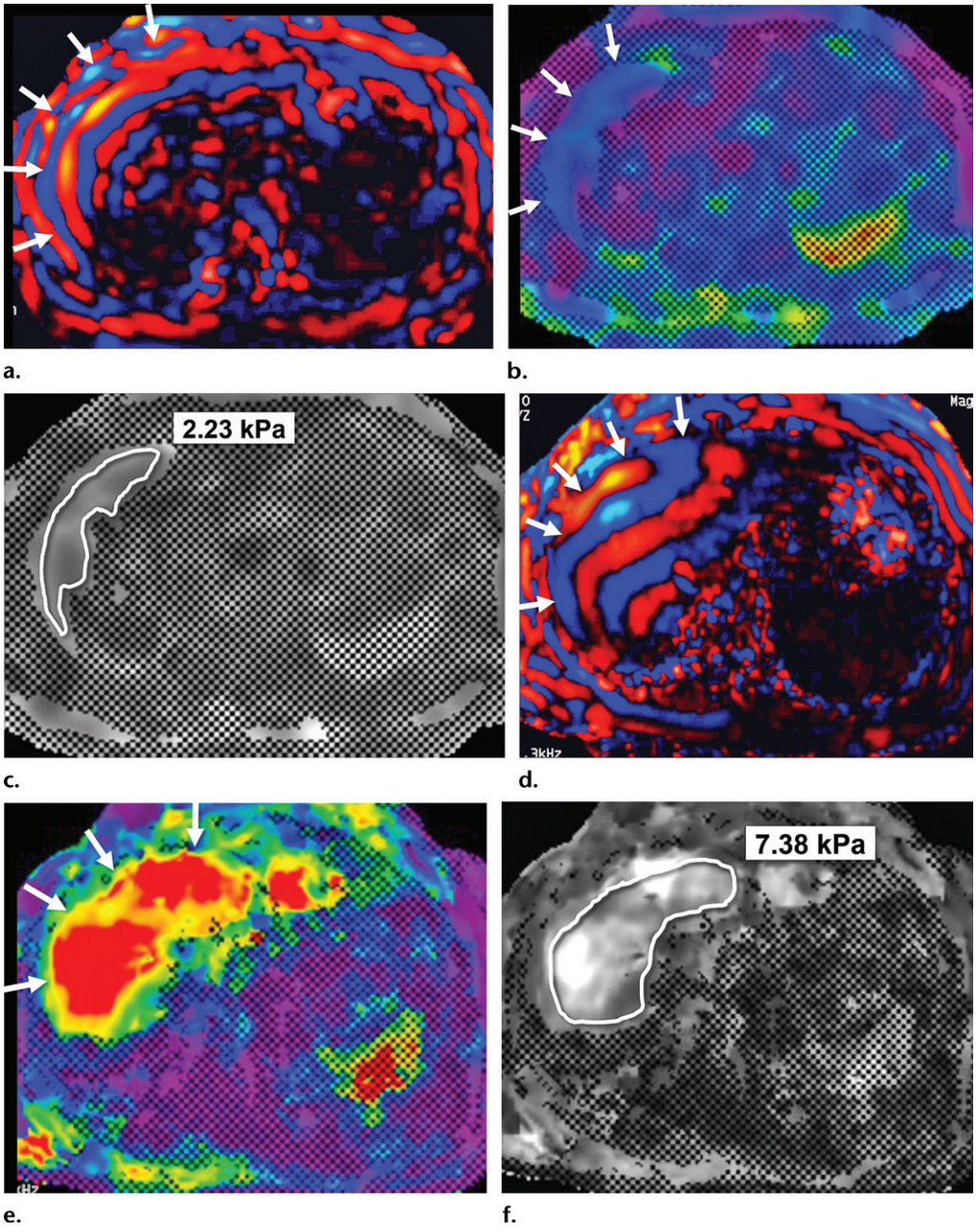
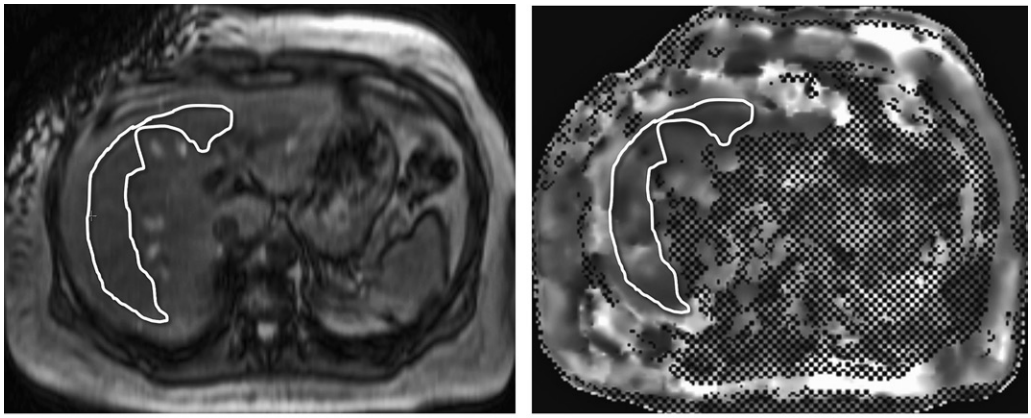


