

ORIGINAL ARTICLE

Utilization of Shear Wave Elastography in the Evaluation of Pediatric Liver Transplant: A Prospective Case-Controlled Study

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ABSTRACT

Background: Liver biopsy is the gold standard for assessing liver allograft fibrosis but is invasive and carries risks, especially in pediatric liver transplant (PLT) recipients. Two-dimensional shear wave elastography (2D-SWE) has emerged as a promising noninvasive alternative. This study aimed to assess 2D-SWE in evaluating children post-liver transplantation (LTx) and to identify clinical and laboratory predictors of liver stiffness.

Methods: In this prospective case-control study, 20 PLT recipients and 20 healthy age- and sex-matched controls were imaged using a GE LOGIQ E10 scanner. Median stiffness, interquartile range (IQR), and IQR/median ratio were calculated based on 12 liver stiffness measurements (LSM). Comparisons between LTx recipients and controls were conducted to determine differences in LSM. A 5.96 kPa cut-off was used to define elevated LSM. Additionally, associations between liver stiffness and demographic data and laboratory findings were assessed to identify potential predictors.

Results: PLT patients exhibited significantly higher liver stiffness compared to controls. No significant differences were observed in ultrasound-guided attenuation parameter (UGAP) scores between the two groups. 44.4% of PLT recipients were above the 5.96 kPa cut-off. Exploratory analyses did not identify significant clinical or laboratory predictors of increased liver stiffness.

Conclusions: 2D-SWE is an effective noninvasive tool for assessing liver stiffness in PLT recipients, demonstrating significantly elevated stiffness compared to healthy controls. Elevated or increasing LSMs may necessitate a liver biopsy, thereby reducing the reliance on routine biopsies as standard protocol. Further studies with larger cohorts are needed to validate SWE cut-off values and explore its longitudinal utility.

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Abbreviations: 2D-SWE, two-dimensional shear wave elastography; AIH, autoimmune hepatitis; ALP, alkaline phosphatase; ALT, alanine aminotransferase; AST, aspartate aminotransferase; BMIz, BMI z-score; GGT, gamma-glutamyl transferase; IQR, interquartile range; kPa, kilopascal; LSM, liver stiffness measurement; LTx, liver transplantation; m/s, meters per second; MRI, magnetic resonance imaging; PFIC, progressive familial intrahepatic cholestasis; PLT, pediatric liver transplant; PSC, primary sclerosing cholangitis; ROI, region of interest; UGAP, ultrasound-guided attenuation parameter; US, ultrasound; WFUMB, world federation for ultrasound in medicine and biology.

1 | Introduction

Liver transplantation (LTx) has become the standard of care for children suffering from life-threatening liver diseases, significantly improving survival rates and quality of life. Current patient survival rates post-transplantation are reported to be 85% at 1 year, 71% between 1 to 5 years, and 80% > 5 years [1]. Long-term complications of LTx such as graft rejection and liver fibrosis occur in up to 60% of children [2]. While liver biopsy has been accepted as the gold standard for the assessment of allograft health [3], it is invasive and carries risks of potentially serious complications such as pneumothorax, hemothorax, and biopsy-related mortality that has also been reported [4, 5]. Additionally, it is subject to intra-observer and interobserver variability, as well as sampling errors [6, 7]. These factors deter its use for evaluating liver fibrosis and progression in pediatric liver transplant (PLT) recipients. Given these limitations, noninvasive methods are preferred for routine assessment. In the Kingdom of Bahrain, where this study was conducted, blood biomarkers and conventional grey-scale abdominal ultrasound (US) imaging are the routine methods of post-LTx assessment. Noninvasive imaging modalities such as US and magnetic resonance imaging (MRI) can depict and quantify tissue stiffness [8]. These methods operate by measuring the velocity of induced shear waves through the tissue, where the velocity of the shear wave, reported in meters per second (m/s) indicates the stiffness value of the tissue, reported in kilopascals (kPa) [9, 10]. US-based elastography offers improved ease of use and reduced cost compared to MRI-based elastography, with one-dimensional transient elastography (TE) and two-dimensional shear wave elastography (2D-SWE) being the two main methods currently in use.

