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Performance of 2-D ultrasound shear wave elastography in liver fibrosis detection using magnetic resonance elastography as the reference standard: A pilot study

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Abstract

Objective—To investigate the correlation between 2-D ultrasound shear wave elastography (SWE) and magnetic resonance elastography (MRE) in liver stiffness measurement and the diagnostic performance of 2-D SWE for liver fibrosis when imaging from different intercostal spaces and using MRE as the reference standard.

Methods—2-D SWE was performed on 47 patients (22 females and 25 males, age 19–77) using the GE LOGIQ E9 scanner. Each of the 47 patients had same day MRE obtained for clinical purposes. The study was HIPAA-compliant and approved by the institutional review board. Informed consent was obtained from each subject. 2-D SWE measurements were acquired from the 9th, 8th, and 7th intercostal spaces. Correlation with MRE was calculated at each intercostal space and multiple intercostal spaces combined. The performance of 2-D SWE in diagnosing liver fibrosis was evaluated with receiver operating characteristic (ROC) curve analysis using MRE as the standard.

Results—The highest correlation between 2-D SWE and MRE was from the 8th and 7th intercostal spaces ($r = 0.68 - 0.76$). The range of the areas under the ROC curve for separating normal or inflamed livers from fibrotic livers using MRE as the clinical reference were 0.84 – 0.92 when using 8th and 7th intercostal spaces individually, and 0.89 – 0.9 when combined.

Conclusion—The results suggest that 2-D SWE and MRE are well correlated when SWE is performed at the 8th and 7th intercostal spaces. The 9th intercostal space is less reliable for diagnosing fibrosis using 2-D SWE. Combining measurements from multiple intercostal spaces does not significantly improve 2-D SWE performance for the detection of fibrosis.

Keywords

shear wave elastography; magnetic resonance elastography; liver fibrosis

Introduction

Liver fibrosis and cirrhosis affect millions of patients worldwide (1). While liver biopsy is still considered the clinical standard for diagnosing and staging of liver fibrosis (2), the potential complications due to the invasiveness of biopsy and the sampling variability significantly compromise its clinical utility (1, 3). An urgent need for non-invasive biomarkers for liver fibrosis exists (1).

Liver elasticity imaging (elastography) is an emerging medical imaging technology that can non-invasively quantify liver stiffness using shear waves (4–10). The shear modulus (G) of liver is calculated by: $G = \rho c^2$ (Eq. 1), where ρ is the density of liver tissue (assumed to be 1000 kg/m^3) and c is the shear wave speed (11). During the last two decades, a variety of elastography methods have been developed (12–14) and many have demonstrated great clinical promise for staging of liver fibrosis. A meta-analysis shows that magnetic resonance elastography (MRE) (15) has outstanding performance for liver fibrosis staging: the AUROC (Area Under ROC curve) is 0.98 for separating F0-F1 vs. F2-F4 (16). For ultrasound-based elastography techniques, a meta-analysis of 50 Fibroscan[®] studies shows a promising AUROC of 0.84 for separating F0-F1 vs. F2-F4 (17); acoustic radiation force impulse (ARFI) shear wave imaging shows a similar diagnostic accuracy to Fibroscan[®] for predicting significant fibrosis (F ≥ 2) (18); Supersonic Shear Imaging (SSI) (19) shows an AUROC of 0.948 for predicting F ≥ 2 in a study with 113 hepatitis C virus patients (9). These results indicate that liver stiffness measured by elastography is an effective biomarker for fibrosis of the liver.

Among the aforementioned elastography techniques, MRE has the best performance in staging liver fibrosis and has great potential for becoming an alternative to liver biopsy. One important feature of MRE is that it provides 2-D quantitative shear elasticity maps of the liver, which is ideal for comprehensive evaluation of the liver stiffness (5). The disadvantages of MRE, however, are related to expense and relative lack of availability, making ultrasound elastography an attractive alternative. Ultrasound elastography has gradually evolved from 1-D measurements (e.g., Fibroscan[®] and ARFI) to 2-D measurements (e.g., SSI) for more comprehensive liver fibrosis evaluation. In addition to SSI, several mainstream clinical ultrasound systems (e.g., General Electric (GE) LOGIQ E9) have recently been developed for abdominal applications of 2-D shear wave elastography (SWE). To date, the ability of 2-D SWE to diagnose liver fibrosis has predominantly been assessed using liver biopsy as the reference standard (9, 10, 20, 21). Given the potential for sampling variability with liver biopsy which is not inherent in MRE, an investigation of the performance of 2-D SWE using MRE as the standard would be informative. It is also critical to identify the ideal acoustic window for 2-D SWE measurements when using MRE as the standard. Therefore, the goals of this study were to: 1) investigate the correlation between MRE and 2-D SWE in the same cohort of liver patients with 2-D SWE measurements obtained from different intercostal spaces; 2) investigate the ability of 2-D SWE to detect liver fibrosis when using MRE as the clinical standard.