Figure 12. Gestalt assessment of MR elastography findings in a healthy nonfibrotic liver **(a–c)** and a fibrotic liver **(d–f)**. **(a)** Wave image shows thin waves (arrows) that darken centrally as they are attenuated by soft normal liver parenchyma (Movie 8). **(b)** On the color elastogram, the liver tissue not covered by the 95% confidence map is blue or purple (arrows) owing to lower stiffness values. **(c)** On the gray-scale elastogram, only the liver periphery (outlined) is not covered by the 95% confidence map. However, this noncoverage is due to the waves being attenuated by healthy liver tissue rather than to a low-quality elastogram. **(d)** Wave image in a fibrotic liver shows waves (arrows) that are thicker than those in **a** and not attenuated centrally, because they move more quickly through the stiffer liver parenchyma (Movie 9). **(e)** On the color elastogram, the liver tissue not covered by the 95% confidence map is red or orange (arrows) owing to elevated stiffness values. **(f)** On the gray-scale elastogram, most of the liver (outlined) is not covered by the 95% confidence map.

largest portion of the liver is drawn on each of four elastograms. The outer margin should be drawn parallel to the liver margin, 1 cm or more from the liver edge, which is determined by correlating the elastogram image with the anatomic information provided on the magnitude image. The inner margin should avoid the edge of the 95% confidence map that is superimposed on the elastogram (8). LSMs are obtained in the largest measurable portion of the liver on each of the four elastograms (51). On each image, a mean LSM, in kilopascals, along with the ROI size, in square centimeters, is obtained. Then, the overall mean liver stiffness is obtained by calculating the weighted arithmetic



a. b.

Figure 13. Magnitude image **(a)** and gray-scale elastogram with a superimposed 95% confidence map **(b)** show matching freehand ROIs. Information on the magnitude image is used to determine which portions of the liver are being sampled on the gray-scale or color elastogram.

mean, which reflects the relative contribution of the area of the liver measured on each image. The weighted arithmetic mean of these measurements is the mean liver stiffness value for the examination (44).

The following is the generic formula for calculating the weighted arithmetic mean (AM_w) of the mean liver stiffness *(m)* for the ROIs drawn on four images, with each image having an ROI size of *w* pixels: $AM_w = (m_1w_1 + m_2w_2 + m_3w_3 + m_4w_4) \div (w_1 + w_2 + w_3 + w_4)$, where m_1, m_2, m_3, and m_4 are the mean liver stiffness values measured on the four elastograms, and w_1, w_2, w_3, and w_4 are the sizes of the ROIs drawn on each of the four elastograms.

In an example case, sample measurements are obtained from the four elastograms as follows: For elastogram 1, the mean liver stiffness and ROI size are 2.6 kPa and 30 cm^2, respectively; for elastogram 2, 3.0 kPa and 40 cm^2, respectively; for elastogram 3, 3.2 kPa and 35 cm^2, respectively; and elastogram 4, 3.2 kPa and 50 cm^2, respectively. Thus, the weighted arithmetic mean is calculated as follows: $[(2.6 \times 30) + (3.0 \times 40) + (3.2 \times 35) + (3.2 \times 50)] \div (30 + 40 + 35 + 50) = 3.0$ kPa. Thus, for this examination, the mean liver stiffness to report for this examination is 3.0 kPa (Fig 14) (44).

Areas to Avoid When Obtaining LSMs

When obtaining LSMs, it is important to sample large portions of the liver on each elastogram. The large sample size improves the reliability of the results and is one of the major advantages of MR elastography, as compared with US-based elastography techniques, with which a significantly smaller portion of the liver is sampled. However, there are areas in the liver that do not reflect the true liver stiffness and thus should be excluded when ROIs are drawn, even if these areas are not covered by the overlaid 95% confidence map. On each of the four elastogram images, including the magnitude images, wave images, gray-scale elastogram, and color elastogram, there are predictable measurement pitfalls to avoid.