FibroScan (Echosens, Paris, France) utilizes the TE method and is the most validated and widely used method to assess LTx in both adults and children [6] though the number of studies on PLT remains small [2, 11–13]. An advantage of 2D-SWE over TE is that color-coded elasticity maps (elastograms) can be superimposed on the existing B-mode image, allowing the operator to obtain real-time information in the region of interest (ROI). As a result, this newer method has seen increasing use in more recent PLT studies [6, 8, 14–18]. The GE LOGIQ E10 (GE Healthcare, Milwaukee, WI, USA) system used in this study allows for both SWE and Ultrasound-Guided Attenuation Parameter (UGAP) measurements to be recorded from the same region. SWE will allow for liver stiffness measurements to be recorded while UGAP measures US attenuation and can aid in steatosis grading. The manufacturer's whitepaper suggests steatosis thresholds of 0.65, 0.71, and 0.77 dB/cm/MHz for $\geq S1$, $\geq S2$, and $\geq S3$, respectively [19].

In August 2024, the World Federation for Ultrasound in Medicine and Biology (WFUMB) revised its 2018 guidelines for US elastography applications. However, validated liver stiffness measurement (LSM) thresholds for detecting PLT patients at risk of fibrosis were not included [20]. A recent PLT study by Kehler et al. [17] which used both E9 and E10 scanners, proposed a cut-off value of 1.41 m/s (5.96 kPa) for the prediction of any fibrosis and a value of 1.63 m/s (7.97 kPa) for significant fibrosis. We hypothesize that PLT recipients will demonstrate significantly higher LSMs as assessed by 2D-SWE compared to healthy controls.

The aim of this study was to evaluate the clinical utility of 2D-SWE in assessing liver stiffness in pediatric patients' post-LTx compared with their healthy counterparts, and to identify clinical and laboratory predictors of 2D-SWE LSMs.

2 | Materials and Methods

2.1 | Study Design and Patient Population

A total of 47 PLT patients were identified from medical records spanning January 1997 to August 2023. Of these, 5 deceased patients were excluded, resulting in 42 living PLT patients. A convenience sample of 20 patients was selected, representing 47.6% of the PLT cohort.

This work was a prospective case-control study involving 20 child and adolescent post-LTx patients and 20 apparently healthy age- and sex-matched controls. This was an open-label study; the patients were known to the principal investigator as their caring physician. LTx patients were recruited from our hospital's PLT list, excluding deceased patients, and were matched with healthy controls recruited from the outpatient clinic while accompanying other siblings presenting with minor symptoms (e.g., constipation, reflux) after ensuring through history and physical examination that they were healthy. The radiologist was not directly involved with the management of these children and was blinded to the medical and laboratory results. Exclusion criteria included individuals with obvious infectious diseases, those who are clinically unstable, and those whose guardians refused consent.

2.2 | Data Collection

For LTx patients, participant demographic data including ethnicity, age, sex, LTx indication, age at LTx, liver transplant center, graft type (living and cadaveric), donor-recipient relationship, medical therapy, and previous complications during or after LTx (infection episodes and non-infectious complications) were collected at enrolment. For the healthy controls, participant demographic data including ethnicity, age, and sex were also collected.

2.3 | Growth Status Assessment

Before scanning, both groups had anthropometric growth parameters including weight in kilograms, height in centimeters, and body mass index (BMI) ($BMI = \frac{\text{weight (kg)}}{\text{height (m)}^2}$), were assessed using a Health-O-Meter Professional height and weight scale (Health-O-Meter 500KL, Boca Raton, FL). BMI z-score (BMIz) was calculated and presented as standard deviations (SD) from age- and sex-specific reference means. The World Health Organization (WHO) child growth standards from birth to 5 years of age and the WHO growth references for school-age children and adolescents aged 5–19 years were used to interpret nutritional status [21, 22]. Accordingly, underweight was defined as BMIz < -2 SD, normal weight as BMIz between -2 SD and +1 SD, possible risk of overweight as BMIz > 1 to 2 SD, overweight as BMIz > 2 to 3 SD while obese was defined as BMIz > +3 SD.