Materials and Methods

GE provided a LOGIQ E9 (LE9) ultrasound system (GE Healthcare, Wauwatosa, WI) with a pre-commercial-release version of 2-D shear wave elastography for this study. One author without a conflict of interest (M.R.C.) served as guarantor to oversee the integrity of the study. Ultrasound 2-D SWE processing was performed by one author (P.S.) who was blinded to MRE and clinical diagnostic results.

Subjects

The institutional review board approved this prospective study which is also compliant with the Health Insurance Portability and Accountability Act. Each participating subject provided written consent. 2-D SWE evaluation of forty-seven patients with known or suspected hepatic disease (22 females and 25 males; age range 19–77 years; body mass index, 16.97–33.77) occurred between May and November 2014. Each patient had a same day MRE obtained for clinical purposes. MRE was not available for one patient due to iron overload. This patient was excluded from the study, reducing the total number of subjects to 46. Table I summarizes the clinical diagnosis of these patients. Inclusion criteria were: both male and female patients scheduled to receive liver MRE for clinically known or suspected liver fibrosis, age 18 to 80 years, and body mass index < 35. Exclusion criteria were: patients lacking capacity to consent, and patients without successful MRE exam.

2-D SWE Measurements and MRE Exams

Measurements were obtained using a LOGIQ E9 with an abdominal 2-D shear wave elastography application. LE9 2-D SWE uses comb-push excitation to produce shear waves and a time-aligned sequential tracking method to detect shear wave signals (22). The comb-push technique simultaneously produces multiple shear waves inside the tissue to improve shear wave signal-to-noise-ratio (SNR), followed by directional filtering to remove the shear wave interferences, which allows robust reconstruction of 2-D shear elasticity maps (23, 24). Two shear wave imaging modes were available on a curvilinear transducer (C1-6-D, GE Healthcare): the high frame rate (HFR) mode and the penetration (PEN) mode. HFR offers higher real-time SWE frame rate with less penetration, while PEN offers higher penetration with lower SWE frame rate. Both modes were used in this study to investigate the tradeoff between frame rate and penetration as well as the repeatability and consistency of the 2-D SWE measurements. The subjects were placed in the left posterior oblique position and with their right arm across their chest. Each patient was scanned by one of the two sonographers who had 27 years and 6 years of experience respectively. Sonographers used the 9th, 8th, and 7th intercostal spaces in the right anterior axillary line to image the liver and obtain measurements. The acquisition region-of-interest (ROI) was placed at least 1.5–2.0 cm from Glisson's capsule to avoid shear wave measurement bias (21). The size of the acquisition ROI was always the same by system default. The depth of the ROI depended on the thickness of the body wall, but should be the same for each patient across different intercostal spaces. Ten repeated SWE measurements were acquired with end-expiration breath holds at each intercostal space. Each SWE acquisition takes about 1 to 2 seconds (acquisition time plus cooling time). The HFR mode was used first to acquire from all three intercostal spaces, and then the PEN mode was used to repeat the acquisitions. Sixty 2-D

SWE total images (10 images x 3 intercostal spaces x 2 imaging modes) were acquired for each subject. Figure 1 shows two example 2-D SWE images, one acquired from a subject with MRE = 1.38 m/s (indicating normal liver), and the other acquired from a subject with MRE = 2.47 m/s (indicating advanced fibrosis).

The MRE exams were performed using a 1.5T MRI scanner (GE Healthcare, Milwaukee, WI), with a pneumatic driver attached to the subject's abdomen to provide a continuous harmonic vibration at 60 Hz (25). The MRE exam images were analyzed following the standardized clinical routine (25).

