Received:
07 July 2018

Revised:
01 October 2018

Accepted:
04 October 2018

<https://doi.org/10.1259/bjr.20180602>

Cite this article as:

Xiang L, Ma F, Yao M, Xu G, Pu H, Liu H, et al. Benign lesion evaluation: Factors causing the “stiff rim” sign in breast tissues using shear-wave elastography. *Br J Radiol* 2019; **91**: 20180602.

FULL PAPER

Benign lesion evaluation: Factors causing the “stiff rim” sign in breast tissues using shear-wave elastography

^{1,2}LIHUA XIANG, MD, ³FANG MA, MD, ^{1,2}MINGHUA YAO, MD, ^{1,2}GUANG XU, MD, ^{1,2}HUAN PU, MD, ^{1,2}HUI LIU, MD, ^{1,2}YAN FANG, MD and ^{1,4}RONG WU, MD. PhD.

¹Department of Medical Ultrasound, Shanghai Tenth People's Hospital, Tongji University School of Medicine, Shanghai, China

²Ultrasound Research and Education Institute, Tongji University School of Medicine, Shanghai, China

³Department of Ultrasound, Shanghai Jiao Tong University Affiliated Sixth People's Hospital, Shanghai, China

⁴Department of Ultrasound, Shanghai General Hospital, Shanghai Jiaotong University School of Medicine, Shanghai, China

Address correspondence to: Mrs Rong Wu

E-mail: wurong7111@163.com

Objective: To investigate the factors causing the “stiff rim” sign in breast lesions using shear-wave elastography.

Methods: A total of 907 patients with 907 lesions were included retrospectively in this study. Traditional ultrasound and shear-wave elastography imaging were both performed. Patients age, maximum diameter, depth, distance, echogenicity, shape, boundary, margin, internal components, CDFI, calcification, echogenicity attenuation and longitudinal growth of lesions were observed and calculated by both univariate and multivariate analyses.

Results: Univariate analyses indicated that the age, depth, shape, margin, internal components, CDFI, calcification and pathology showed significant difference between the benign lesions with and without a “stiff rim”, whereas there was no correlation of “stiff rim” with maximum diameter, distance, boundary, echogenicity,

echo attenuation and longitudinal growth of the lesions. Multivariate analysis expressed that CDFI, margin, internal components, depth and age were significantly associated with the “stiff rim” sign in breast benign lesions, whereas there was no correlation with the pathology, shape or calcification of the lesions.

Conclusions: The “stiff rim” sign can be helpful for differentiation between benign and malignant lesions. Older patients with a “stiff rim” sign whose benign masses are deep, poorly defined, heterogeneous and have a positive CDFI should be examined more closely to avoid unnecessary false-positives.

Advances in knowledge: The “stiff rim” sign can be helpful for differentiation between benign and malignant lesions. Positive CDFI, poorly defined margin, heterogeneous internal components, deep depth and older age were significantly associated with the “stiff rim” sign in benign breast lesions.

INTRODUCTION

Breast cancer is one of the most significant malignant tumors that affect females. Breast cancer severely affects females's health, and its morbidity has been increasing in recent years.^{1,2} Early detection and therapy can help reduce the mortality of breast cancer. Traditional ultrasound is a main auxiliary method because of its high sensitivity, low price and relative safety. We need an additional modality to avoid the unnecessary surgery or biopsy as the specificity is low with traditional ultrasound techniques.

Shear-wave elastography (SWE) enables differentiation between benign and malignant lesions based on their stiffness. Benign lesions tend to be harder than the surrounding normal tissue, while softer than malignant lesions.^{3–5} SWE, a highly reproducible technique, provides a quantitative value for Young elastic modulus (in kilopascals) or velocity

(in m s⁻¹) of tissues by imaging the shear wave propagation within the tissue.^{6–11}

Since shear-wave velocity (SWV) is not the only way to diagnose breast tumors and the measurement of hardness in lesions is different, Evans et al⁹ and Tozaki and Fukuma¹² reported that typical peritumoral stiffness might be a sign of malignancy for breast lesions. Furthermore, Zhou et al¹³ called peritumoral stiffness the “stiff rim” sign and demonstrated that this sign might have a significant role in the diagnosis of breast lesions. However, we find some lesions are benign using the traditional ultrasound and have been shown by biopsy or surgery to exhibit the “stiff rim” sign. Moreover, there have been no reports related to factors that influence the “stiff rim” sign in benign lesions. Therefore, the aim of our study was to analyze the factors that influence the “stiff rim” sign in benign breast lesions.