2.4 | Blood Pressure Measurement

Blood pressure measurements were recorded for each patient using an age- and size-appropriate pediatric cuff and sphygmomanometer (Hillrom, Welch Allyn Tycos, USA) following a standard method [23]. Both systolic and diastolic blood pressure measurements were documented.

2.5 | Liver Function Test

Blood samples were collected at enrolment prior to US examination. Laboratory data for liver functions, namely, serum total proteins, albumin, globulin, bilirubin (total, direct and indirect), alkaline phosphatase (ALP), alanine aminotransferase (ALT), aspartate aminotransferase (AST), and gamma-glutamyl transferase (GGT) were recorded and compared to reference ranges.

2.6 | Measurements of Liver Stiffness and Steatosis by 2D-SWE

Measurements of liver stiffness and steatosis by 2D-SWE were performed by a single experienced senior pediatric radiologist who was an expert in 2D-SWE. A GE LOGIQ E10 system with a C1-6-D convex array ultrasound probe at a central frequency of 4 MHz was used.

A standard imaging protocol [24] was followed with patients who had fasted for at least 4 h. Liver imaging was performed using an intercostal approach; patients were positioned supine with the right arm raised, with breath held, and at least 10 mm below the liver capsule. For LTx patients, the transducer was positioned to avoid scar tissue, typically along the midline. Initially, an attenuation map and quality map of the liver were created to ensure the selection of a homogeneous area with a high signal-to-noise ratio. Subsequently, 12 UGAP and 12 SWE measurements were recorded for each patient. The UGAP measurements were recorded in dB/cm/MHz, while SWE measurements were recorded in both m/s and kPa, and the interquartile range (IQR) and median scores were recorded for both UGAP and SWE. An IQR/Median ratio of <15% is advised for UGAP measurements and <30% for SWE results recorded in kPa [20].

2.7 | Statistical Analysis

IBM SPSS Statistics 29 (IBM Corp. Released 2023. IBM SPSS Statistics for Windows, Version 29.0.2.0 Armonk, NY: IBM Corp) was used for statistical analysis. Categorical variables were presented as frequency and percentage while continuous variables were presented as mean and SD or median and IQR according to distribution normality. Demographic data of LTx patients and their matched controls were compared using the Mann–Whitney *U* test, Fisher's exact test, and Pearson's Chi-square test. The Wilcoxon rank-sum test was performed to test for differences between SWE measurements for the LTx and control groups. LTx patients above and below a cut-off value of 5.96 kPa were compared regarding demographic data, LTx indication, immunosuppressive medications used, and LFT abnormalities using Fisher's

exact test, Pearson's chi-square test, or Mann–Whitney *U* test. A *p* value <0.05 was considered statistically significant. To account for multiple comparisons, a Bonferroni correction was applied, adjusting the significance threshold to $\alpha=0.025$. Effect sizes ($r = \frac{|Z|}{\sqrt{N}}$), were interpreted based on Cohen's guidelines, where $r=0.2$ indicates a small effect, $r=0.5$ a medium effect, and $r=0.8$ a large effect [25].

3 | Results

3.1 | Participant Characteristics

Of the 40 participants imaged, two LTx patients were excluded due to difficulty holding their breath during scanning. As a result, a total of 36 participants were included in the study, comprising 18 PLT patients and 18 age- and sex-matched healthy controls. All LTx patients had living donors. Due to the non-normal distribution of the data, median and IQR values are reported. It was observed that no statistically significant differences existed between the PLT patients and the healthy controls in terms of age, weight, height, BMI, systolic blood pressure, or diastolic blood pressure (all *p* values >0.05). The distribution of sex and ethnicity was also comparable between the two groups, indicating successful matching based on these demographic variables, see Table 1.

