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Use of shear wave elastography for the diagnosis and follow-up of biliary atresia: A meta-analysis

Ellen S Wagner, Hussien Ahmed H Abdelgawad, Meghan Landry, Belal Asfour, Mark B Slidell, Ruba Azzam

Abstract

BACKGROUND
Timely differentiation of biliary atresia (BA) from other infantile cholestatic diseases can impact patient outcomes. Additionally, non-invasive staging of fibrosis after Kasai hepatopancreatostomy has not been widely standardized. Shear wave elastography is an ultrasound modality that detects changes in tissue stiffness. The authors propose that the utility of elastography in BA can be elucidated through meta-analysis of existing studies.

AIM
To assess the utility of elastography in: (1) BA diagnosis, and (2) post-Kasai fibrosis surveillance.

METHODS
A literature search identified articles that evaluated elastography for BA diagnosis and for post-Kasai follow-up. Twenty studies met criteria for meta-analysis: Eleven for diagnosis and nine for follow-up post-Kasai. Estimated diagnostic odds ratio (DOR), sensitivity, and specificity of elastography were calculated through a random-effects model using Meta-DiSc software.
RESULTS
Mean liver stiffness in BA infants at diagnosis was significantly higher than in non-BA, with overall DOR 24.61, sensitivity 83%, and specificity 79%. Post-Kasai, mean liver stiffness was significantly higher in BA patients with varices than in patients without, with DOR 16.36, sensitivity 85%, and specificity 76%. Elastography differentiated stage F4 fibrosis from F0-F3 with DOR of 70.03, sensitivity 96%, and specificity 89%. Elastography also differentiated F3-F4 fibrosis from F0-F2 with DOR of 24.68, sensitivity 85%, and specificity 81%.

CONCLUSION
Elastography has potential as a non-invasive modality for BA diagnosis and surveillance post-Kasai. This paper’s limitations include inter-study method heterogeneity and small sample sizes. Future, standardized, multi-center studies are recommended.

Key Words: Biliary atresia; Cholestasis; Hepatic portoenterostomy; Fibrosis; Esophageal and gastric varices; Elasticity imaging techniques

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Wagner E et al. SWE for BA

gastrointestinal endoscopy, with no standardized guidelines for non-invasive staging of hepatic fibrosis nor timing for endoscopic evaluation for potential variceal evolution. Invasive procedures carry risks, both procedural as well as those related to sedation or anesthesia[4]. Delays at each juncture, both in diagnosis and in post-KPE surveillance, can have a potentially detrimental impact on patient outcome.

Ultrasound elastography (UE) is an emerging imaging modality that uses applied force via ultrasound probe to measure the elastic properties of tissue[5,6]. UE can be classified into strain imaging and shear wave imaging. Strain imaging relies on a normal external force (push) or intrinsic forces (i.e., respiration or cardiovascular movement) within the body. For this reason, strain imaging is difficult to quantify and reproduce, particularly in deeper organs, leading to limited applicability in the liver. As a result, strain imaging was not the focus of this analysis[7,8].

Shear wave imaging, also called shear wave elastography (SWE) utilizes a dynamic stress and can be further classified into transient elastography (TE), point shear wave elastography (pSWE; also called VTQ or Virtual Touch Quantification on some platforms), and two-dimensional shear wave elastography (2D-SWE; also called VTIQ or Virtual Touch IQ on some platforms)[8,9]. TE, which is performed using the FibroScan (Echosens, Paris, France) system, utilizes a mechanical punch to generate forces and measure unidirectional pressure waves[5]. pSWE and 2D-SWE differ from TE in that they utilize B mode ultrasound imaging guidance, which enables direct visualization of tissue, as well as an acoustic radiation force impulse (ARFI) in order to measure tissue stress. pSWE enables the measurement of average shear wave speed within a region of interest while 2D-SWE uses multiple foci of tissue displacement along an axis to generate a quantitative map of shear wave speed[3].