Figure 1. Flowchart showing including of patients undergo breast biopsy or surgery with SWE imaging. SWE, shear-wave elastography.

METHODS AND MATERIALS

Patients

A total of 1613 patients approved by the institutional review board were enrolled retrospectively in the present study. Imaging was performed between December 2015 and December 2016. Patients were excluded because of one or more criterion as follows¹: patients who were unwilling or afraid to undergo biopsy or surgery²; patients whose SWE imaging was incomplete⁴; patients who had previous chemotherapy or currently in chemotherapy. One lesion per patient was included, and if patients displayed more than one lesion, lesions were chosen based on high breast imaging reporting and data system (BI-RADS) score or large diameter (if the BI-RADS were similar). 567 patients were excluded because of there were no pathological findings and there were 137 patients whose SWE imaging were incomplete and 2 patients selected conserved therapy rather than surgery. Therefore, 907 lesions were included in the present study (Figure 1).

Ultrasound and SWE examination

The conventional ultrasound and SWE examinations were conducted by Aixplorer® system (SuperSonic Imagine, Aix-en-Provence, France) equipped with linear probe (frequency, 4-15MHz). The scans were obtained by one of five sonographers (1-3 years experience in ultrasound and 1-2 years in SWE). Supine, chest and fully exposed axilla were the basic positions. Firstly, the ultrasound was conducted, and transverse and longitudinal planes were carried out for each lesion to obtain the corresponding morphological features. Then, we chose the plane

Table 1. Pathology

Finding	No. of lesions	%
Malignant	202	22.27
Invasive ductal carcinoma	144	15.88
Ductal carcinoma <i>in situ</i>	19	2.10
Invasive lobular carcinoma	5	0.55
Lobular carcinoma <i>in situ</i>	1	0.11
Others		
Mucinous carcinoma	8	0.88
Invasive apocrine carcinoma	2	0.22
Invasive papillary carcinoma	8	0.88
Non-invasive papillary carcinoma	7	0.77
Undefined invasive carcinoma	8	0.88
Benign	705	77.73
Adenosis	310	34.18
Fibroadenoma	331	36.50
Intraductal papillomas	25	2.76
Fibrotic scar tissue	9	1.00
Benign phyllodes tumor	7	0.77
Others		
Inflammation	18	2.00
Tubular adenoma	2	0.22
Lipomyoma	1	0.11
Lymphnode	1	0.11
Venous hemangioma	1	0.11

in which the breast lesions were shown at maximum diameter and switched to SWE. The range of SWE was set up at 180 Kpa according to Zhou et al.¹³ which indicated that 180 Kpa showed a higher consensus than <180 Kpa. Three elastography images were taken at both transverse and longitudinal planes. If the image was too large to select the entire lesion for SWE acquisition, the region of interest was set to encompass a select part of the lesion. Patients were asked to hold their breath during SWE imaging. All of the imaging data were stored in a hard disk for further analysis.

Imaging analysis

The transverse diameter, anteroposterior diameter and vertical diameter were measured, and the biggest value was used as the maximum diameter of lesion. We calculated the depth of lesions (from the skin to the center of lesion), distance of lesions (from the skin to the closest margin of lesions), echogenicity (hyper-, iso-, hypo-, mixed-), shape (regular or irregular), boundary (clear or unclear), margin (well-defined or poorly defined), internal components (homogeneous or heterogeneous), color Doppler flow signal (CDFI; negative or positive), calcification (negative or positive), echogenicity attenuation (negative or positive) and longitudinal growth (negative or positive). All of these measurements were conducted by two sonographers, the

Figure 2. A 48-year-old female with invasive ductal carcinoma of the left breast. Conventional ultrasound image (a) shows a poorly defined, heterogeneous lesion with depth >10 mm. Color Doppler image (b) demonstrates a positive CDFI. SSI SWE image (c) indicates the "stiff rim" sign, and histopathological analysis (d) reveals grade III invasive ductal carcinoma with HE staining (original magnification, $\times 200$). CDFI, color Doppler flow signal; HE, hematoxylin and eosin; SSI, SuperSonic imaging; SWE, shear-wave elastography.

final determination was in consensus. Patients were divided into different groups according to the depth (<10 mm, 10–20 mm and >20 mm) and distance (<10 mm, 10–20 mm and >20 mm). As for the elasticity imaging assessment, the "stiff rim" sign was defined when the periphery color of the lesions were distinctly harder compared with the internal and the surrounding tissue according to the color map ranging from blue (softest) to red (hardest).

