Eur Radiol (2017) 27:5337–5343
DOI 10.1007/s00330-017-4909-6

ULTRASOUND

Hepatic shear wave elastography in children under free-breathing and breath-hold conditions

Caroline Jung[1] · Michael Groth[2] · Kay Uwe Petersen[3] · Anna Hammel[1] · Florian Brinkert[4] · Enke Grabhorn[4] · Sören Alexander Weidemann[5] · Jasmin Busch[2] · Gerhard Adam[1] · Jochen Herrmann[2]

Received: 17 November 2016 / Revised: 17 March 2017 / Accepted: 23 May 2017 / Published online: 20 June 2017

Abstract

Objectives To compare hepatic 2D shear wave elastography (2D SWE) in children between free-breathing and breath-hold conditions, in terms of measurement agreement and time expenditure.

Methods A cohort of 57 children (12.7±4.3 years) who underwent standardized 2D SWE between May and October 2015 were retrospectively evaluated. Liver elastograms were obtained under free-breathing and breath-hold conditions and time expenditure was measured. Median stiffness, interquartile range (IQR), and IQR/median ratio were calculated based on 12, six, and three elastograms. Results were compared using Pearson correlation coefficient, intraclass correlation coefficient (ICC), Bland-Altman analysis, and Student's *t*.

Results Median liver stiffness under free-breathing and breath-hold conditions correlated strongly (7.22±4.5kPa vs. 7.21±4.11kPa; r=0.97, P<0.001). Time to acquire 12 elastograms with free-breathing was lower than that with breath-holding (79.3±32.5sec vs. 143.7±51.8sec, P<0.001). Results for median liver stiffness based of 12, six, and three elastograms demonstrated very high agreement for free-breathing (ICC 0.993) and for breath-hold conditions (ICC 0.994).

Conclusions Hepatic 2D SWE performed with free-breathing yields results similar to the breath-hold condition. With a substantially lower time requirement, which can be further reduced by lowering the number of elastograms, the free-breathing technique may be suitable for infants and less cooperative children not capable of breath-holding.

Key Points

- *Hepatic 2D SWE performed with free-breathing yields results similar to breath-hold condition.*
- *Benefit of the free-breathing approach is the substantially lower time requirement.*
- *Lowering the number of elastograms can further reduce time expenditure.*
- *Free-breathing 2D SWE is suitable in children with suspected liver disease.*

Keywords Liver elastography · Ultrasound · Shear wave · Free-breathing · Children

Abbreviations

2D SWE	Two dimensional shear wave elastography
ICC	Intraclass correlation coefficient
IQR	Interquartile range
SD	Standard deviation
MRI	Magnetic resonance imaging
ROI	Region of interest
TE	Transient elastography

✉ Jochen Herrmann
j.herrmann@uke.de

[1] Department of Diagnostic and Interventional Radiology and Nuclear Medicine, University Medical Center Hamburg-Eppendorf, 20246 Hamburg, Germany

[2] Section of Pediatric Radiology, Department of Diagnostic and Interventional Radiology and Nuclear Medicine, University Medical Center Hamburg-Eppendorf, 20246 Hamburg, Germany

[3] Section for Addiction Research and Therapy, University Department for Psychiatry and Psychotherapy, 72076 Tübingen, Germany

[4] Department of Pediatric Gastroenterology, University Medical Center Hamburg-Eppendorf, 20246 Hamburg, Germany

[5] Institute of Pathology, University Medical Center Hamburg-Eppendorf, 20246 Hamburg, Germany

Introduction

Over the past years, a number of noninvasive in vivo stiffness-imaging techniques have been developed. Ultrasound-based methods and magnetic resonance imaging (MRI) can depict and quantify tissue elasticity [1]. Various studies have shown relatively good agreement between elasticity measurements and the degree of hepatic fibrosis in adults [2–5]. In children, the significance of liver elastography for assessment of parenchymal changes in liver disease is less well-established. Normal values have been reported [6, 7] and potential applications identified such as in biliary atresia [8, 9], non-alcoholic fatty liver disease [10], and other primary hepatic disorders [11–13].