3.2 | Liver Stiffness

Descriptive statistics indicated that liver stiffness was significantly higher in LTx patients compared to controls, see Table 2. Due to the non-normal distribution of liver stiffness data, a Wilcoxon Signed-Rank Test was employed. LTx patients had a median liver stiffness of 5.65 kPa (IQR=5.29, 6.71), ranging from 4.43 to 12.25 kPa, while controls exhibited a median of 4.29 kPa (IQR=3.75, 4.91), ranging from 2.77 to 5.49 kPa. A statistically significant difference in liver stiffness was observed between groups ($Z=-3.42$, $p<0.001$), with 17 (94.4%) out of 18 pairs showing higher stiffness in LTx patients. The effect size was large ($r=0.81$).

3.3 | UGAP Scores

The median score for patients was 0.56 dB/cm/MHz (IQR=0.54, 0.59), ranging from 0.45 to 0.67 dB/cm/MHz, compared to 0.57 dB/cm/MHz (IQR=0.52, 0.59), ranging from 0.46 to 0.65 dB/cm/MHz in controls, see Table 2. The Wilcoxon Signed-Rank Test revealed no significant difference in UGAP scores between the two groups ($Z=-0.11$, $p=0.92$). UGAP scores were higher in 8 pairs and lower in 10 pairs, suggesting no consistent pattern of difference. The effect size was negligible ($r=0.03$). The Pearson's Chi-square test found no correlation between UGAP and BMI ($p=0.356$).

3.4 | Multiple Comparisons Adjustment

To account for multiple comparisons, a Bonferroni correction was applied, adjusting the significance threshold to $\alpha=0.025$

TABLE 1 | Demographic characteristics of the study participants at time of imaging.

Characteristic	Patients (n = 18)	Controls (n = 18)	p
Age (years)	10.5 (8.1, 14.8)	10.7 (7.9, 14.7)	0.81 ^a
Sex			1.00 ^b
Male	10 (55.6)	10 (55.6)	
Female	8 (44.4)	8 (44.4)	
Ethnicity			0.189 ^c
Middle Eastern (Arab)	17 (94.4)	13 (72.2)	
Asian	1 (0.6)	4 (22.2)	
African	0 (0.0)	1 (5.6)	
Weight (kg)	32.3 (20.5, 32.3)	40.6 (21.2, 45.8)	0.40 ^a
Height (cm)	139.8 (124.2, 154.4)	143.7 (119.6, 162.0)	0.68 ^a
BMI (kg/m²)	16.3 (14.9, 19.1)	18.9 (15.3, 22.4)	0.31 ^a
Nutritional status			0.326 ^c
Underweight (BMIz < -2 SD)	4 (22.2)	1 (5.6)	
Normal weight (BMIz -2 to +1 SD)	12 (66.7)	11 (61.1)	
Possible risk of overweight (BMIz > 1 to 2 SD)	1 (5.6)	4 (22.2)	
Overweight (BMIz > 2 to 3 SD)	0 (0.0)	1 (5.6)	
Obese (BMIz > 3 SD)	1 (5.6)	1 (5.6)	
Systolic blood pressure (mmHg)	107.5 (98.0, 116.0)	108.0 (101.0, 118.0)	0.86 ^a
Diastolic blood pressure (mmHg)	68.5 (63.0, 73.3)	67.8 (64.0, 72.0)	0.71 ^a

Note: Data are presented as median (interquartile range) or number (%). p values < 0.05 are statistically significant.

Abbreviations: BMI, body mass index; BMIz, body mass index z-score; SD, standard deviation.

^aMann–whitney U test.

^bFisher's exact test.

^cPearson's chi-square test.

TABLE 2 | Descriptive statistics and the results of liver stiffness and ultrasound-guided attenuation parameter.

Variable	Patients (n = 18)	Controls (n = 18)	Z	p ^a	Significant pairs [*]	Effect size (r)
Liver Stiffness (kPa)	5.65 (5.29, 6.71)	4.29 (3.75, 4.91)	-3.42	< 0.001	17/18 (94.4)	0.81
UGAP (dB/cm/MHz)	0.56 (0.54, 0.59)	0.57 (0.52, 0.59)	-0.11	0.91	8/18 (44.4)	0.03

Note: Data are presented as median (interquartile range) or number (%).

Abbreviation: UGAP, ultrasound-guided attenuation parameter.

^aWilcoxon signed-rank test. p values < 0.05 are statistically significant.