Pathological findings

All of the participants in this retrospective study underwent biopsy or surgery, and the pathological findings were regarded as standard reference.

Statistical analysis

All of quantitative data were expressed as average $\pm$ standard deviation ($X \pm SD$). Univariate analyses were first performed using a *t* test or X^2 test to select the correlated factors followed

by a multivariate analysis. Diagnostic value, sensitivity, specificity, area under the receiver operator characteristic curve (AUC) and 95% confidence interval (95% CI) were calculated in both conventional ultrasound and SWE images. The data were analyzed by SPSS v. 22.0 (IBM, Armonk, NY). $p < 0.05$ was considered significant [$p < 0.1/n$ ($n-1$) comparing between subgroup (n : number of subgroup)].

RESULTS

The mean age of the patients was 45.41 ± 14.93 years (range from 15 to 99 years, median: 45 years). The mean diameter of the lesions was 17.67 ± 11.65 mm (range from 3 to 99 mm, median: 15 mm). The pathologic findings consisted of 22.27% (202/907) of samples were malignant lesions and 77.73% (705/907) of samples were benign lesions. Among the 202 malignant masses, 144 were invasive ductal carcinoma, 19 were ductal carcinoma *in situ*, 5 were invasive lobular carcinoma, 1 was lobular carcinoma *in situ* and 33 were others, including 8 mucinous carcinomas, 8

Figure 3. A 39-year-old female with adenosis of the left breast. Conventional ultrasound image (a) shows a poorly defined, homogeneous lesion with depth >10 mm. Color Doppler image (b) demonstrates a positive CDFI. SSI SWE image (c) indicates the “stiff rim” sign, and histopathological analysis (d) reveals adenosis with HE staining (original magnification, $\times 200$). CDFI, color Doppler flow signal; HE, hematoxylin and eosin; SSI, SuperSonic imaging; SWE, shear-wave elastography.

invasive papillary carcinomas, 8 undefined invasive carcinomas, 7 non-invasive papillary carcinomas and 2 invasive apocrine carcinomas. Of the 705 benign masses there were 310 adenosis, 331 fibroadenomas, 25 intraductal papillomas, 9 fibrotic scar tissues, 7 benign phyllodes tumor and 23 others, including 18 inflammations, 2 tubular adenomas, 1 lipomyoma, 1 lymph node and 1 venous hemangioma (Table 1).

When performing traditional ultrasound, 35.5% (322/907) of all masses were shown to be benign, consisting of 15 with BI-RADS 2 and 307 with BI-RADS 3. Furthermore, using ultrasound 64.5% of all masses were shown to be malignant, consisting of 375 with BI-RADS 4a, 82 with BI-RADS 4b, 111 with BI-RADS 4c and 17 with BI-RADS 5. The “stiff rim” sign was detected by SWE in 286 of the masses (173 malignant and 113 benign, Figures 2–4 and the remaining 621 masses (29 malignant and 592 benign, Figure 5) exhibited no “stiff rim” sign. Conventional ultrasound demonstrated a sensitivity of 97.52%, specificity of 45.11% and AUC of 0.713 [95% CI (0.679–0.747)] ($p < 0.001$), whereas the “stiff rim”

sign showed a sensitivity of 85.64%, specificity of 83.97% and AUC of 0.848 [95% CI (0.816–0.880)] ($p < 0.001$). There was a significant difference between conventional ultrasound and the “stiff rim” sign ($p < 0.001$); results are shown in Table 2.