Ultrasound elastography of the liver may be affected by different sources of variability [5]. In addition to factors based on the underlying disease, patient comorbidities, and place of measurement [14–17], also respiratory motion may decrease the accuracy of results. Deep inspiration and liver displacement during free respiration can cause artefacts [18, 19]. Guidelines recommended that ultrasound liver elastography should be performed with breath-holding and be based on ten successful single elastograms to obtain meaningful results [5, 20, 21]. However, this procedural requirement may be difficult to fulfil in the paediatric population. In cooperating children capable of apnoea, multiple breath-holding manoeuvres are needed to acquire a full set of elastograms, resulting in relatively long examination times. In smaller children and patients with substantial comorbidities, breath-holding is generally not possible. For practical reasons, some studies have adopted a free-breathing approach for noncooperative paediatric patients [5, 7, 13], but the validity of the generated values is uncertain [7].

The physical properties of two-dimensional shear wave elastography (2-D SWE) allow for fast image acquisition that theoretically could reduce the need for breath-holding. In 2-D SWE, a "push pulse" is induced deep in the tissue by an acoustic radiation force. The momentum of this propagating ultrasonic pulse is used to generate lateral shear waves in the tissue [22]. The excitation pulse and image acquisition in 2-D SWE is much faster than the respiratory rate and may be less influenced by operator and patient movement [23]. So far, only a few studies on hepatic 2-D SWE measurements in paediatric patients have been done [24, 25]. A preliminary study using 2-D SWE found no significant differences in stiffness values obtained from a group of children, when stratified according to breath-hold and free-breathing examinations [24].

The purpose of this study was to compare hepatic 2-D SWE in children between free-breathing and breath-hold conditions, in terms of measurement agreement and examination time expenditure.

Materials and methods

Subjects

This retrospective study was legitimated by the local medical statutes (according to §12 Hamburger Krankenhausgesetz) and written informed consent was waived. All examinations were conducted according to the Declaration of Helsinki. All paediatric patients who underwent a standard ultrasound examination, including 2-D SWE measurements under free-breathing and breath-hold conditions, between May 2015 and October 2015 were evaluated. Exclusion criteria were insufficient documentation and incomplete examinations. Of 62 consecutive patients, five patients were excluded primarily because of incomplete examinations. The final cohort included 57 children (36 females and 21 males; mean age ± standard deviation [SD], 12.7 ± 4.3 years). The primary diagnoses for referral were: liver transplantation (n = 14), alpha-1-antitrypsin deficiency (n = 12), autoimmune hepatitis (n = 11), hepatic disease of unknown origin (n = 7), primary sclerosing cholangitis (n = 2), Alagille syndrome (n = 2), Wilson's disease (n = 2), liver cirrhosis of unknown origin (n = 1), acute liver failure (n = 1), portal vein thrombosis (n = 1), cystic fibrosis (n = 1), biliary atresia (n = 1), nonalcoholic steatohepatitis (n = 1), and Gilbert-Meulengracht syndrome (n = 1).

Ultrasound examination

Ultrasound examinations were performed using a predefined protocol with prospective documentation and carried out by a single paediatric radiologist (J.H., with 12 years of experience in paediatric liver ultrasound). All examinations were performed with a commercial scanner (GE Logiq 9 ultrasound system, GE Medical Systems, Milwaukee, WI, USA). Doppler ultrasound examination included a real-time morphologic evaluation of the liver parenchyma and colour mapping of the hepatic artery, portal vein, hepatic veins, and inferior vena cava. The 2-D SWE was performed with a C1-5 MHz curved array transducer on patients in the supine position after a minimum of two hour fasting (Fig. 1). In native livers, an intercostal approach with the right arm elevated was chosen. Patients who had a split liver transplantation of the left lobe were examined via the epigastric abdominal wall. The region of interest (ROI) of the elastogram, comprising the shear wave colour map, was positioned in the liver parenchyma ≥ 1–2 cm below the liver capsule. Vessels and focal lesions were omitted.