Post processing

All 2-D ultrasound SWE images were post-processed by one author blinded to the MRE and clinical diagnosis results. For each LE9 2-D SWE image, a circular ROI (~2 cm²) was drawn on the 2-D shear elasticity map to obtain a shear wave speed measurement, as shown in Fig. 1. The ROI automatically eliminates pixels that are outside of the elasticity map or are not color-filled (which indicates unreliable measurements), and a mean shear wave speed within the ROI is obtained. One mean shear wave speed value was obtained from each 2-D SWE image. A failed 2-D SWE acquisition was defined as less than 50% of color filling of the elasticity map. After recording all measurements, the data was further screened based on the following criteria: if one intercostal space had more than 5 failed acquisitions, all 10 acquisitions from this intercostal space were counted as failed; for the 10 measurements from the same intercostal space, if the interquartile range (IQR)/median ratio was greater than 30% (i.e. poor repeatability), then all 10 measurements were counted as failed (26). After this screening, only repeatable and consistent 2-D SWE measurements were preserved. Table II summarizes the success rate of 2-D SWE on the LE9 after the data screening. Figure 2 shows the average IQR/Median ratios of the shear wave speed measurements from each intercostal space for all of the subjects.

The median value of the 10 shear wave speed measurements obtained from each intercostal space was first calculated and then was used for analysis. To investigate the potential advantage or necessity of combining measurements from multiple intercostal spaces, the median value of the shear wave speed measurements from all intercostal spaces combined was also calculated. Because the 9th intercostal space had either the highest IQR/Median ratio or the lowest success rate (Table II and Fig. 2), an additional subset was created in which the median value of the shear wave speed measurements from the 8th and 7th intercostal spaces were calculated. Before combining the data from multiple intercostal spaces, a new IQR/Median ratio was calculated and measurements with > 30% ratio were removed (2 patient data sets were removed when combining all intercostal spaces; 1 patient data set was removed when combining 8th and 7th intercostal spaces).

Statistical analysis

Linear regression was used to fit the liver stiffness measurements between LE9 2-D SWE and MRE. Pearson product-moment correlation (r) was used to evaluate the correlation between 2-D SWE and MRE. The MRE measurements were converted from shear modulus (kPa) to shear wave speed (m/s) using Eq. 1. The analysis was conducted for each imaging

mode at each intercostal space, all intercostal spaces combined, and then the 8th and 7th intercostal spaces combined. The ability of LE9 2-D SWE to differentiate livers without fibrosis (MRE = 1.71 m/s, indicating normal liver or inflammation but no fibrosis (25)) from liver with fibrosis (stage 1 and above) was evaluated by using receiver operating characteristic (ROC) curve analysis ($\alpha = 0.05$ for 95% confidence interval) using Matlab 8.2.0.701 (The MathWorks, Natick, MA). The differentiation of these two groups is clinically important because patients with normal MRE typically do not need liver biopsy. The ability of 2-D SWE to detect stage 4 fibrosis or cirrhosis (MRE = 2.24 m/s) was not assessed because the studied patient population was skewed with only 5 out of 46 patients having advanced fibrosis.

Results

Figure 3 shows the scatter plots and linear regression analysis between shear wave speed measurements of 2-D SWE and MRE, and between the HFR and PEN modes of 2-D SWE at different intercostal spaces. The MRE and LE9 2-D SWE correlated well at the 8th and 7th intercostal spaces (linear regression slope: 0.87–1.06; r : 0.68–0.76) but not at the 9th intercostal space. The poor correlation at the 9th intercostal space can be partially explained by the unstable 2-D SWE measurements, as suggested by the higher IQR/Median ratio for both modes of 2-D SWE in Fig. 2. The two imaging modes of LE9 2-D SWE achieved high correlation at the 8th and 7th intercostal spaces (linear regression slope: 0.97–0.99; r : 0.94). Because the HFR mode was used to scan all 3 intercostal spaces before switching to PEN mode to repeat the measurements, the high correlation suggests good repeatability of the shear wave speed measurements for the LE9 2-D SWE. However, neither the HFR mode nor the PEN mode correlated well at the 9th intercostal space. This again suggests less reliable shear wave speed measurements at this intercostal space for 2-D SWE.