On the magnitude images, which provide the best anatomic detail of the liver, it is important to avoid the liver edge (≥1 cm from liver edge), nonhepatic tissues, fissures, gallbladder fossa, and large blood vessels (30,33). The left hepatic lobe can have significant motion artifact due to cardiac pulsations and thus should be avoided as well, unless no motion artifact is identified. On the wave images, areas of poor wave propagation, wave distortion (Fig 15a, Movie 10), and low-amplitude waves should be avoided (30). On the gray-scale and color elastograms, the crosshatched regions on the superimposed 95% confidence map must be excluded from measurements. Finally, on the color elastogram, hot spots (discussed in the next section) need to be recognized and excluded from measurements (Fig 15b).

Hot Spots.—Liver hot spots are focal areas of elevated liver stiffness that are artifactual and do not reflect actual regions of increased stiffness (33). On color elastograms, hot spots appear as focal red or orange regions. The 95% confidence map may not recognize hot spots, leaving them uncovered and available to measure. However, hot spots need to be recognized by the interpreting radiologist, because including the values for these regions will spuriously increase mean LSMs, potentially making a normal liver appear abnormal or overstaging liver fibrosis.

Many hot spots occur in predictable locations. The two most common areas where hot spots occur are just beneath the passive driver (passive

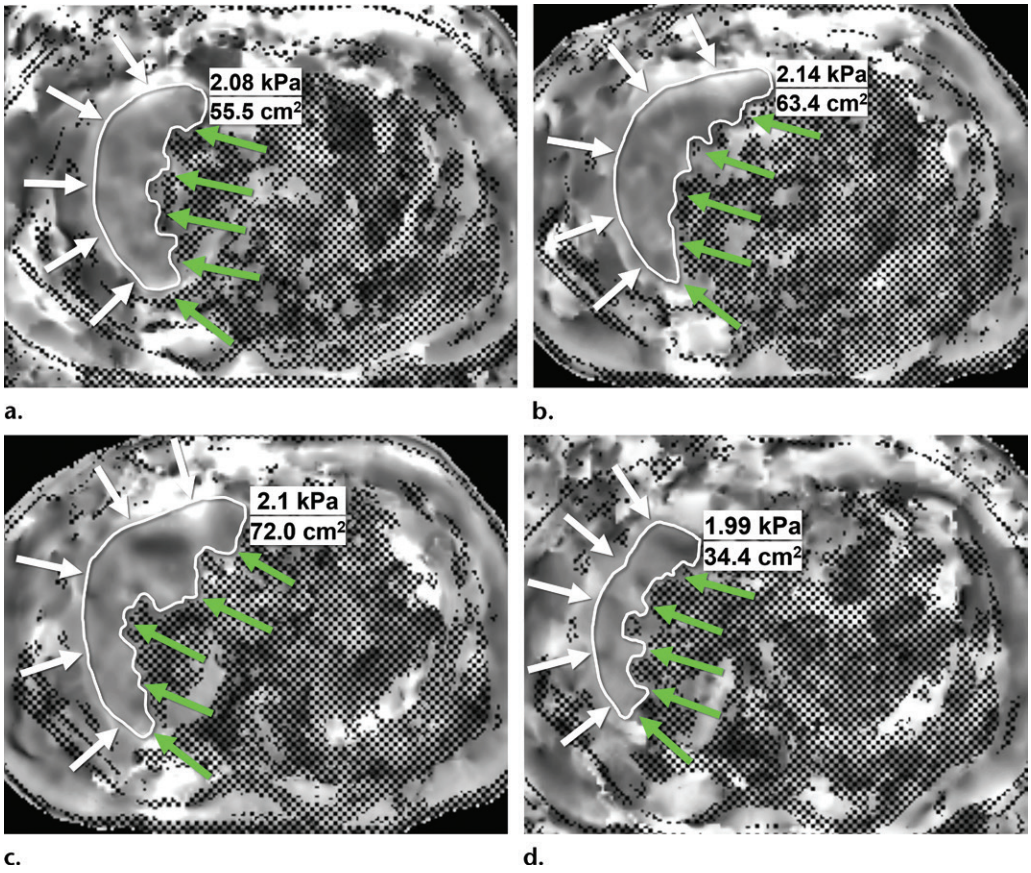


Figure 14. Acquisition of LSMs and calculation of the mean liver stiffness. Four gray-scale elastograms with superimposed confidence maps show the proper way to obtain LSMs. Using the freehand ROI tool, the largest portion of the liver is drawn on each of the four elastogram sections. The outer margin (white arrows) should be drawn parallel to the liver margin, 1 cm or more from the liver edge. The inner margin (green arrows) should avoid the 95% confidence map. For this examination, four measurements were obtained. The weighted mean LSM was calculated as follows: [(2.08 × 55.5) + (2.14 × 63.4) + (2.1 × 72.0) + (1.99 × 34.4)] ÷ (55.5 + 63.4 + 72.0 + 34.4) = 2.1 kPa. Therefore, 2.1 kPa was the mean liver stiffness reported for this examination.