The free-breathing examination was first performed by automatic acquisition of serial elastograms [26]. The measurements were stopped when 12 successful elastograms had been recorded. A breath-hold examination was

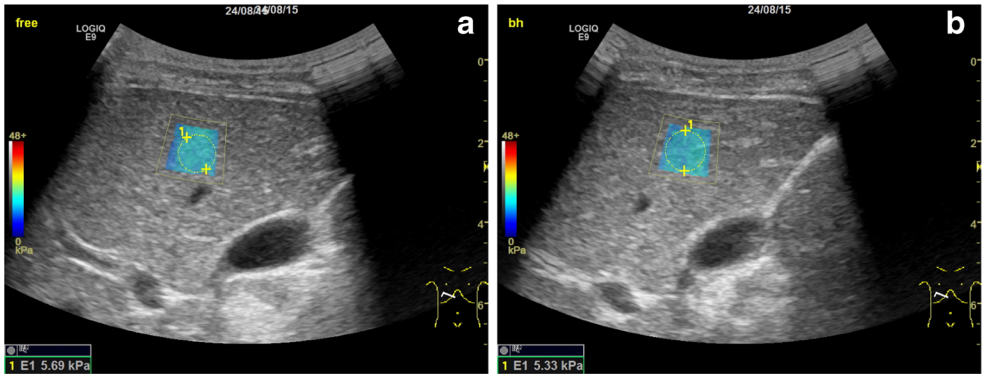

Fig. 1 2D-SWA measurement of the liver in a 10-year-old girl with an Alpha-1-Antitrypsin deficiency under free-breathing (A) and breath-hold (B) conditions. Rectangular color-coded SWE map and the circular region of interest (ROI) are positioned in the right lobe of the liver. The colour scale shows the measured elasticity within the rectangular SWE map, which is homogenously distributed in both conditions showing similar quantitative results based on twelve elastograms (5.69 kPA ± 0.65 vs. 5.33 kPA ± 0.41)

subsequently performed at the same location and with the same parameters as during the free-breathing exam. Patients were asked to stop breathing after low inspiration. The examination was stopped when 12 successful measurements had been recorded with a maximum of four single elastograms per breath-hold. For both conditions, elastograms with substantial artefacts and incomplete fill-in (<90%) were discarded. Directly after the acquisition, one circular ROI was positioned in each elastogram with the ROI diameter chosen as large as possible to omit the artefacts and missing data. The mean ROI size positioned within the elastograms under breath-holding and free-breathing conditions was 0.78 ± 0.25 cm^2 and 0.9 ± 0.18 cm^2, respectively. The duration of acquisition was extracted for each condition.

Histologic fibrosis staging

Within 12 months of the SWE measurement, liver specimens were available in 17 patients (mean age 13.4 ± 4.4 years) either by percutaneous liver biopsy (16 patients) or by wedge excision (one patient). The mean interval between the sample taking and the SWE measurement was 4.9 months (range, 0–12 months). The percutaneous biopsy was performed with a 18-gauge needle (Bard Monopty Disposable Core Biopsy Instrument, Tempe, USA). The mean length of biopsy specimens was 16.5 ± 8.1 mm and included a mean of 11.4 ± 5.2 portal tracts. One case of a small, capsular specimen was excluded from the fibrosis staging. All specimens were analysed by a single pathologist (S.M.), who was blinded to SWE results. Liver fibrosis was evaluated semiquantitatively according to the METAVIR scoring system [27], (F0 = absent, F1 = stellate enlargement of portal tract without septa formation, F2 = enlargement of portal tract with rare septa formation and intact architecture, F3 = numerous septa but no obvious cirrhosis, and F4 = cirrhosis).

Statistical analysis

Median SWE (liver stiffness) value, interquartile range (IQR), and IQR/median ratio (all expressed as the mean ± SD, in kPa) were calculated for each patient and each condition (free-breathing and breath-hold) based on the full set of 12, the first six, and the first three single elastograms recorded. Agreement of the results based on 12, six and three elastograms were tested by calculating intraclass correlation coefficients (ICC, absolute agreement condition). To analyse the association between free-breathing and breath-hold conditions, Pearson correlation and Bland-Altman analyses were performed. To test for differences between SWE parameters and measurement time, Student's *t* tests were used. To compare median SWE values between fibrosis stages F0, F1 and ≥ F2, an analysis of variance (ONEWAY) was calculated for free-breathing and breath-hold measurements followed by post hoc tests (Scheffe's test, LSD test). A two-sided *P* value < .05 was considered statistically significant. IBM SPSS Statistics 24 software was used for statistical analysis.

Results

As shown in the representative 2-D SWE examination of the liver in a 10-year-old girl under free-breathing (Fig. 1A) and breath-hold (Fig. 1B) conditions, the measured elasticity was homogenously distributed in both conditions. A total of 684 single measurements (12 for each of 57 patients) were conducted under both conditions.