^{*}Results of the 18 patients who underwent liver transplantation.

($\alpha = 0.05/2$). The difference in liver stiffness remained significant ($p < 0.001$), whereas the difference in UGAP scores was not significant ($p = 0.91$).

Figure 1A presents the distribution of liver stiffness across different ages for both patients and controls. The scatter plot indicates no clear correlation between age and liver stiffness in either group. Figure 1B presents the distribution of UGAP across different ages for both patients and controls. The scatter plot indicates no clear correlation between age and UGAP in either group.

The PLT patients were divided into two groups, those above the cut-off and those below and their characteristics at the time of

scanning were investigated, see Table 3. No significant associations for increased LSM were identified.

Table 4 gives a description of the different complications that occurred during or after LTx. 72.2% of patients had some form of complication, be it infectious episodes or non-infectious complications, with 75% of patients that were above the 5.96 kPa cut-off. Although patients with a cut-off higher than 5.96 kPa had a higher rate of complications than those with a lower cut-off (75.0% versus 70.0%, respectively), this difference was not statistically significant (p value = 1.000).

In general, there was no statistical difference between those above or below the cut-off. For those above the cut-off, the

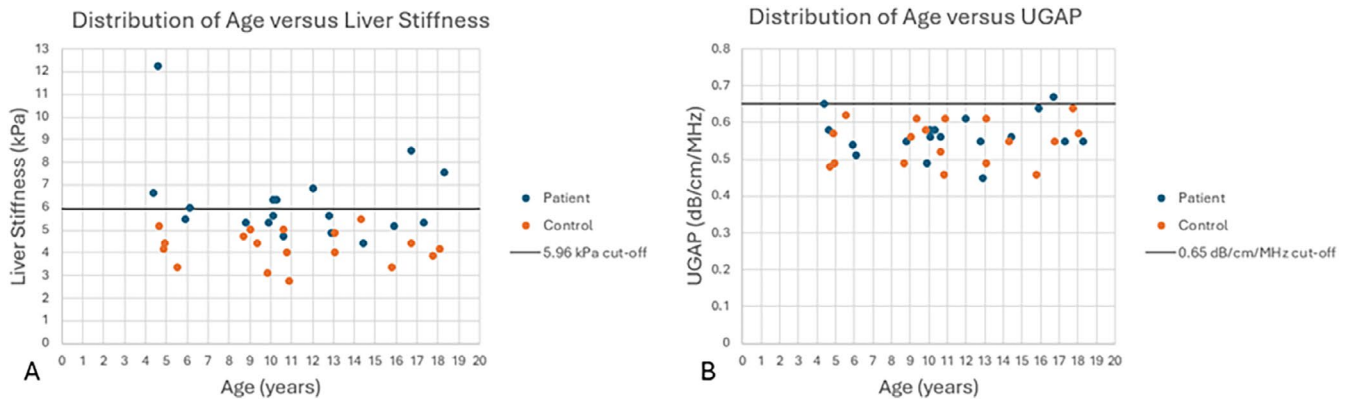


FIGURE 1 | (A) Scatter plot of the distribution of Age versus Liver Stiffness for both patients and controls. The line denotes the 5.96 kPa cut-off used in the study. (B) Scatter plot of distribution of Age versus Liver UGAP for both patients and controls. The line denotes the 0.65 dB/cm/MHz cut-off used in the study.

most common complication was rejection occurring in 50% of cases, though no statistically significant associations were found.

4 | Discussion

The study's primary finding indicates that PLT patients exhibit significantly higher LSMs compared to age- and sex-matched healthy controls. Specifically, the median liver stiffness was significantly higher in LTx patients compared to controls, demonstrating a large effect size. In contrast, UGAP scores did not differ significantly between the two groups, suggesting that while liver stiffness is elevated in LTx patients, steatosis as measured by UGAP may not be significantly affected in this cohort. In our cohort, only 2/18 patients had $\text{UGAP} \geq 0.65 \text{ dB/cm/MHz}$ (0.65 dB/cm/MHz, BMI 15.6 kg/m²; 0.67 dB/cm/MHz, BMI 19.5 kg/m²) with no correlation found between UGAP and BMI.