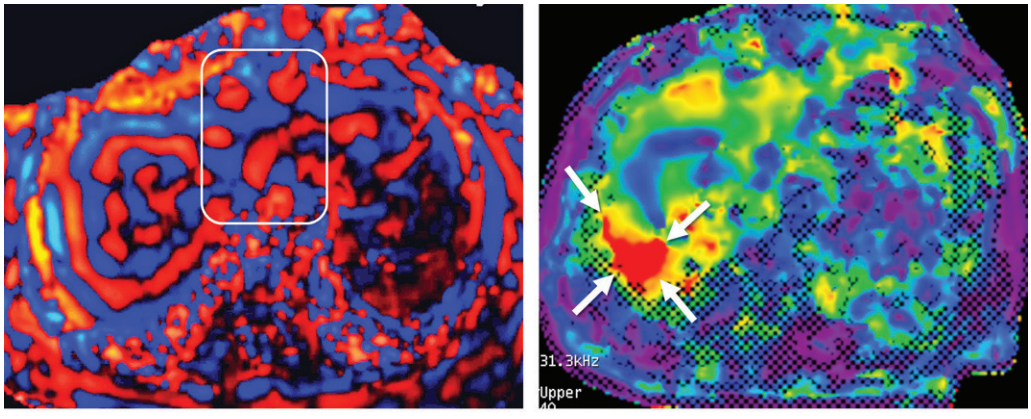
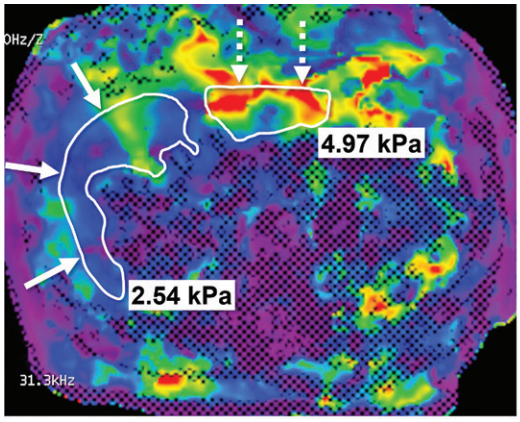


Figure 15. Two areas to avoid when obtaining LSMs. **(a)** Wave image shows wave distortion (rectangle) in the left hepatic lobe (Movie 10). **(b)** Color elastogram shows a liver dome hot spot (arrows) posteriorly.

driver hot spot) and along the liver dome (liver dome hot spot). The passive driver hot spot is seen most commonly in the anterior aspect of the liver, just beneath the passive driver, and is likely to result from excessive or disorganized vibrations created by the adjacent driver (Fig 16).

The liver dome hot spot is due to the orientation of waves as they pass obliquely through the liver dome owing to the shape of the liver (Fig 17). Oblique waves will appear thicker than waves that pass transversely through the liver and thus have artificially elevated liver stiffness values. This



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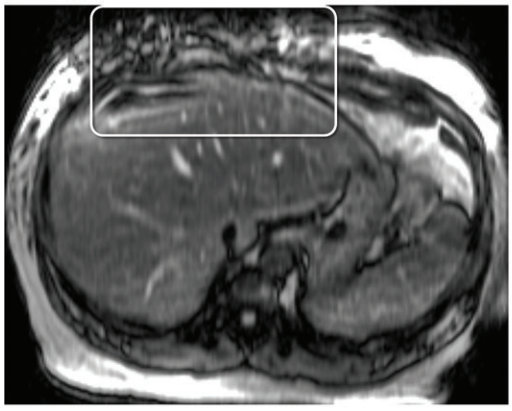

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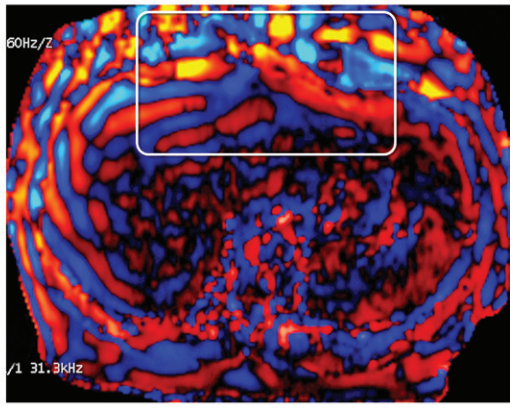

c.