SWE has been studied extensively in adult liver literature with studies in pediatric liver disease emerging only recently[6]. And yet, while multiple authors have addressed the utility of SWE for diagnosis and management in BA, there have been no large-scale studies nor meta-analyses on this modality. The aim of this meta-analysis is to evaluate the utility of SWE in: (1) the differentiation of BA from other cholestatic liver diseases of infancy, and (2) the assessment of fibrosis progression in post-KPE follow-up.

MATERIALS AND METHODS

This review was conducted in strict accordance with the Cochrane handbook of systematic reviews of interventions[10]. We followed the Preferred Reporting Items for Systematic Review and Meta-Analysis of Diagnostic Test Accuracy studies (PRISMA-DTA statement)[11]. The review was publicly registered with the Open Science Framework (OSF). The statistical analysis was performed by co-authors H.A., who has over four years as a biostatistician in a clinical research organization, and M.L., who is a clinical research coordinator employed by the University of Chicago.

Search strategy and eligibility criteria

PubMed, Scopus, Web of Science, EBSCO, and Cochrane Central were searched for English language studies with information on BA and elastography from 2010 to 2021. Two of the authors performed the literature search using the keywords: “Elastography” AND “biliary atresia”.

Full texts were reviewed to select eligible studies for meta-analysis. Studies were included if the following criteria were met: (1) The study used SWE to differentiate BA from other cholestatic liver diseases of infancy; (2) the study used SWE in the follow-up of patients with BA for the development of fibrosis/cirrhosis post-KPE; and (3) the study assessed the accuracy of SWE for the diagnosis or follow-up of liver fibrosis based on the cut-off point for liver stiffness and/or spleen stiffness values.

Exclusion criteria were as follows: (1) Full text article was not available and/or abstract and article were not available in English; (2) the study was not specific to BA and/or did not utilize SWE (3) the study evaluated the accuracy of SWE combined with other diagnostic methods; (4) the study used SWE as a reference test to study novel biomarkers; and (5) the study was a review article, letter to the editor, case report, editorial, case series, or consensus statement. Only studies with reliable data for extraction and analysis were included in the meta-analysis.

Data extraction

Two authors independently reviewed and extracted the data from each included study. Data were extracted for study characteristics (e.g., first author and year of publication, study period, study setting, study design, and sample size), baseline characteristics of the included patients (e.g., age of patients, laboratory date, age at diagnosis), and diagnostic data (e.g., sensitivity, specificity, predictive values).

Risk of bias assessment

Two researchers assessed the risk of bias of studies included using version 2 of the Quality Assessment of Diagnostic Test Accuracy Studies (QUADAS-2) tool[12]. QUADAS-2 examines seven items on the representation of patient spectrum, selection criteria, reference standard, verification bias, timing, and study withdrawals. Both reviewers scored the tool independently; all disagreements were discussed and consensus was reached.
Data analysis

Heterogeneity was assessed by visual inspection of the forest plots and measured by I-square and Chi-Square tests. In case of significant heterogeneity ($P < 0.1$), a random effect model was used. Continuous data were pooled as standardized mean difference (SMD) in a meta-analysis model using inverse variance method with the respective 95% confidence intervals. We used Comprehensive Meta Analysis (CMA, United States) software version 3.3.070 for windows. Methods described in reference[13] were utilized to compute missing standard deviations. The diagnostic accuracy indicators of each test were pooled as sensitivity, specificity, and diagnostic odds ratio (DOR) with the corresponding 95% confidence intervals by the DerSimonian-Laird random effect model using MetaDiSc Beta-1.4 software. In addition, the Summary Receiver Operating Characteristic (SROC) curve was used for the evaluation of diagnostic tests and represents the relationship between true positive and negative rates considering the varying diagnostic thresholds among studies. The summary of the test performance was represented with an AUC of 1.0 (100%) indicating perfect discriminatory ability to distinguish BA from non-BA.

Seven studies used SWE machinery that reported results in units of m/s as opposed to kPa, with four being evaluated for diagnostic test accuracy[14-18] and two for utility of SWE for follow-up[19,20]. Values reported in m/s were converted to kPa as per reference[8] (Supplementary material).