Univariate analyses indicated that age ($p = 0.001$), depth ($p = 0.001$), shape ($p = 0.001$), margin ($p = 0.001$), internal components ($p < 0.001$), CDFI ($p < 0.001$), calcification ($p = 0.014$) and pathology ($p < 0.001$) showed significant differences between the benign lesions with and without a “stiff rim” sign. When comparing the lesion depth, there were significant differences between <10 and >20 mm ($p = 0.001$) and between <10 and 10 – 20 mm ($p = 0.007$), whereas no significant difference was observed between 10 – 20 and >20 mm ($p = 0.041$). Similar results were observed when adenosis lesions were compared with other pathologies ($p < 0.001$) and fibroadenomas were compared with other pathologies ($p = 0.003$), however there was no significance observed between adenosis compared with fibroadenoma ($p = 0.056$). We observed no correlation of “stiff rim” sign with

Figure 4. A 32-year-old female with inflammation of the left breast. Conventional ultrasound image (a) shows a well-defined, heterogeneous lesion with depth > 10 mm. Color Doppler image (b) demonstrates a positive CDFI. SSI SWE image (c) indicates the "stiff rim" sign, and histopathological analysis (d) reveals inflammatory granulation tissue with abscess with HE staining (original magnification, $\times 200$). CDFI, color Doppler flow signal; HE, hematoxylin and eosin; SSI, SuperSonic imaging; SWE, shear-wave elastography.

respect to maximum diameter (0.196), distance ($p = 0.960$), boundary ($p = 0.869$), echogenicity ($p = 0.069$), echo attenuation ($p = 0.334$) and longitudinal growth (0.660); results are shown in Table 3.

Multivariate analysis demonstrated that CDFI ($p = 0.003$), margin ($p = 0.011$), internal components ($p = 0.004$), depth ($p = 0.009$) and patient age ($p = 0.012$) were significantly associated with the "stiff rim" sign, while there was no correlation with pathology ($p = 0.074$), shape ($p = 0.358$) and calcification ($p = 0.133$). The odds ratio was 2.103 for CDFI [95% CI (1.277–3.464)], 2.044 for margin [95% CI (1.180–3.541)], 1.922 for internal components [95% CI (1.237–2.986)], 1.820 for depth [95% CI (1.159–2.858)] and 0.979 for patient age [95% CI (0.963–0.995)]; results are shown in Table 4.

DISCUSSION

Ultrasound elastography is a new technology that has been developed in recent years which helps distinguish malignant

lesions from benign lesions because malignant lesions are harder than benign.^{3–5} SWE produces a coded color map transferred by the velocity of the mass based on the shear wave. Therefore, SWE can provide quantitative analysis for each lesion. The World Federation for Ultrasound in Medicine and Biology (WFUMB) provides the guidelines for ultrasound elastography in the breast.¹⁴ Many studies^{6,9,12,15–21} have proved the diagnostic value of SWE and confirmed its effectiveness.

Some reports have shown limits of SWE. Berg et al¹⁶ and Wang et al¹⁸ have shown the most important value is the maximum value (E_{max}), whereas Evans et al⁹ indicated the most important value is the mean (E_{mean}). The possible reasons for the differing results could be the sample (region of interest) was different. It is difficult to measure the lesions correctly when the elastography imaging does not fully capture the lesions or if there is a stiff range in peripheral lesions. If the quantitative measurement does not meet our clinical needs,

Figure 5. A 32-year-old female with fibroadenoma of the left breast. Conventional ultrasound image (a) shows a well-defined, homogeneous lesion with depth <10 mm. Color Doppler image (b) demonstrates a positive CDFI. SSI SWE image (c) indicates there is no “stiff rim” sign and that the color map is even. Histopathological analysis (d) reveals fibroadenoma with HE staining (original magnification, $\times 200$). CDFI, color Doppler flow signal; HE, hematoxylin and eosin; SSI, SuperSonic imaging; SWE, shear-wave elastography.

the qualitative analysis might provide supplement for the differentiation between malignant and benign lesions.

In our study, ultrasound was associated with a sensitivity of 97.52%, specificity of 45.11% and AUC of 0.713 [(95% CI (0.679–0.747))] ($p < 0.001$). When considering the “stiff rim” sign as the indicator for malignancy, the corresponding sensitivity was 85.64%, specificity was 83.97% and AUC was 0.848 [(95% CI (0.816–0.880))] ($p < 0.001$). We observed a significant difference between ultrasound and SWE ($p < 0.001$). Our results were slightly lower than a previous study by Zhou *et al*¹³ which showed the sensitivity was 60.7%, specificity was 97.8% and

the accuracy was 0.793. These results differ from ours that the possible reason was that the number of participants included in our study is larger and the pathological composition is different from Zhou *et al*.¹³ The purpose of our study was to investigate the factors that may cause a “stiff rim”. Our results proved the “stiff rim” sign could be helpful for differentiation between malignant and benign lesions.