Figure 16. Passive driver hot spot. **(a)** Color elastogram with 95% confidence map shows a passive driver hot spot (dashed arrows), which is not covered by the 95% confidence map, in the anterior left hepatic lobe. This portion of the liver should not be included in the LSMs. Compare the spurious liver stiffness value measured in this hot spot (4.97 kPa) with the valid measurement (2.54 kPa) (solid arrows) obtained in the right lobe on the same image. **(b)** Magnitude image shows that the cause of the hot spot is probably excessive or disorganized vibrations from the adjacent passive driver (rectangle). **(c)** Wave image shows wave distortion (rectangle) in a region matching the hot spot location in **a**.

is why the liver dome should be avoided on the four acquired elastograms. Hot spots may also be due to random areas of wave distortion. Finally, radiologists should be aware that a hot spot can also correspond to a mass (tumor) in the liver or an area of focal fibrosis. Thus, it is important to correlate the elastogram findings with findings from other MRI pulse sequences (40).

Hot spots are conspicuous only when the background liver stiffness is normal or a lower stage of liver fibrosis is present. In livers that have higher levels of fibrosis or cirrhosis, the liver parenchyma is stiffer and therefore conducts mechanical shear waves much more efficiently. Thus, there is a low probability of a hot spot being created. Even if a hot spot is created, it may blend with or be obscured by the stiff background liver parenchyma (Fig 18).

Causes of Increased Liver Stiffness Mimicking Fibrosis or Cirrhosis

In some cases, elevated liver stiffness may not be due to fibrosis or cirrhosis. For example, liver stiffness values will increase after a meal, especially in patients with chronic liver disease (34–39). A normal liver has a minimal or no increase in liver stiffness following a meal. It is possible that this phenomenon can be used to detect early fibrosis. However, no conclusive studies have been performed to show the advantage and/or utility of postprandial liver MR elastography in liver fibrosis staging. For this reason, patients should fast 4–6 hours before undergoing liver MR elastography.

Other causes of increased liver stiffness include acute inflammation (Fig 19a, 19b) (52–54), extrahepatic cholestasis (55,56), passive hepatic congestion (Fig 19c, 19d) (57,58), and infiltrative processes (8,33,59). Since causes other than fibrosis or cirrhosis can lead to increased LSMs, the measurements should always be interpreted in conjunction with clinical and laboratory findings for other possible causes of the increased liver stiffness. It is important to note that the factors just described may lead to artificially increased, but not decreased, LSMs. Therefore, if a normal liver stiffness value is obtained, this should be accepted and considered reliable. Finally, the results of most studies (24,28,52,60) have shown that hepatic steatosis does not significantly affect LSMs.

Recording Results in the Radiology Report

After LSMs are obtained and the mean liver stiffness is calculated, this information needs to be included in the radiology report. A dictation