RESULTS

Electronic search yielded 243 studies with 42 identified as potentially meeting inclusion criteria (Figure 1). Full text articles were retrieved and assessed for final eligibility. After the review of all full text articles, 22 were excluded due to study design and unreliable data for extraction, the use of SWE as an adjunct to the primary study of a novel biomarker, and subject comparison to healthy controls (as opposed to other cholestatic infants). Eleven studies on the utility of SWE in accurately differentiating BA from other cholestatic liver diseases of infancy met criteria for inclusion, as well as nine studies that evaluated the utility of SWE in assessing and monitoring the development of hepatic fibrosis/cirrhosis post-KPE. The studies included were mostly single center, retrospective analyses conducted in infants and children (age 0-18 years) and published in peer-reviewed journals between 2010 and 2021. Detailed individual study characteristics are presented in Table 1.

The overall quality of the included studies assessed by the QUADAS-2 (Figure 2), was moderate to high. All analyzed studies were found to have low risk of bias in five or more of the seven items, with the exception of[21], which showed unclear risk of bias in two of seven items and high risk of bias in patient selection. Unclear risk of bias was reported in patient selection due to lack of clear selection criteria in several studies. Potential risk of bias in the index test was recorded in several studies due to lack of reporting on blinding relative to reference standard results. Potential bias in reference standards emerged due to the use of multiple different reference standards (surgical exploration, intraoperative cholangiography, liver biopsy) with possibility for incorrect classification of BA. Finally, bias in the flow and timing was primarily due to a lack of reported details in some of the included studies.

SWE for the diagnosis of BA

Data on SWE for distinguishing BA from other cholestatic neonatal liver diseases were collected from 11 studies with 1307 total patients (560 with BA and 747 without BA). The mean liver stiffness value was significantly higher in the BA group compared to the non-BA group (overall SMD = 2.30 kPa, 95%CI: 1.69, 2.90, $P < 0.0001$). Pooled studies were heterogeneous ($P < 0.01$, $I^2 = 94\%$) (Figure 3). Of the 11 studies included, five reported on performing diagnostic test analysis using liver biopsy as the reference test, one study[22] used surgical exploration or cholangiography, and the reference was not specified in another[16].

The forest plot of sensitivity and specificity for the diagnostic performance of the liver stiffness value measured by SWE for differentiating BA from other etiologies of neonatal cholestasis is shown in Figure 4A. The pooled sensitivity was 83% (95%CI: 80%, 86%) and specificity was 79%, (95%CI: 76%, 82%). The SROC curves of SWE for the diagnosis of BA are illustrated in Figure 4B. The SROC curve was symmetric, and the AUC was 0.91, Q was 0.84 (SE = 0.02). The DOR was 24.61, (95%CI: 12.74, 47.53, $I^2 = 72.4\%$) as shown in Figure 4C. Two of the 11 articles did not report a cut-off value for differentiating between BA and non-BA[14,15] and were excluded from this analysis.

SWE for the follow-up of patients with BA

Data on SWE to assess liver disease progression in post-KPE follow-up were collected from nine studies including 327 total patients (101 patients with varices, 124 patients without varices, 41 patients with fibrosis (F0-F2), and 61 patients with fibrosis (F3-F4). Fibrosis stage is reported via METAIR standards, a scale from F0 to F4 where F0 shows no signs of histologic fibrosis, F2 represents moderate fibrosis with few bridges/septa, F3 is numerous septa without cirrhosis, and F4 signifies cirrhosis.