Many studies have shown the patient’s age is not significantly correlated with a “stiff rim”, which differs from our results.^{22–24} The possible reason for conflicting results might be the thickness of the breast tissue in older vs younger females. In addition,

Table 2. Diagnostic value of ultrasound and “stiff rim” sign for breast lesions

Modalities	Sensitivity (%)	Specificity (%)	AUC	95% CI	P ₁	P ₂
Ultrasound	97.52	45.11	0.713	0.679–0.747	<.001	<.001
Stiff rim	85.64	83.97	0.848	0.816–0.880	<.001	

AUC, area under the curve; CI, confidence interval;

P₁, compared with pathology; P₂, compared with each other.

Table 3. Correlation of "stiff rim" sign with patients and features of benign lesions

Factors	All benign lesions (<i>n</i> = 705)	"Stiff rim" sign		<i>p</i> - Value
		Negative (<i>n</i> = 592)	Positive (<i>n</i> = 113)	
Age (y)	42.10 ± 12.78	40.72 ± 12.74	44.62 ± 12.46	0.001
Maximum diameter (mm)	16.10 ± 10.56	15.87 ± 10.69	17.27 ± 9.82	0.196
Depth (No.)				0.001
<10 mm	311	276	35	0.041 ^a
10–20 mm	374	304	70	0.001 ^b
>20 mm	20	12	8	0.007 ^c
Distance (no.)				0.960
<10 mm	554	465	89	
≥10 mm	151	127	24	
Shape (no.)				0.001
Regular	429	376	53	
Irregular	276	216	60	
Boundary (no.)				0.869
Clear	584	491	93	
Unclear	121	101	20	
Margin (no.)				0.001
Well-defined	624	537	87	
Poorly defined	81	55	26	
Echogenicity (no.)				0.069
Hypoechoogenicity	679	574	105	
Others	26	18	8	
Internal components (no.)				<0.001
Homogeneous	501	440	61	
Heterogeneous	204	152	52	
CDFI (no.)				<0.001
Negative	576	497	79	
Positive	129	95	34	
Calcification (no.)				0.014
Negative	602	514	88	
Positive	103	78	24	
Echo attenuation (no.)				0.334
Negative	696	586	110	
Positive	9	6	3	
Longitudinal growth (no.)				0.660
Negative	676	569	107	
Positive	29	23	6	
Pathology (no.)				<0.001
Adenosis	310	274	36	0.003 ^d

(Continued)

Table 3. (Continued)

Factors	All benign lesions (<i>n</i> = 705)	“Stiff rim” sign		<i>p</i> - Value
		Negative (<i>n</i> = 592)	Positive (<i>n</i> = 113)	
Fibroadenoma	331	275	56	<0.001 ^e
Others	64	43	21	0.056 ^f

CDFI, color Doppler flow signal;

^aCompared 10-20 mm with >20 mm.

^bCompared <10 mm with >20 mm.

^cCompared <10 mm with >20 mm.

^dCompared fibroadenoma with others.

^eCompared adenosis with others.

^fCompared adenosis with fibroadenoma.

pressure from operators could vary depending on tissue thickness. All of the breast lesions we calculated is benign which might be another reason causing the different findings.

Our results showed the depth was correlated with the “stiff rim” sign because the deeper lesions were more likely to have a “stiff rim”. Chang *et al*²² showed the depth of lesions could affect the quality of the image. Thomas *et al*²⁴ indicated the penetration of the shear wave was weak in lesions that were greater than 1 cm deep. Furthermore, Raza *et al*²³ indicated that there were more false-positive and false-negative results. The presence of a “stiff rim” could be caused by a desmoplastic reaction or the infiltration of cancer cells into the interstitial tissues,^{6,25,26} low shear wave amplitude and/or noise within the malignant lesion²⁷ or internal biological factors.²⁸ Both Raza *et al*²³ and Thomas *et al*²⁴ showed that the penetration of ultrasound and SWE decrease in deeper lesions.