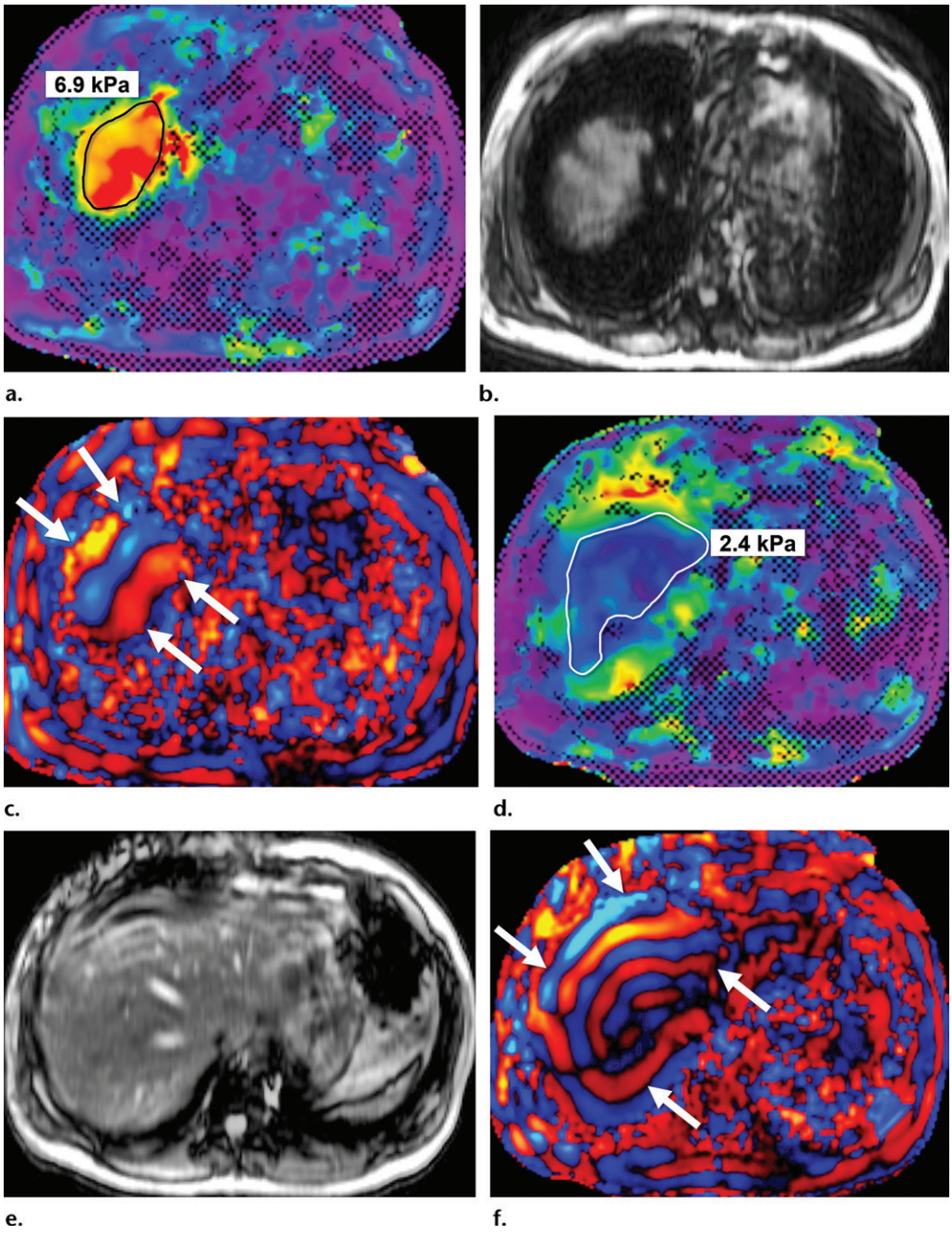

Figure 17. Liver dome hot spot illustrated by comparing two sections obtained at MR elastography: a liver dome section **(a–c)** and a section from a better location below this level **(d–f)**. **(a)** Color elastogram of the liver dome, with a superimposed confidence map, shows a hot spot that is not covered by the confidence map. This hot spot has a spuriously high LSM (6.9 kPa) and should not be included in the measurements. **(b)** Magnitude image shows the location of the liver dome hot spot. **(c)** Wave image shows thicker obliquely oriented waves (arrows) compared with the lower liver section in **f**, resulting in a spuriously high LSM. **(d)** Color elastogram with a superimposed confidence map shows a valid LSM of 2.4 kPa in the lower portion of the liver. **(e)** Corresponding magnitude image shows a location in the liver that is better than the dome for obtaining liver sections. **(f)** Wave image shows waves (arrows) in the lower region of the liver that are thinner than those in the liver dome.

template can be helpful for structuring the radiology report. We have created a structured report template that can be used as a stand-alone MR elastography template or added to a diagnostic MRI template. The MR elastography report template is available at *https://radreport.org/home/50792*. Important items to report include the number of LSMs obtained and the calculated mean liver stiffness. Including an MR elastography table that lists the thresholds for each fibrosis stage, which are based on imaging at a driver frequency of 60 Hz, is helpful (Fig 20) (8). Finally, the report can include a reminder that liver stiffness values should be interpreted in