Median liver stiffness (Fig. 2) did not differ significantly between the free-breathing and breath-hold approaches, and the Pearson analysis (Fig. 2A) revealed strong correlation (free-breathing, 7.22 ± 4.5 kPa; range, 3.6–29.5 kPa; breath-hold, 7.21 ± 4.1 kPa; range, 3.6–26.3 kPa; $r = 0.97$, $P < .0001$) (Table 1). To test for agreement of elasticity values measured under free-breathing and breath-hold in each patient, a Bland-

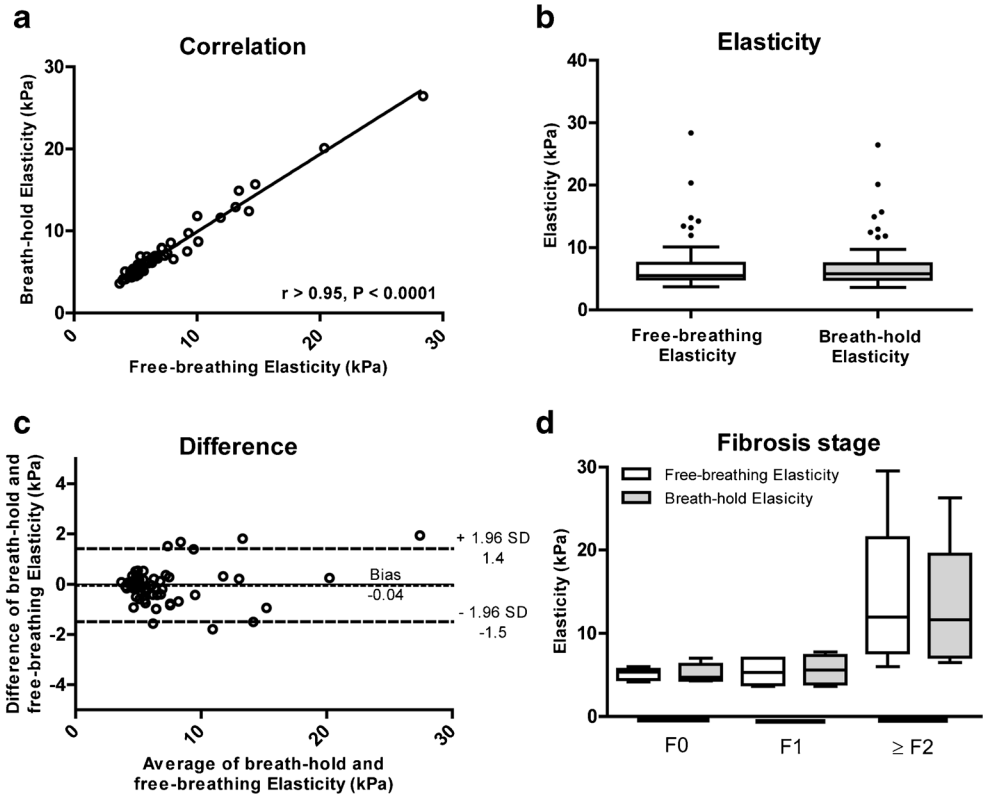

Fig. 2 (A-D) Median liver stiffness in 57 patients calculated on 12 elastograms under free-breathing and breath-hold conditions. A Pearson correlation of free-breathing and breath-hold elasticity. A strong correlation of the measurement results obtained under both condition was noted ($r > 0.97$; $p < 0.0001$). **B** Box-plot analysis of median liver stiffness. The central boxes represent median liver stiffness values from the lower to upper quartile (25th to 75th percentiles). The middle line represents the median. The vertical line extends from the minimum to maximum values within 1.5 interquartile range and shows the presence of outliers in the measurements. These were not excluded from analysis. **C** Bland-Altman plot of differences in median liver stiffness (kPa) obtained under free-breathing and breath-hold condition for each patient. The solid line (y=0) is a line of perfect agreement. The dotted line represents the mean of difference of elasticity ratings under both conditions (−0.04 kPa). The dashed line defines the limits of agreement (max. 1.5 kPa, equals 1.96 SD of the mean of difference). **D** Box-plot analysis of median liver stiffness in a subset of patients with histologic fibrosis staging according to METAVIR score (n=16). Analysis of variance demonstrated significant differences of elasticity between F0, F1, and ≥ F2 for free-breathing and breath-hold condition (P =.04 and P =.032). Group-wise comparison (Scheffe's test and LSD test): − free-breathing elasticity (F0 vs. F1, P =.977 and P =.938; F0 vs. ≥ F2, P =.078 and P =.027; F1 vs. ≥ F2, P =.074 and P =.025). - breath-hold elasticity (F0 vs. F1, P =.988 and P =.877; F0 vs. ≥ F2, P =.061 and P =.02; F1 vs. ≥ F2, P =.066 and P =.022)