Figure 4 shows the scatter plots and linear regression analysis of shear wave speed measurements by MRE and 2-D SWE when combining the measurements from different intercostal spaces. The upper row shows the results of combining all intercostal spaces; the lower row shows the results of combining the 8th and 7th intercostal spaces. Clearly, combining the 8th and 7th intercostal spaces shows better correlation (linear regression slope: 0.91–0.97; r : 0.70–0.73) than combining all of the interspaces (linear regression slope: 0.88–0.89; r : 0.54–0.68), probably due to the unstable 2-D SWE measurements from the 9th intercostal space. There is no significant change of correlation between MRE and 2-D SWE or HFR and PEN after combining the 8th and 7th intercostal spaces. HFR and PEN again showed tight correlation with each other, suggesting robust repeatability. Both modes showed similar correlation to MRE both before and after the combination.

Figure 5 shows the ROC curves for LE9 2D-SWE in differentiating the normal or inflamed liver (MRE = 1.71 m/s) from fibrotic liver (stage 1 and above) when imaging from different intercostal spaces. The MRE cutoff value of 1.71 m/s was used for the analysis (25). The AUROC, 95% CI AUROC, cutoff value for optimal operating point and corresponding sensitivity and specificity were summarized in Table III. The two imaging modes achieved comparable AUROC, sensitivity and specificity from the 8th and 7th intercostal spaces. The highest AUROC (0.92) was from the HFR mode when imaging from the 7th intercostal

space. The PEN mode from the 8th intercostal space had the highest sensitivity of 0.88 and specificity of 0.84. The PEN mode had a slightly higher shear wave speed cutoff value than the HFR mode.

Figure 6 shows the performance of 2-D SWE in differentiating the same groups of patients when using the shear wave speed measurements combined from multiple intercostal spaces. Table IV summarizes the ROC analysis results. Combining 8th and 7th intercostal spaces only achieved slightly higher AUROC than that of using the same intercostal spaces individually (Table III). The performance of combining all intercostal spaces is comparable to that of combining only 8th and 7th intercostal spaces, which suggests that the unstable 2-D SWE measurements from the 9th intercostal space did not significantly alter the overall performance of 2-D SWE in detection of fibrosis. Both HFR and PEN modes achieved similar sensitivity and specificity, which are also similar to the values from Table III. These results suggest that combining measurements from multiple intercostal spaces does not necessarily improve the performance of 2-D SWE in differentiating normal or inflamed livers from fibrotic livers when using MRE as the reference standard.

Finally, a box plot of the shear wave speed measurements from 2-D SWE and MRE for all the patients was generated to present the data distribution, as shown in Fig. 7. The box plots were categorized as normal/inflamed liver or fibrotic liver. Data from the 8th and 7th intercostal spaces were combined for 2-D SWE.

Discussion

This study investigated the correlation between 2-D ultrasound SWE and MRE in liver stiffness assessment among the same cohort of patients. 2-D SWE and MRE were best correlated at the 8th and 7th intercostal spaces. 2-D SWE demonstrated robust ability to differentiate normal or inflamed livers from fibrotic livers when using MRE as the clinical standard. No significant improvement was observed when combining measurements from multiple intercostal spaces as compared to using each intercostal space separately.

2-D SWE provides 2-D quantitative shear elasticity maps of the liver, which results in a larger sampling area of liver stiffness measurement than 1-D elastography methods such as Fibroscan[®] and ARFI, and liver biopsy. The 2-D maps provide more samples of liver stiffness measurement within a given time, which may reduce the sampling variability and improve the clinical efficiency of liver elastography. The 2-D elasticity maps, on the other hand, also increase the complexity of data analysis and postprocessing. Different vendors of 2-D ultrasound SWE use different criteria to perform quality control of the displayed 2-D elasticity maps. In this study we rejected 2-D maps that were less than 50% color filled, which is a sign of poor shear wave signal quality. We also used the IQR/Median ratio to further scrutinize the data to reject the measurements with low repeatability. Guidelines need to be developed to standardize the data analysis process for 2-D ultrasound SWE.

The study results suggest that combining measurements from multiple intercostal spaces does not significantly improve the performance of 2-D SWE in detection of fibrosis. One possible reason is that the sampling regions of the 7th and 8th intercostal spaces are relatively

close as compared to the size of the liver. Therefore, liver stiffness appears to be relatively uniform and 2-D SWE performance at each intercostal space was almost identical to the combined. Another possible reason is that 10 acquisitions per intercostal space are more than enough given the small variation across different acquisitions. Therefore, doubling the acquisition to 20 by combining the two intercostal spaces does not significantly change the results. This implies that in clinical practice, one can identify the best acoustic window and just make 2-D SWE measurements from only this window. This will reduce the data acquisition time for each patient. However, one still needs to make repeated measurements from the same acoustic window to obtain robust liver stiffness assessment. The repeated measurements can also provide metrics such as IQR/Median to indicate the robustness of the 2-D SWE stiffness measurements.