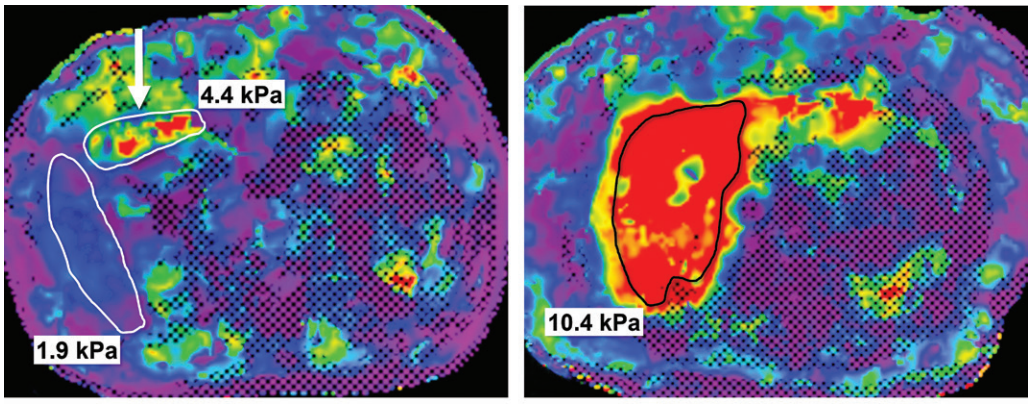

Figure 18. Background liver stiffness in two patients. **(a)** Color elastogram with a superimposed confidence map shows a passive driver hot spot (arrow) in the anterior region of the liver. This spot is conspicuous owing to the normal stiffness of the background tissue in the adjacent liver, which is blue. LSM of the hot spot yielded an artificially elevated stiffness value of 4.4 kPa, as compared with the valid LSM of 1.9 kPa in the lateral right lobe. **(b)** Color elastogram with a superimposed confidence map in another patient, who has cirrhosis, shows red and orange regions throughout the liver, indicating diffuse elevated background liver stiffness, which may obscure hot spots. The LSM for this region was 10.4 kPa.

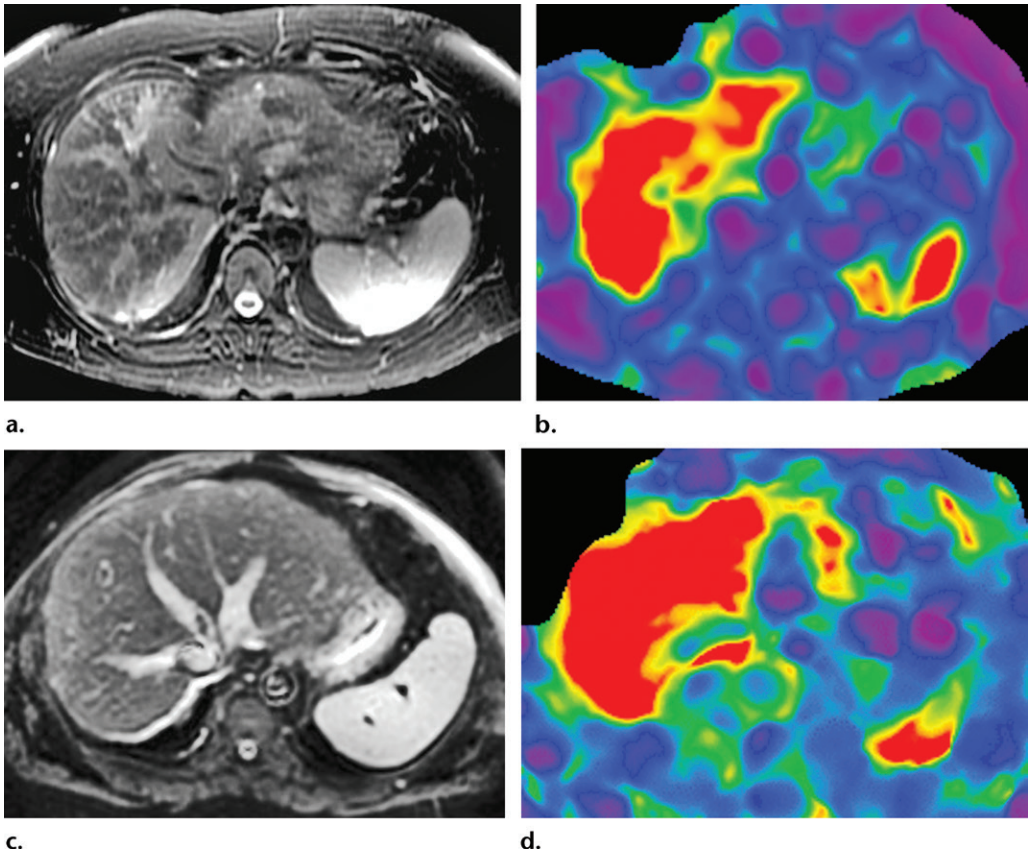

Figure 19. Elevated liver stiffness related to causes other than fibrosis in two patients. **(a, b)** Axial T2-weighted MR image **(a)** and color elastogram **(b)** in a patient with acute hepatitis show patchy edema throughout the liver **(a)** and diffuse increased liver stiffness (red and orange regions in **b**). **(c, d)** Axial T2-weighted MR image **(c)** and color elastogram **(d)** in a patient with passive hepatic congestion show dilated hepatic veins **(c)** and diffuse increased liver stiffness (red and orange regions in **d**).

conjunction with clinical and laboratory results for other causes of increased liver stiffness.