Altman analysis was performed (Fig. 2C). The mean difference between the measurements obtained under both conditions was −0.04 kPa and the agreement of values (two standard deviations) was within ± 1.5 kPa. Variability (as measured by IQR and the ratio IQR/Median) was slightly increased under free-breathing compared to breath-hold

Table 1 Median liver stiffness in 57 children under free-breathing and breath-hold conditions

Parameter	Free-breathing condition	Breath-hold condition	PCC	P-value
Median liver stiffness (kPa)				
- 12 elastograms	7.22 ± 4.5	7.21 ± 4.1	0.979	0.953
- 6 elastograms	7.18 ± 4.8	7.17 ± 4.0	0.977	0.922
- 3 elastograms	7.14 ± 4.7	7.09 ± 4.0	0.977	0.749
ICC	0.993	0.994		

- All data are means ± standard deviations unless otherwise indicated.

- Association of free-breathing and breath-hold conditions were analysed with Pearson's correlation coefficient (PCC) and two-sided Student's t (P-value).

- Agreement of the results based on 12 elastograms, first six elastograms and first three elastograms were tested by calculating intraclass correlation coefficients (ICC, absolute agreement condition)

Table 2 Interquartile range (IQR) of median liver stiffness in 57 children under free-breathing and breath-hold conditions

Parameter	Free-breathing condition	Breath-hold condition	PCC	P-value
IQR (kPa)				
- 12 elastograms	1.11 ± 0.8	0.91 ± 0.6	0.707	0.008
- 6 elastograms	1.12 ± 1.1	0.83 ± 0.6	0.703	0.008
- 3 elastograms	0.79 ± 0.8	0.60 ± 0.6	0.529	0.036
ICC	0.761	0.593		

- All data are means ± standard deviations unless otherwise indicated.

- IQR = interquartile range of median liver stiffness measurements.

- Association of free-breathing and breath-hold conditions were analysed with Pearson's correlation coefficient (PCC) and two-sided Student's *t* (P-value).

- Agreement of the results based on 12 elastograms, first six elastograms and first three elastograms were tested by calculating intraclass correlation coefficients (ICC, absolute agreement condition)

conditions (IQR 1.11 ± 0.8 kPa vs. 0.91 ± 0.6 kPa, P =.008; IQR/Median 0.16 ± 0.08 vs. 0.13 ± 0.06, P =.005) (Tables 2 and 3).

Fibrosis staging according to METAVIR score was available in 16 patients (F0, n=5; F1, n=6; F2, n=3; F2, n=1; F4, n=1). Comparisons of elasticity between patients with F0, F1, ≥ F2 showed significant differences between the stages under the free-breathing condition and breath-hold condition (P =.04 and P =.032; Fig. 2D).

The time required for 12 measurements under free-breathing conditions was lower compared to that needed for 12 measurements under breath-hold conditions (79.27 ± 32.52 sec vs. 143.73 ± 51.83 sec, P < .001). The time expenditure may be further reduced by lowering the number of elastograms. Results for median liver stiffness based of the full set of 12 elastograms, the first six elastograms, and the first three elastograms demonstrated very high agreement for free-breathing (ICC 0.993) and for breath-hold conditions (ICC 0.994) (Table 1). There were also no significant differences regarding median liver stiffness between breath-hold and free-breathing results calculated with lower number of elastograms (Table 1).