While the expanding body of research supports the utility of 2D-SWE, concerns remain regarding the variability of measurements across different US scanners and clinical centers. Several factors contribute to this issue, including the challenges in comparing results between devices due to variations in technologies and algorithms used by different manufacturers. To date, no studies have directly compared different 2D-SWE scanners in either adult or pediatric LTx patients. In a study conducted by Vuorenmaa et al. [26], the reproducibility of 2D-SWE measurements was evaluated both between operators and between devices in healthy muscle tissues. The results indicated no significant differences in SWE measurements between two different operators, demonstrating the technique's reliability when performed by different users. However, the study did find significant discrepancies in SWE measurements between the two scanners, highlighting how device-specific factors can influence measurement variability.

The highest LSM observed in the control group was 5.49 kPa, aligning with the results of Kehler et al. [17], who identified a threshold of 5.96 kPa for any liver fibrosis. While this 5.96 kPa cut-off was applied in the current study, future research may support the use of a lower threshold. As mentioned previously,

Kehler et al. utilized both the GE LOGIQ E10 and the older E9 scanners, allowing for a direct comparison. Liver biopsies were not possible to conduct in this center, so we cannot verify our results using this method. The significant difference in liver stiffness between LTx patients and healthy controls highlights the potential of 2D-SWE as a valuable tool in the routine monitoring of PLT recipients. Given the invasive nature and associated risks of liver biopsy, SWE offers a safer and practical alternative for assessing graft health and detecting fibrosis early. Early detection of increased liver stiffness through SWE facilitates timely clinical interventions. Such proactive management strategies have the potential to mitigate the progression of liver fibrosis, enhance graft longevity, and ultimately improve long-term patient outcomes.

The exploratory analyses examining potential predictors of increased liver stiffness—such as indications for transplantation, liver transplant center, age at LTx, follow-up duration post-LTx, graft type, donor-recipient relationship, liver graft from a disease carrier donor, previous rejection episodes, LFTs at the time of scanning, and the number of immunosuppressants (≤ 2 vs. ≥ 3) used—did not yield significant associations. This lack of significant predictors may be attributed to the small sample size, limiting the study's power to detect subtle associations. Additionally, the homogeneity of the cohort regarding certain variables, such as the predominant use of living-related donors (94.4%), may have further constrained the ability to identify distinct predictors. Future studies with larger and more diverse populations are necessary to elucidate potential factors influencing liver stiffness in PLT recipients.

One patient exhibited a markedly elevated LSM of 12.25 kPa. This individual was diagnosed with progressive familial intrahepatic cholestasis (PFIC), received a transplant from a carrier mother, and experienced a previous graft rejection episode. LFTs revealed elevated levels of ALT at 38 U/L and GGT at 144 U/L, suggesting underlying factors such as ongoing inflammation or graft dysfunction that may have contributed to the increased liver stiffness.

Over time, the liver might be exposed to multiple episodes of rejection, leading to higher stiffness values; however, in this study, we found that those with higher SWE values had a shorter time since the transplant compared to those with lower values. This

TABLE 3 | Liver transplant patient characteristics at the time of scan.