In the "Impression" section of the radiology report, one of the impression statements should summarize the elastography component of the study. An impression might be "Mean liver stiffness of 2.6 kPa consistent with normal or inflammation."

Mean liver stiffness (weighted mean of [ ] measurements): [ ] kPa.
MR elastography estimates of hepatic stiffness (at 60 Hz) correlate with hepatic fibrosis stages as:
<2.5 kPa: Normal
2.5 - 2.9 kPa: Normal or Inflammation
2.9 - 3.5 kPa: Stage 1 to 2 Fibrosis
3.5 - 4 kPa: Stage 2 to 3 Fibrosis
4 - 5 kPa: Stage 3 to 4 Fibrosis
>5 kPa: Stage 4 Fibrosis or Cirrhosis
(These are broad categories and results should be interpreted with clinical and laboratory findings for other possible causes of increased liver stiffness.)

Figure 20. MR elastography section of a radiology report dictation template. (Reprinted, with permission, from reference 8.)

MR Elastography Technologist Checklist

1. The passive driver was fastened firmly to the abdominal wall..... Yes ☐ No ☐
2. The passive driver was applied during end-expiration..... Yes ☐ No ☐
3. The calibration scan, localizer scan and MRE were all obtained during end-expiration..... Yes ☐ No ☐
4. Images include the widest portion of liver (excluding dome & inferior tip of right lobe) ... Yes ☐ No ☐
5. The driver amplitude setting for this scan was: _____%
6. The driver frequency setting was 60 Hz for this scan Yes ☐ No ☐

Technologist MRE QC:

1. The magnitude images show signal loss in the SQ fat just below the passive driver..... Yes ☐ No ☐
2. The phase images show shear waves in the liver..... Yes ☐ No ☐

If the MRE needed to be repeated:

1. What was the reason? _____
2. Which radiologist was contacted for input (if applicable)? _____
3. What was changed for the repeat scan? _____

Technologist: _____

Figure 21. MR elastography *(MRE)* technologist checklist. The quality control *(QC)* checklist can be completed by MRI technologists for each MR elastography examination. Use of this checklist may help improve communication between the MRI technologist and interpreting radiologist. *SQ* = subcutaneous.

Liver stiffness values are usually reported to the nearest decimal point (eg, 2.6 kPa rather than 2.63 kPa). At 60 Hz, most normal livers will have a mean stiffness of less than 2.5 kPa (8,51,61,62). Liver stiffness progressively increases with increasing stages of fibrosis (24). Liver inflammation also can cause an increase in liver stiffness (63,64).

Communication between the MR Elastography Technologist and Radiologist

Communication between the MRI technologist who performs the MR elastography examination and the radiologist is important for quality control. For example, if a low-quality elastogram is created, it is important to know what factors, such as the driver power output setting or phase of respiration in which the passive driver was applied, may have contributed to this result. Knowledge of the contributing factors is useful for improving the quality of current or subsequently obtained MR elastography studies. For this reason, an MR elastography technologist checklist such as the one shown in Figure 21 can be helpful if it is completed by the technologist performing the MR elastography examination. Using this form on a regular basis can serve as a method of communicating with the interpreting radiologist while reinforcing the proper MR elastography technique for technologists. While the proposed checklist is probably not needed in high-volume practices or centers where the staff have several years of experience, it may be useful during the initial stages of implementing liver MR elastography into a clinical practice, or it can be used to train new technologists.

Conclusion

MR elastography is currently the best noninvasive imaging technique available for measuring liver stiffness to evaluate for possible liver fibrosis or cirrhosis. However, obtaining and reporting accurate and reliable LSMs with MR elastography requires optimal imaging technique, quality control evaluation of images, and proper

interpretation and reporting of elastogram findings. The six most important technical components that need to be optimized are patient fasting, proper passive driver placement, MR elastography section positioning over the largest portion of the liver, use of MR elastography–related sequences at end expiration, choosing the best timing of the MR elastography sequence, and optimizing several key MR elastography pulse sequence parameters.

Quality control steps need to be conducted immediately after MR elastography examinations and are performed by reviewing the magnitude, phase, and wave images and evaluating the diagnostic quality of the elastograms. Finally, the interpreting radiologist needs to understand *(a)* the proper method of performing LSM, *(b)* the areas to avoid when acquiring these measurements, *(c)* the conditions other than fibrosis or cirrhosis that can lead to increased liver stiffness, and *(d)* how to record elastography results in the radiology report.

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