The present study showed that CDFI, internal components and margin were associated with a “stiff rim” sign. These results might suggest that lesions with blood flow may grow faster. When the perimeter of the tension is bigger, shear wave velocity and attenuation may be different in heterogeneous lesions. In addition, lesions with poorly defined margins might have tension in the perimeter.

Our current study has four main limitations. First, the imaging analysis was performed by two sonographers, and there was no analysis related to observer variability. Both Burnside *et al*²⁹ and Regner *et al*³⁰ showed there was difference among observers.

Second, the quality of the elastography image was not standardized. Previous studies have shown the quality of the elastography image is dependent on transducer frequency, bandwidth, and radio frequency sampling rate associated with size and depth of lesions.³¹⁻³⁴ Barr *et al*³⁵ indicated that the correct identification of benign and malignant lesions increases when the quality of the image and quantitative measurement is combined. Third, we performed our study using the range of >180 kpa, which might have affected our estimation for “stiff rim” sign. Zhou *et al*¹³ found that the diagnostic value was higher using <180 kpa compared with >180 kpa. Finally, we used one probe frequency in our study. The probe frequency might influence the quality of the images and has been shown to cause different results in previous studies.³¹⁻³⁴ Furthermore, the quality of SWE, especially SuperSonic imaging, needs further study.

CONCLUSIONS

Benign breast lesions in older patients with deep depth, poorly defined margin, heterogeneous internal components and a positive CDFI were more likely show “stiff rim” sign thus might cause false-positive.

ACKNOWLEDGMENT

There was no any individuals who contributed to the research described in the paper or to the development of the manuscript but who do not fulfil the criteria to be listed as an author.

CONFLICTS OF INTEREST

This work was approved by all authors and tacitly or explicitly by the responsible authorities and there was no conflicts

Table 4. Multivariate analysis of factors associated with the “stiff rim” sign

Characteristic	B	Wald	<i>p</i> -value	OR	95% CI
Age	-0.021	6.383	0.012	0.979	0.963–0.995
Depth	0.599	6.766	0.009	1.820	1.159–2.858
Margin	0.715	6.518	0.011	2.044	1.180–3.541
Internal components	0.653	8.446	0.004	1.922	1.237–2.986
CDFI	0.743	8.529	0.003	2.103	1.277–3.464

CDFI, color Doppler flow signal; CI, confidence interval; OR, odds ratio;

of interest. This work was supported in part by Grant SHDC12016233 from Shanghai Hospital Development Center, Grants 81471673 and 81671699 from the National Natural

Science Foundation of China, Grant PD2014-7 from Shanghai PuDong district Municipal Commission of Health and Family Planning