Discussion

In the present study, we evaluated whether 2-D SWE of the liver can be performed under free-breathing conditions in children with suitable reliability and time expenditure. Current consensus recommends ultrasound elastography to be performed while breath-holding, as several studies have shown that the measurements are variably influenced by respiration [5]. In one study, expiratory liver stiffness measured by transient elastography (TE) was significantly higher than inspiratory liver stiffness in 39.8% of patients [18]. In another study, deep inspiration led to overestimation of values [28]. However, this respiratory influence has not been consistently shown for all ultrasound elastography techniques [29]. Horster et al. demonstrated that a Valsava manoeuvre leads to increased liver stiffness when measured by TE, but no significant changes when measured by the acoustic radiation force impulse (ARFI) technique [19]. Recently, ARFI-based 2-D elastography in children on the Aixplorer platform (SuperSonic Imagine SSI, Aix-en-Provence, France) revealed comparable mean stiffness values when stratified according to breath-hold and free-breathing conditions [24]. Accordingly, when applying the 2-D SWE technique in our study, we found

Table 3 Ratio of the interquartile range (IQR) and median liver stiffness in 57 children under free-breathing and breath-hold conditions

Parameter	Free-breathing condition	Breath-hold condition	PCC	P-value
IQR/Median				
- 12 elastograms	0.16 ± 0.08	0.13 ± 0.06	0.494	0.005
- 6 elastograms	0.15 ± 0.11	0.12 ± 0.08	0.414	0.016
- 3 elastograms	0.11 ± 0.08	0.08 ± 0.06	0.368	0.017
ICC	0.625	0.505		

- All data are means ± standard deviations unless otherwise indicated.

- IQR/Median = interquartile range of median liver stiffness (IQR) divided by median liver stiffness.

- Association of free-breathing and breath-hold conditions were analysed with Pearson's correlation coefficient (PCC) and two-sided Student's *t* (P-value).

- Agreement of the results based on 12 elastograms, first six elastograms and first three elastograms were tested by calculating intraclass correlation coefficients (ICC, absolute agreement condition)

no effect of respiratory motion on the diagnostically relevant median liver stiffness values.

The lower impact of respiratory motion on liver stiffness values obtained from the 2-D SWE technique used in our study may be explained by the very fast image acquisition resulting from applying an ultrasonic excitation pulse. Averaging the shear wave propagation in the liver may, in large part, contribute to smoothing out the inhomogeneity of motion. When comparing IQR, IQR/Median ratios and SD obtained under free-breathing and breath-hold conditions, we noticed only low-scale differences with a relatively larger spread, indicating higher signal heterogeneity, in the free-breathing group. The diagnostic significance of reported SDs is not yet clear. With 2-D SWE elastograms that offer a larger field of view covering substantial liver regions, higher or lower SDs may be of interest as they could reflect structural macroscopic changes occurring in liver disease. In that case, finding higher motion-induced variation is important to avoid misinterpretation.

A benefit of doing free-breathing examinations in children is lower time expenditure. In general, we were able to acquire a maximum of four measurements in one breath-hold cycle. With the breath-hold approach, repetitions due to failed attempts and time to recover from apnoea periods contributed to a longer total examination time. The time expenditure can be further reduced by lowering the number of elastograms. We observed high agreement of liver stiffness when calculating values based on the first six or three elastograms instead of the vendor-suggested 12 elastograms [5, 26]. The findings were similar for breath-hold and free-breathing conditions. Other studies have reported similar accuracy with a lower number of single measurements obtained with the Aixplorer ultrasound system [30, 31].

Our study has the following limitations: (1) The study design is retrospective, and is, therefore, dependent on medical documentation and principally prone to selection bias. (2) We provide histological analysis to compare to liver stiffness measurements only in a subset of patients with available biopsy. As this study was designed to test the measurement agreement of hepatic 2-D SWE under free-breathing and breath-hold conditions, we believe that histological correlation is not needed to answer this question. However, some uncertainties remain in very young-aged children (<6–8 years) who were not included in our study because of the inability to follow the breath-hold protocol. With higher respiratory rates and a generally lower capacity to remain still, reduced accuracy due to motion artefacts remains an issue in young children. (3) A relatively low number of children with increased liver stiffness were examined, and further investigations are needed to address motion variability in cases of higher fibrosis stages. In our study, differences between the two conditions increased with higher stiffness values (over 10 kPa) without evidence of systematic over- or underestimation of free-breathing measurements. It is known that heterogeneity of hepatic elasticity and viscosity increases with progressing fibrosis stages, and stronger attenuation of the ARFI push pulse within a stiffer organ can lead to more variable measurements in cirrhotic patients [5, 32–34]. (4.) Operator dependency was not assessed in our study. Children are often unwilling to cooperate with different examiners and do not tolerate extended examination times. However, previous adult and experimental studies have shown good inter-observer agreement for different ultrasound elastography techniques including 2-D SWE demonstrating a high level of reproducibility [4, 35].