The mean liver stiffness value was significantly higher in patients with varices in comparison to patients without varices (overall SMD 1.38 kPa, 95%CI: 1.02, 1.74, $P < 0.00001$). Pooled studies were homogenous ($P = 0.29$, $I^2 = 19\%$) (Figure 5A). Only three studies reported data on the diagnostic
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</table>

Point SW: Point shear wave elastography; 2D SW: Two-dimensional shear wave elastography; VTIQ: Virtual Touch IQ, alternative nomenclature for two-dimensional shear wave elastography; VTQ: Virtual touch quantification, alternative nomenclature for point Shear Wave Elastography; TE: Transient elastography; KPE: Kasai hepatopancreaticoenterostomy; BA: Biliary atresia; EV: Esophageal varices; GV: Gastric varices; ARFI: Acoustic radiation force impulse.
performance of spleen stiffness measured by SWE for predicting the presence of varices in patients with BA post-KPE. The mean spleen stiffness value was significantly higher in patients with varices when compared to patients without varices (overall SMD 1.66 kPa, 95% CI: 1.19, 2.14, \( P < 0.00001 \)). Pooled studies were homogenous (\( P = 0.42, I^2 = 0\% \)) (Figure 5B).

The forest plot of the sensitivity and specificity for the diagnostic performance of liver stiffness value measured by SWE to predict the presence of varices is shown in Figure 6A. The pooled sensitivity was 85% (95% CI: 79%, 91%), while the specificity was 86%, 95% CI (67%, 83%). Illustrated in Figure 6B, the SROC curve was symmetric and the AUC was 0.86 with Q value of 0.80 (SE = 0.05). The DOR was 16.36, 95% CI (8.18, 32.70), \( I^2 = 0\% \), showing no heterogeneity among the pooled studies (Figure 6C).

Three studies utilized spleen stiffness measured by SWE to predict the presence of varices with endoscopy as a reference test. The pooled sensitivity was 84% (95% CI: 69%, 94%), while the specificity was 84%, 95% CI (73%, 92%). The AUC of the SROC curve was 0.91, with Q value of 0.85 (SE = 0.40). The DOR was 28.93, 95% CI (8.99, 93.14), \( P = 0\% \), showing no heterogeneity among the pooled studies (Supplementary Figure 1).

Four studies used liver stiffness value measured by SWE to predict the presence of liver fibrosis F4 (vs F0-3) when liver biopsy was the reference test. The forest plot for the sensitivity and specificity of the diagnostic performance of liver stiffness value measured by SWE to predict the presence of liver fibrosis F4 is shown in Figure 7A. The pooled sensitivity was 96% (95% CI: 79%, 100%), while the specificity was 89%, 95% CI (81%, 94%). The SROC curves of liver stiffness value measured by SWE are illustrated in Figure 7B. The AUC of the SROC curve was 0.95, with Q value of 0.89 (SE = 0.04). The DOR was 70.04, 95% CI: 16.06, 305.40), \( P = 0\% \), showing no heterogeneity among the pooled studies (Figure 7C).

Three studies used the liver stiffness value measured by SWE to predict the presence of liver fibrosis F3-4 (vs F0-2) when liver biopsy was the reference test. The pooled sensitivity was 85% (95% CI: 71%, 94%), and specificity 81%, 95% CI (67%, 91%). The AUC of the SROC curve was 0.91, with Q value of 0.84 (SE = 0.04). The DOR was 24.68, 95% CI (7.43, 82.01), \( P = 0\% \), showing no heterogeneity among the pooled studies (Supplementary Figure 2).

**DISCUSSION**

Early diagnosis of BA is crucial to patient outcomes. At present, diagnosis depends on invasive liver biopsy and intraoperative cholangiogram. The present meta-analysis is the first to our knowledge to assess the potential utility of preoperative SWE in establishing the diagnosis of BA. In our meta-analysis, we observed that liver stiffness value measured by SWE had high diagnostic accuracy for differentiating BA from other neonatal cholestasis (AUC = 0.91) with high summary sensitivity of 83% as well as summary specificity of 79% and DOR of 24.61. Notably, several of the studies used different...
Figure 2 Quality assessment by Quality Assessment of Diagnostic Test Accuracy Studies (QUADAS-2) of the included studies.