In this study, we chose three of the most commonly used intercostal spaces for liver stiffness measurement using 2-D SWE, because currently there is no established clinical protocol on the acoustic window used for liver 2-D SWE. The majority of the scans were performed in the right lobe of the liver via the three intercostal spaces. It is commonly assumed in ultrasound elastography studies that liver fibrosis is a diffuse disease and stiffness should be relatively uniform across the liver. The results of this study show that individual intercostal space data (9th intercostal space excluded) is almost identical to combined intercostal space data, which also suggests that liver stiffness measurements obtained from different intercostal spaces are relatively uniform. Therefore, as mentioned above, this study implies that in clinical practice one can shorten the data acquisition time for each patient by just acquiring repeated 2-D SWE measurements from the best acoustic window.

The correlation between the two different 2-D SWE imaging modes is stronger than the correlation between 2-D SWE and MRE. The good correlation between ultrasound measurements demonstrated high repeatability of the technique. Figure 8 shows the results of intra- and inter-rater reliability tests using the 8th intercostal space SWE results under the PEN mode. The Pearson correlation (r) was 0.996 and the intra-class correlation (ICC) was 0.995 for intra-rater correlation; and the Pearson correlation was 0.991 and the ICC was 0.987 for inter-rater correlation: both indicating excellent intra-and inter-rater reliability. The lower correlation between 2-D SWE and MRE may result from many factors such as the location of the ROI, the frequency of the induced shear waves (MRE at 60 Hz, 2-D SWE ranges from 50 to 400 Hz), and the shear wave speed calculation methods can contribute to the discrepancy between 2-D SWE and MRE. Nevertheless, the linear regression between MRE and 2-D SWE shows good correlation and slopes close to one (for the 7th and 8th intercostal spaces), which suggests good agreement between the two techniques in the same cohort of patients. The highest correlation between 2-D SWE and MRE were observed at the 7th and 8th intercostal spaces. One possible reason is that in this study, the majority of the 2-D SWE measurements were from the right lobe of the liver, which is also where MRE is typically acquired. Liver stiffness is relatively uniform within the imaging region of both modalities. Because 2-D SWE measurements are most stable and robust from the 7th and 8th intercostal spaces, the highest correlation with MRE was found from these two intercostal spaces.

The HFR mode of 2-D SWE showed slightly higher success rate than the PEN mode. PEN outputs more acoustic energy to produce stronger shear waves, which requires longer cooling time than the HFR mode and therefore slows down the frame rate. This makes the PEN mode more susceptible to motion artifacts caused by probe, breathing, or cardiac motion. The results showed that the two modes had similar performance in diagnosing liver fibrosis and had high correlation. In practice one can select modes based on the amount of physiologic motion observed in the patient.

In this study, we categorized normal livers and inflamed livers without fibrosis into the same group to evaluate the performance of 2-D SWE in detecting liver fibrosis, following the MRE cutoff values proposed in (25). Note that liver stiffness can still increase significantly with inflammation, especially with acute inflammation (27). For patients with MRE 1.71 m/s, the liver is either normal or inflamed but without fibrosis. We did not further differentiate the two due to limited number of samples.

There are some limitations of this study. First, the patient population is relatively small and the number of subjects with advanced fibrosis (MRE 2.24 m/s) was only 5, which makes it difficult to assess the ability of 2-D SWE to diagnose advanced liver fibrosis. Because this study was prospective, it was impossible to control the distribution of patients with different stages of liver fibrosis. Second, this study excluded patients with body mass index greater than 35. These patients can be challenging for 2-D SWE because the thick subcutaneous adipose tissue can significantly attenuate the ultrasound push beam and result in poor shear wave generation. Obesity remains as a critical challenge for all 2-D SWE approaches that use acoustic radiation force for shear wave generation (28, 29). Alternative ultrasound shear wave elastography approaches with improved penetration are currently being developed (30).

In conclusion, our study shows that liver stiffness measurements from 2-D ultrasound SWE and MRE correlate best at the 8th and 7th intercostal spaces. Combining liver stiffness measurements from multiple intercostal spaces does not significantly improve the sensitivity and specificity of diagnosing liver fibrosis when using 2-D SWE. Repeated liver stiffness measurements from a single intercostal space that provides the best acoustic window may be sufficient for diagnosing liver fibrosis.