REFERENCES

- Mohey N, Hassan TA. Value of mammography and combined grey scale ultrasound and ultrasound elastography in the differentiation of solid breast lesions. *Egypt J Rad Nuc Med* 2014; **45**: 253–61. doi: <https://doi.org/10.1016/j.ejnm.2013.11.002>
- Siegel R, Naishadham D, Jemal A. Cancer statistics, 2013. *CA Cancer J Clin* 2013; **63**: 11–30. doi: <https://doi.org/10.3322/caac.21166>
- Garra BS. Imaging and estimation of tissue elasticity by ultrasound. *Ultrasound Q* 2007; **23**: 255–68. doi: <https://doi.org/10.1097/ruq.0b013e31815b7ed6>
- Sewell CW. Pathology of benign and malignant breast disorders. *Radiol Clin North Am* 1995; **33**: 1067–80.
- Gao L, Parker KJ, Lerner RM, Levinson SF. Imaging of the elastic properties of tissue—a review. *Ultrasound Med Biol* 1996; **22**: 959–77. doi: [https://doi.org/10.1016/S0301-5629\(96\)00120-2](https://doi.org/10.1016/S0301-5629(96)00120-2)
- Athanasiou A, Tardivon A, Tanter M, Sigal-Zafrani B, Bercoff J, Defieux T, et al. Breast lesions: quantitative elastography with supersonic shear imaging—preliminary results. *Radiology* 2010; **256**: 297–303. doi: <https://doi.org/10.1148/radiol.10090385>
- Tanter M, Bercoff J, Athanasiou A, Defieux T, Gennisson JL, Montaldo G, et al. Quantitative assessment of breast lesion viscoelasticity: initial clinical results using supersonic shear imaging. *Ultrasound Med Biol* 2008; **34**: 1373–86. doi: <https://doi.org/10.1016/j.ultrasmedbio.2008.02.002>
- Cosgrove DO, Berg WA, Doré CJ, Skyba DM, Henry JP, Gay J, et al. Shear wave elastography for breast masses is highly reproducible. *Eur Radiol* 2012; **22**: 1023–32. doi: <https://doi.org/10.1007/s00330-011-2340-y>
- Evans A, Whelehan P, Thomson K, McLean D, Brauer K, Purdie C, et al. Quantitative shear wave ultrasound elastography: initial experience in solid breast masses. *Breast Cancer Res* 2010; **12**: R104. doi: <https://doi.org/10.1186/bcr2787>
- Bercoff JCA, Bacrie CC. Shear Wave™ Elastography: a new real time imaging mode for assessing quantitatively soft tissue viscoelasticity. *Proceedings of the 2008 IEEE International Ultrasonics Symposium Beijing, China* 2008; 321–4.
- Bercoff J, Tanter M, Fink M. Supersonic shear imaging: a new technique for soft tissue elasticity mapping. *IEEE Trans Ultrason Ferroelectr Freq Control* 2004; **51**: 396–409. doi: <https://doi.org/10.1109/TUFFC.2004.1295425>
- Tozaki M, Fukuma E. Pattern classification of ShearWave™ Elastography images for differential diagnosis between benign and malignant solid breast masses. *Acta Radiol* 2011; **52**: 1069–75. doi: <https://doi.org/10.1258/ar.2011.110276>
- Zhou J, Zhan W, Chang C, Zhang X, Jia Y, Dong Y, et al. Breast lesions: evaluation with shear wave elastography, with special emphasis on the “stiff rim” sign. *Radiology* 2014; **272**: 63–72. doi: <https://doi.org/10.1148/radiol.14130818>
- Barr RG, Nakashima K, Amy D, Cosgrove D, Farrokhi A, Schafer F, et al. WFUMB guidelines and recommendations for clinical use of ultrasound elastography: Part 2: breast. *Ultrasound Med Biol* 2015; **41**: 1148–60. doi: <https://doi.org/10.1016/j.ultrasmedbio.2015.03.008>
- Chang JM, Moon WK, Cho N, Yi A, Koo HR, Han W, et al. Clinical application of shear wave elastography (SWE) in the diagnosis of benign and malignant breast diseases. *Breast Cancer Res Treat* 2011; **129**: 89–97. doi: <https://doi.org/10.1007/s10549-011-1627-7>
- Berg WA, Cosgrove DO, Doré CJ, Schäfer FK, Svensson WE, Hooley RJ, et al. Shear-wave elastography improves the specificity of breast US: the BE1 multinational study of 939 masses. *Radiology* 2012; **262**: 435–49. doi: <https://doi.org/10.1148/radiol.11110640>
- Evans A, Whelehan P, Thomson K, Brauer K, Jordan L, Purdie C, et al. Differentiating benign from malignant solid breast masses: value of shear wave elastography according to lesion stiffness combined with greyscale ultrasound according to BI-RADS classification. *Br J Cancer* 2012; **107**: 224–9. doi: <https://doi.org/10.1038/bjc.2012.253>
- Wang ZL, Li JL, Li M, Huang Y, Wan WB, Tang J. Study of quantitative elastography with supersonic shear imaging in the diagnosis of breast tumours. *Radiol Med* 2013; **118**: 583–90. doi: <https://doi.org/10.1007/s11547-012-0903-x>
- Youk JH, Gweon HM, Son EJ, Chung J, Kim JA, Kim EK. Three-dimensional shear-wave elastography for differentiating benign and malignant breast lesions: comparison with two-dimensional shear-wave elastography. *Eur Radiol* 2013; **23**: 1519–27. doi: <https://doi.org/10.1007/s00330-012-2736-3>
- Lee SH, Chang JM, Kim WH, Bae MS, Cho N, Yi A, et al. Differentiation of benign from malignant solid breast masses: comparison of two-dimensional and three-dimensional shear-wave elastography. *Eur Radiol* 2013; **23**: 1015–26. doi: <https://doi.org/10.1007/s00330-012-2686-9>
- Gweon HM, Youk JH, Son EJ, Kim JA. Visually assessed colour overlay features in shear-wave elastography for breast masses: quantification and diagnostic performance. *Eur Radiol* 2013; **23**: 658–63. doi: <https://doi.org/10.1007/s00330-012-2647-3>
- Chang JM, Moon WK, Cho N, Kim SJ. Breast mass evaluation: factors influencing the quality of US elastography. *Radiology* 2011; **259**: 59–64. doi: <https://doi.org/10.1148/radiol.10101414>
- Raza S, Odulate A, Ong EM, Chikarmane S, Harston CW. Using real-time tissue elastography for breast lesion evaluation: our initial experience. *J Ultrasound Med* 2010; **29**: 551–63.
- Thomas A, Fischer T, Frey H, Ohlinger R, Grunwald S, Blohmer JU, et al. Real-time elastography—an advanced method of ultrasound: First results in 108 patients with breast lesions. *Ultrasound Obstet Gynecol* 2006; **28**: 335–40. doi: <https://doi.org/10.1002/uog.2823>
- Itoh A, Ueno E, Tohno E, Kamma H, Takahashi H, Shiina T, et al. Breast disease: clinical application of US elastography for diagnosis. *Radiology* 2006; **239**: 341–50. doi: <https://doi.org/10.1148/radiol.2391041676>
- Garra BS, Cespedes EI, Ophir J, Spratt SR, Zurbier RA, Magnant CM, et al. Elastography of breast lesions: initial clinical results. *Radiology* 1997; **202**: 79–86. doi: <https://doi.org/10.1148/radiology.202.1.8988195>
- Barr RG. Shear wave imaging of the breast: still on the learning curve. *J Ultrasound Med* 2012; **31**: 347–50.