Variable	Total, n = 18 (100)	Above 5.96 kPa cut-off, n = 8 (44.4)	Below 5.96 kPa cut-off, n = 10 (55.6)	p
Liver transplant indication				
PFIC	5 (27.8)	3 (37.5)	2 (20.0)	0.608 ^a
Metabolic disorders*	5 (27.8)	2 (25.0)	3 (30.0)	1.000 ^a
Biliary atresia	4 (22.2)	1 (12.5)	3 (30.0)	0.588 ^a
Cystic fibrosis	1 (5.6)	1 (12.5)	0 (0.0)	0.444 ^a
Hemochromatosis	1 (5.6)	0 (0.0)	1 (10.0)	1.000 ^a
Overlap syndrome (AIH + PSC)	1 (5.6)	1 (12.5)	0 (0.0)	0.444 ^a
Idiopathic hepatic cirrhosis	1 (5.6)	0 (0.0)	1 (0.0)	1.000 ^a
Liver transplant centre location				0.299 ^b
India	7 (38.9)	3 (37.5)	4 (40.0)	
Turkey	6 (33.3)	4 (50.0)	2 (20.0)	
Saudi Arabia	5 (27.8)	1 (12.5)	4 (40.0)	
Age at liver transplant (year)	2.1 (0.9, 8.4)	2.8 (1.8, 8.5)	1.1 (1.0, 8.1)	0.274 ^c
Time after transplantation (year)	7.2 (2.1, 9.5)	2.5 (2.1, 9.2)	7.9 (4.7, 12.0)	0.203 ^c
Graft type				1.000 ^a
Split liver graft	15 (83.3)	7 (87.5)	8 (80.0)	
Auxiliary liver graft	3 (16.7)	1 (12.5)	2 (20.0)	
Donor type				1.000 ^a
Living related	17 (94.4)	8 (100.0)	9 (90.0)	
Living unrelated	1 (5.6)	0 (0.0)	1 (10.0)	
Donor graft with disease heterogeneity				0.637 ^a
Yes	9 (50.0)	5 (62.5)	4 (40.0)	
No	9 (50.0)	3 (37.5)	6 (60.0)	
Previous graft rejection				0.321 ^a
Yes	6 (33.3)	4 (50.0)	2 (20.0)	
No	12 (66.7)	4 (50.0)	8 (80.0)	
Liver function test results**				
Normal	5 (27.8)	3 (37.5)	2 (20.0)	0.608 ^a
Albumin (High, > 54 g/L)	2 (11.1)	0 (0.0)	2 (20.0)	0.477 ^a
Albumin (Low, < 38 g/L)	2 (11.1)	0 (0.0)	2 (20.0)	0.477 ^a
Bilirubin (Low, < 5 g/L)	1 (5.6)	1 (12.5)	0 (0.0)	0.444 ^a
Globulin (High, > 30 g/L)	3 (16.7)	0 (0.0)	3 (30.0)	0.216 ^a
ALP (High, > 417 U/L)	1 (5.6)	0 (0.0)	1 (10.0)	1.000 ^a
ALP (Low, < 129 U/L)	1 (5.6)	0 (0.0)	1 (10.0)	1.000 ^a
ALT (High, > 33 U/L)	4 (22.2)	3 (37.5)	1 (10.0)	0.275 ^a
AST (High, > 40 U/L)	1 (5.6)	0 (0.0)	1 (10.0)	1.000 ^a
GGT (High, > 38 U/L)	3 (16.7)	2 (25.0)	1 (10.0)	0.559 ^a

(Continues)

TABLE 3 | (Continued)

Variable	Total, n = 18 (100)	Above 5.96 kPa cut-off, n = 8 (44.4)	Below 5.96 kPa cut-off, n = 10 (55.6)	p
Immunosuppressives used				
Tacrolimus	18 (100)	8 (100.0)	10 (100.0)	NA ^a
Prednisolone	17 (94.4)	8 (100.0)	8 (80.0)	1.000 ^a
Mycophenolic acid	6 (33.3)	4 (50.0)	2 (20.0)	0.178 ^a
Cyclosporine A	2 (11.1)	1 (12.5)	1 (10.0)	0.867 ^a
Azathioprine	5 (27.8)	3 (37.5)	2 (20.0)	0.410 ^a
Basiliximab	1 (5.6)	0 (0.0)	1 (10.0)	1.000 ^a
Number of immunosuppressives				1.000 ^a
1–2	10 (55.6)	4 (50.0)	6 (60.0)	
3–5	8 (44.4)	4 (50.0)	4 (40.0)	

Note: Data are presented as number (%) or median (interquartile range). *p*-values < 0.05 are statistically significant.

Abbreviations: AIH, autoimmune hepatitis; ALP, alkaline phosphatase; ALT, alanine aminotransferase; AST, aspartate aminotransferase; GGT, gamma-glutamyl transferase; NA, not applicable; PFIC, progressive familial intrahepatic cholestasis; PSC, primary sclerosing cholangitis.

^aFisher's exact test.