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Figure 1.
2-D ultrasound SWE images in a patient without fibrosis (a) and in a patient with advanced fibrosis (b).

Figure 2.

Plot of the average Interquartile Range (IQR)/Median ratios of shear wave speed measurements from individual intercostal spaces. The error bar was plotted from the standard deviation.

Figure 3. Scatter plots and linear regression analysis of shear wave speed measurements by MRE and 2-D SWE at different intercostal spaces.

Figure 4.

Scatter plots and linear regression analysis of shear wave speed measurements by MRE and 2-D SWE when combining measurements from different intercostal spaces.

Figure 5.
ROC curves of LE9 2-D SWE in differentiating normal or inflamed livers from fibrotic livers with MRE 1.71 m/s as the threshold.

Figure 6.

ROC curves of LE9 2-D SWE in differentiating normal or inflamed livers from fibrotic livers with MRE 1.71 m/s as the threshold. The shear wave speed measurements were combined from multiple intercostal spaces.

Figure 7.

Box plot of the shear wave speed measurements from 2-D SWE and MRE for all the patients. On each box, the central red mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points (± 2.7 standard deviation) excluding the outliers, which are plotted individually (the red cross mark).

Figure 8.

Intra- and inter-rater reliability tests for the SWE technique used in this study. The data points were from the 8th intercostal space under PEN mode. The Pearson correlation (r) and the intra-class correlation (ICC) are also shown in the plot.

Table I

Clinical diagnosis of the liver patients enrolled in this study

Diagnosis	No. of Patients (<i>n</i> = 46)
PSC	15
HCV	9
NAFLD (combine NASH and hepatic steatosis)	8
PBC	2
AIH and PSC	1
PSC and NAFLD	1
PBC and NAFLD	1
HCC and HCV	1
Liver transplant for NAFLD	1
Liver transplant for PBC	1
Liver transplant for NAFLD and HCV	1
Unknown	5

PSC: Primary sclerosing cholangitis

HCV: Hepatitis C

NAFLD: Non-alcoholic fatty liver disease

NASH: Non-alcoholic steatohepatitis

PBC: Primary biliary cirrhosis

AIH: Autoimmune hepatitis

HCC: Hepatocellular carcinoma

Table II

Success rate for liver stiffness measurements on the LE9 2-D SWE

LE9 High Frame Rate				
Intercostal space	9th	8th	7th	Overall
Total number of acquisitions	440	460	470	1370
Successful measurements	420	438	446	1304
Success rate	95%	95%	95%	95%

LE9 Penetration				
Intercostal space	9th	8th	7th	Overall
Total number of acquisitions	430	450	460	1340
Successful measurements	378	420	417	1215
Success rate	88%	93%	91%	91%

ROC analysis of LE9 2-D SWE in differentiating normal or inflamed livers from fibrotic livers with MRE as the standard

Table III

	LE9 SWE HFR			LE9 SWE PEN		
	9 th Space	8 th Space	7 th Space	9 th Space	8 th Space	7 th Space
AUROC	0.73	0.84	0.92	0.76	0.88	0.88
95% CI AUROC	0.52–0.88	0.66–0.94	0.81–0.97	0.55–0.89	0.70–0.97	0.74–0.96
Cutoff (m/s)	1.55	1.44	1.44	1.55	1.53	1.56
Sensitivity	0.67	0.76	0.83	0.85	0.88	0.88
Specificity	0.81	0.85	0.88	0.6	0.84	0.83

Table IV

ROC analysis of LE9 2-D SWE (combining measurements from multiple intercostal spaces) in differentiating normal or inflamed livers from fibrotic livers with MRE as the reference standard

All Intercostal Spaces Combined		
	LE9 SWE HFR	LE9 SWE PEN
AUROC	0.86	0.88
95% CI AUROC	0.71–0.95	0.72–0.96
Cutoff (m/s)	1.4	1.57
Sensitivity	0.84	0.89
Specificity	0.84	0.84

8th and 7th Intercostal Spaces Combined		
	LE9 SWE HFR	LE9 SWE PEN
AUROC	0.9	0.89
95% CI AUROC	0.77–0.97	0.73–0.97
Cutoff (m/s)	1.43	1.61
Sensitivity	0.83	0.72
Specificity	0.88	0.96