In order to minimize variability and to enhance diagnostic performance of elastography measurements, the most suitable technique for the patient should be identified. In MRI elastography, image acquisition takes too long to avoid artefacts under free-breathing conditions, and respiratory gating is mandatory in patients unable to breath-hold [32]. As MRI is generally less accessible for children, fast ultrasound elastography techniques may be a more favourable alternative. Our study shows that 2-D SWE of the liver in children can indeed be performed under free-breathing conditions with a reduced number of elastograms and yield results comparable to those under breath-hold conditions but with a significantly lower time expenditure. By adopting a fast free-breathing protocol, ultrasound assessment of liver stiffness using 2-D SWE seems possible in less cooperative children with suspected liver disease.

Compliance with ethical standards

Guarantor The scientific guarantor of this publication is PD Dr. med Jochen Herrmann.

Conflict of interest The authors of this manuscript declare no relationships with any companies, that have products or services may be related to the subject matter of the article.

Funding The authors state that this work has not received any funding.

Statistics and biometry One of the authors has significant statistical expertise.

Ethical approval Institutional Review Board approval was obtained.

Informed consent Written informed consent was waived by the Institutional Review Board.

Methodology
- retrospective
- performed at one institution

References

1. Yoshimitsu K, Mitsufuji T, Shinagawa Y et al (2016) MR elastography of the liver at 3.0 T in diagnosing liver fibrosis grades; preliminary clinical experience. Eur Radiol 26:656–663
2. Mariappan YK, Glaser KJ, Ehman RL (2010) Magnetic resonance elastography: a review. Clin Anat 23:497–511
3. Rockey DC (2008) Noninvasive assessment of liver fibrosis and portal hypertension with transient elastography. Gastroenterology 134:8–14
4. Ferraioli G, Tinelli C, Zicchetti M et al (2012) Reproducibility of real-time shear wave elastography in the evaluation of liver elasticity. Eur J Radiol 81:3102–3106
5. Barr RG, Ferraioli G, Palmeri ML et al (2015) Elastography assessment of liver fibrosis: society of radiologists in ultrasound consensus conference statement. Radiology 276:845–861
6. Hanquinet S, Courvoisier D, Kanavaki A, Dhouib A, Anooshiravani M (2013) Acoustic radiation force impulse imaging-normal values of liver stiffness in healthy children. Pediatr Radiol 43:539–544
7. Eiler JKU, Albers D et al (2012) Standard value of ultrasound elastography using acoustic radiation force impulse imaging (ARFI) in healthy liver tissue of children and adolescents. Ultraschall in Med 33:474–479
8. Shin NY, Kim MJ, Lee MJ et al (2014) Transient elastography and sonography for prediction of liver fibrosis in infants with biliary atresia. J Ultrasound Med 33:853–864
9. Zhou LY, Jiang H, Shan QY et al (2017) Liver stiffness measurements with supersonic shear wave elastography in the diagnosis of biliary atresia: a comparative study with grey-scale US. Eur Radiol. doi:10.1007/s00330-016-4710-y
10. Nobili V, Pinzani M (2010) Paediatric non-alcoholic fatty liver disease. Gut 59:561–564
11. Tutar O, Beser OF, Adaletli I et al (2014) Shear wave elastography in the evaluation of liver fibrosis in children. J Pediatr Gastroenterol Nutr 58:750–755
12. Leschied JR, Dillman JR, Bilhartz J, Heider A, Smith EA, Lopez MJ (2015) Shear wave elastography helps differentiate biliary atresia from other neonatal/infantile liver diseases. Pediatr Radiol 45: 366–375
13. Noruegas MJ, Matos H, Goncalves I, Cipriano MA, Sanches C (2012) Acoustic radiation force impulse-imaging in the assessment of liver fibrosis in children. Pediatr Radiol 42:201–204
14. D'Onofrio M, Gallotti A, Mucelli RP (2010) Tissue quantification with acoustic radiation force impulse imaging: measurement repeatability and normal values in the healthy liver. AJR Am J Roentgenol 195:132–136