Figure 3 Forest plot comparing the liver stiffness value (Kpa) between the patients with and without biliary atresia. Dillman, Wang (2020), Leschied, and Liu each have multiple analyses due to different shear wave elastography modes and/or phases of study (training, validation). Point SW: Point shear wave elastography; 2D SW: Two-dimensional shear wave elastography; VTIQ: Virtual touch IQ, alternative nomenclature for two-dimensional shear wave elastography; VTQ: Virtual touch quantification, alternative nomenclature for point shear wave elastography.
Figure 4 Forest plot of liver stiffness value measured by shear wave elastography to differentiate biliary atresia from other neonatal cholestasis. A: Diagnostic sensitivity and specificity; B: Summary receiver operating characteristic curve; C: Diagnostic odds ratio. Point SW: Point shear wave elastography; 2D SW: Two-dimensional shear wave elastography; VTIQ: Virtual touch IQ, alternative nomenclature for two-dimensional shear wave elastography; VTQ: Virtual touch quantification, alternative nomenclature for point shear wave elastography.

reference standards (five utilized liver biopsy, one utilized surgical exploration or cholangiography, and one did not specify its reference standard). When interpreted within the context of pathophysiology of BA, with fibrosis beginning at bile duct obliteration, in comparison to non-BA cholestasis which has variable degrees of fibrosis, these results reflect the potential for SWE to aid in the diagnostic process.

Post-KPE, a significant number of patients develop persistent cholestasis, portal hypertension, and progressive fibrosis. Risk stratification for these patients continues to be a clinical challenge for hepato-
logists. The second portion of this analysis explored the potential utility of SWE for accurately assessing the progression of hepatic fibrosis post-KPE. We observed significant differences in liver and spleen stiffness in patients with varices. The diagnostic accuracy of liver stiffness value measured by SWE was similar to spleen stiffness value to predict the presence of varices post-KPE (AUC = 0.86 and 0.92, respectively). The pooled sensitivity was comparable between liver stiffness and spleen stiffness (85% vs 84%), but the pooled specificity of spleen stiffness was higher than liver stiffness (84% vs 76%). Notably, only three studies investigated spleen stiffness and five investigated liver stiffness to predict the presence of post-KPE varices.

This analysis also demonstrated significant predictive efficacy for the presence and severity of biopsy-proven liver fibrosis in four studies. Liver stiffness value measured by SWE to determine advanced liver fibrosis (F4 vs F0-3) has high diagnostic accuracy (AUC = 0.95), sensitivity (96%) and specificity (89%). Liver stiffness value measured by SWE to differentiate between F3-4 and F0-2 fibrosis has a lower diagnostic accuracy (AUC = 0.91), with sensitivity (85%) and specificity (81%). This is in line with studies in the adult literature, which have found increased accuracy of SWE for high grade (stage F3-4) fibrosis in comparison to F0-F2\[23\].

Although the findings from this meta-analysis are compelling, there are notable limitations to the analysis. The studies included in this analysis were mostly small and single-center, which limits generalizability across large, non-homogenous populations. Furthermore, each study analyzed for BA diagnosis was performed on infants of different average age (with ranges from two to 140 d of life); given the rapid evolution of fibrosis in BA, the variety of ages analyzed may influence the results.

In addition to the use of different reference standards (liver biopsy vs surgical exploration or cholangiogram), there were notable differences in methodology from study to study, in particular regarding patients’ fasting status and sedation, sonographer characteristics (blinded vs non-blinded, level of expertise, etc.), number of measurements obtained, and measurement quality standards. Previous analyses of SWE technology have highlighted significant differences in results obtained depending on sedation and fasting status, operator dependence, and probe choice\[5,24-27\]. This demonstrates the importance of methodological unity in comparison between data sets. While our results are promising, this is an important implication in terms of broad applicability of our meta-analysis and the need for further, well-designed trials to address the potential utility of SWE in BA.