^bPearson's chi-square test.

^cMann–Whitney *U* test.

*Argininosuccinic aciduria (*n* = 2), propionic acidemia (*n* = 2), tyrosinemia (*n* = 1).

**Some patients had more than one liver function abnormality.

TABLE 4 | Complications during or after liver transplantation.

Complications*	Total, n = 13/18 (72.2)	Above 5.96 kPa cut-off, n = 6/8 (75.0)	Below 5.96 kPa cut-off, n = 7/10 (70.0)	p ^a
Infection episodes				
Tonsillitis	4 (22.2)	1 (12.5)	3 (30.0)	0.588
Acute gastroenteritis	3 (16.7)	1 (12.5)	2 (20.0)	1.000
Cytomegalovirus	3 (16.7)	1 (12.5)	2 (20.0)	1.000
Pneumonia	2 (11.1)	1 (12.5)	1 (10.0)	1.000
Other infections**	4 (22.2)	2 (25.0)	2 (20.0)	1.000
Non-infectious complications				
Rejection	6 (33.3)	4 (50.0)	2 (20.0)	0.321
Biliary stricture	2 (11.1)	2 (25.0)	0 (0.0)	0.183
Early poor graft function	2 (11.1)	1 (12.5)	1 (10.0)	1.000
Bleeding	2 (11.1)	1 (12.5)	1 (10.0)	1.000
Portal vein thrombosis	1 (5.6)	1 (12.5)	0 (0.0)	0.444
Gastric perforation	1 (5.6)	0 (0.0)	1 (10.0)	1.000
Chylous ascites	1 (5.6)	1 (12.5)	0 (0.0)	0.444

Note: Data are presented as numbers (%). *p* values < 0.05 are statistically significant.

*Some patients had more than one complication.

**Herpetic gingivostomatitis, Epstein-Barr virus infection, lymphadenitis, colitis, and viremia (*n* = 1 each).

^aFisher's exact test.

finding might be attributed to earlier rejection episodes, or long-term adaptation of the liver [27]. Nonetheless, this finding was not statistically significant.

Several limitations must be acknowledged. Firstly, the study's relatively small sample size may limit the generalizability of the findings and the ability to detect significant associations in

subgroup analyses. The single-center design may also restrict the applicability of the results to broader populations with different demographic and clinical characteristics. Additionally, although the radiologist was blinded to the medical and laboratory results, the visibility of the scar during the scan identified the patient as a transplant recipient, making it challenging to eliminate scanning bias. This partial unblinding and the presence of surgical scars could have influenced the radiologist's measurements. Moreover, the cross-sectional design of the study precludes the assessment of longitudinal changes in liver stiffness and the temporal relationship between increased stiffness and clinical outcomes such as graft rejection or fibrosis progression. Furthermore, most LTx patients in this study received living-related donor grafts, which may not reflect outcomes associated with cadaveric or unrelated-living donors. In our institution, liver biopsy facilities are available for children with chronic liver diseases prior to LTx. However, due to technical and anatomical challenges, as well as the preferences of the LTx centers, our patients did not undergo liver biopsies locally. Instead, these procedures were performed overseas at specialized LTx centers to ensure patient safety. Consequently, histological reports for these liver biopsies were not available in our medical records. The exclusion of patients with who could not hold their breath during scanning may have introduced selection bias, potentially excluding patients with other complicating factors. Despite these limitations, the findings of this study are important due to the robust methodology employed that is in accord with the cut-off reported in the literature [17], enhancing its validity. Moreover, this study lays the foundation for future research in this area.

5 | Conclusions

This study demonstrates that 2D-SWE is a valuable noninvasive tool for assessing liver stiffness in PLT recipients, with significantly higher stiffness measurements observed compared to healthy controls. The use of SWE can potentially facilitate early detection of liver fibrosis and graft-related complications, thereby improving patient management and long-term outcomes, and circumventing the need for additional liver biopsies with their associated morbidity and mortality. Future studies should focus on validating SWE cut-off values, exploring its longitudinal utility, and integrating it with other noninvasive assessment modalities to optimize the monitoring and care of PLT patients.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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