15. Toshima T, Shirabe K, Takeishi K et al (2011) New method for assessing liver fibrosis based on acoustic radiation force impulse: a special reference to the difference between right and left liver. J Gastroenterol 46:705–711
16. Yoneda M, Suzuki K, Kato S et al (2010) Nonalcoholic fatty liver disease: US-based acoustic radiation force impulse elastography. Radiology 256:640–647
17. Chen S, Sanchez W, Callstrom MR et al (2013) Assessment of liver viscoelasticity by using shear waves induced by ultrasound radiation force. Radiology 266:964–970
18. Yun MH, Seo YS, Kang HS et al (2011) The effect of the respiratory cycle on liver stiffness values as measured by transient elastography. J Viral Hepat 18:631–636
19. Horster S, Mandel P, Zachoval R, Clevert DA (2010) Comparing acoustic radiation force impulse imaging to transient elastography to assess liver stiffness in healthy volunteers with and without valsalva manoeuvre. Clin Hemorheol Microcirc 46:159–168
20. Tang A, Cloutier G, Szeverenyi NM, Sirlin CB (2015) Ultrasound elastography and MR elastography for assessing liver fibrosis: part 2, Diagnostic performance, confounders, and future directions. AJR Am J Roentgenol 205:33–40
21. Tang A, Cloutier G, Szeverenyi NM, Sirlin CB (2015) Ultrasound elastography and MR elastography for assessing liver fibrosis: part 1, principles and techniques. AJR Am J Roentgenol 205:22–32
22. Palmeri ML, Nightingale KR (2011) Acoustic radiation force-based elasticity imaging methods. Interface Focus 1:553–564
23. Frulio N, Trillaud H (2013) Ultrasound elastography in liver. Diagn Interv Imaging 94:515–534
24. Franchi-Abella S, Corno L, Gonzales E et al (2016) Feasibility and diagnostic accuracy of supersonic shear-wave elastography for the assessment of liver stiffness and liver fibrosis in children: a pilot study of 96 patients. Radiology 278:554–562
25. Belei O, Sporea I, Gradinaru-Tascau O et al (2016) Comparison of three ultrasound based elastographic techniques in children and adolescents with chronic diffuse liver diseases. Med Ultrason 18: 145–150
26. Song P, Macdonald M, Behler R et al (2015) Two-dimensional shear-wave elastography on conventional ultrasound scanners with time-aligned sequential tracking (TAST) and comb-push ultrasound shear elastography (CUSE). IEEE Trans Ultrason Ferroelectr Freq Control 62:290–302
27. (1994) Intraobserver and interobserver variations in liver biopsy interpretation in patients with chronic hepatitis C. The French METAVIR Cooperative Study Group. Hepatology 20:15–20
28. Karlas T, Pfrepper C, Troeltzsch M, Wiegand J, Keim V (2010) Acoustic radiation force impulse liver stiffness measurement: interlobe differences demand standardized examination procedures. Eur J Gastroenterol Hepatol 22:1387
29. Hall TJ, Milkowski A, Garra B et al. (2013) RSNA/QIBA: Shear wave speed as a biomarker for liver fibrosis staging. 2013 Ieee International Ultrasonics Symposium (Ius). 10.1109/Ultsym.2013.0103:397–400
30. Ferraioli G, Tinelli C, Dal Bello B et al (2012) Accuracy of real-time shear wave elastography for assessing liver fibrosis in chronic hepatitis C: a pilot study. Hepatology 56:2125–2133
31. Procopet B, Berzigotti A, Abraldes JG et al (2015) Real-time shear-wave elastography: applicability, reliability and accuracy for clinically significant portal hypertension. J Hepatol 62:1068–1075
32. Huwart L, Peeters F, Sinkus R et al (2006) Liver fibrosis: non-invasive assessment with MR elastography. NMR Biomed 19: 173–179
33. Venkatesh SK, Yin M, Ehman RL (2013) Magnetic resonance elastography of liver: technique, analysis, and clinical applications. J Magn Reson Imaging 37:544–555
34. Romero-Gomez M, Gomez-Gonzalez E, Madrazo A et al (2008) Optical analysis of computed tomography images of the liver predicts fibrosis stage and distribution in chronic hepatitis C. Hepatology 47:810–816
35. Mulabecirovic ABM, A; Gilja, OH; Flesland Havre, R (2016) In vitro quantification of tissue elasticity using three shear wave elastography platforms on liver fibrosis phantoms. Ultraschall in Med 37:E9_05