Patient factors aside, several study centers utilized different SWE platforms (TE vs pSWE vs 2D-SWE) and machines (detailed in Table 1), each of which reported results in either kPa or m/s. As such, analysis relied upon interconversion of results from Young’s modulus to shear modulus (kPa to m/s) \[7\]. While there is a well-documented mathematical proof enabling this interconversion, the proof relies upon assumptions about tissue characteristics, notably that the tissue has constant density and homogeneity, displays isotropic and elastic characteristics, and is linear under compressible stress (Supplementary material)\[7,8\]. The inherent characteristics of an inflamed, potentially fibrotic liver do not fit well into this description, which is important to mention given an analysis that relies heavily on
interconversion between results\cite{28,29}. In a similar vein, a recent study by Darweesh et al\cite{30} found that cholestasis itself can increase liver stiffness measurements in adult patients, separate to histologic findings of fibrosis; future studies must take this potential confounder into account. This meta-analysis must be interpreted within the context of these limitations, with future studies taking important steps to address potential limitations and barriers to interpretation during the study design, data collection and analysis phases of work.

CONCLUSION

Despite non-standardized methodology across analyzed articles as well as reliance upon data interconversion, this meta-analysis highlights the potential of SWE as a non-invasive method to assist in both the diagnosis as well as post-KPE follow-up of BA. Further standardized, multi-center studies are needed in order to better elucidate this potential. By applying uniform methods, machinery, and data reporting (in
Figure 7 Forest plot of liver stiffness value measured by shear wave elastography to predict the presence of liver fibrosis F4 (vs F0-3) in post-Kasai patients. A: Diagnostic sensitivity and specificity; B: Summary receiver operating characteristic curve; C: Diagnostic odds ratio.

either kPa or m/s), further studies may be able to identify SWE as a non-invasive tool with utility both in diagnosis of BA as well as post-KPE prediction of outcomes.

**ARTICLE HIGHLIGHTS**

**Research background**

Biliary atresia (BA) is a progressive infantile cholestatic disease. Diagnosis is confirmed by intraoperative cholangiogram; any delays to diagnosis and palliating Kasai hepatoportoenterostomy can increase the odds of needing liver transplant. Following Kasai, patients will need surveillance for progression of liver disease, which often requires liver biopsy.
Research motivation
Because the diagnosis and surveillance of BA both involve invasive procedures, there are risks for delay and/or adverse outcomes at each stage. By using non-invasive shear wave elastography (SWE), which measures changes in tissue stiffness, to identify liver stiffness thresholds for BA diagnosis and evolution of fibrosis post-Kasai, clinicians may be able to accurately diagnose and surveil BA without invasive procedures.

Research objectives
The authors performed a meta-analysis on studies into the utility of SWE for BA diagnosis and post-Kasai surveillance in order to determine whether existing literature could help identify liver stiffness thresholds for BA diagnosis and development of fibrosis post-Kasai.

Research methods
A literature search yielded twenty studies, eleven for diagnosis and nine for follow-up post-Kasai. Diagnostic odds ratio (DOR), sensitivity, and specificity of elastography were calculated through a random-effects model.

Research results
Mean liver stiffness in BA infants was higher than in cholestatic infants without BA with DOR 24.61, sensitivity 83%, specificity 79%. Mean liver stiffness post-Kasai was significantly higher in patients with varices than those without (DOR 16.36, sensitivity 85%, specificity 76%). SWE differentiated META VIR F4 fibrosis from F0-F3 (DOR 70.03, sensitivity 96%, specificity 89%) as well as F3-F4 fibrosis from F0-F2 (DOR 24.68, sensitivity 85%, specificity 81%).

Research conclusions
SWE may be a useful, non-invasive modality for the diagnosis and post-Kasai surveillance in BA. The analysis is limited by methodological heterogeneity between studies as well as small sample sizes.

Research perspectives
In order for SWE to be useful for future BA cases, larger, standardized, multi-center studies are recommended to establish appropriate protocols.

FOOTNOTES
Author contributions: Wagner ES performed literature search, data acquisition and interpretation, manuscript drafting, and final approval; Abdelgawad HAH performed data acquisition, statistical analysis and interpretation, manuscript structure, drafting, and revisions; Landry M performed statistical analysis and interpretation, manuscript structure and revisions; Asfour B performed figure compilation and manuscript revisions; Slidell MB performed manuscript compilation, revisions, and final approval; Azzam R performed project structure, data acquisition and interpretation, manuscript revisions, and final approval.

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