28. Evans A, Whelehan P, Thomson K, McLean D, Brauer K, Purdie C, et al. Invasive breast cancer: relationship between shear-wave elastographic findings and histologic prognostic factors. *Radiology* 2012; **263**: 673–7. doi: <https://doi.org/10.1148/radiol.12111317>
29. Burnside ES, Hall TJ, Sommer AM, Hesley GK, Sisney GA, Svensson WE, et al. Differentiating benign from malignant solid breast masses with US strain imaging. *Radiology* 2007; **245**: 401–10. doi: <https://doi.org/10.1148/radiol.2452061805>
30. Regner DM, Hesley GK, Hangiandreou NJ, Morton MJ, Nordland MR, Meixner DD, et al. Breast lesions: evaluation with US strain imaging--clinical experience of multiple observers. *Radiology* 2006; **238**: 425–37. doi: <https://doi.org/10.1148/radiol.2381041336>
31. Bouchard RR, Dahl JJ, Hsu SJ, Palmeri ML, Trahey GE. Image quality, tissue heating, and frame rate trade-offs in acoustic radiation force impulse imaging. *IEEE Trans Ultrason Ferroelectr Freq Control* 2009; **56**: 63–76. doi: <https://doi.org/10.1109/TUFFC.2009.1006>
32. Chandrasekhar R, Ophir J, Krouskop T, Ophir K. Elastographic image quality vs. tissue motion in vivo. *Ultrasound Med Biol* 2006; **32**: 847–55. doi: <https://doi.org/10.1016/j.ultrasmedbio.2006.02.1407>
33. Havre RF, Elde E, Gilja OH, Odegaard S, Eide GE, Matre K, et al. Freehand real-time elastography: impact of scanning parameters on image quality and in vitro intra- and interobserver validations. *Ultrasound Med Biol* 2008; **34**: 1638–50. doi: <https://doi.org/10.1016/j.ultrasmedbio.2008.03.009>
34. Righetti R, Srinivasan S, Kumar AT, Ophir J, Krouskop TA. Assessing image quality in effective Poisson's ratio elastography and poroelastography: I. *Phys Med Biol* 2007; **52**: 1303–20. doi: <https://doi.org/10.1088/0031-9155/52/5/007>
35. Barr RG, Zhang Z. Shear-wave elastography of the breast: value of a quality measure and comparison with strain elastography. *Radiology* 2015; **275**: 45–53. doi: <https://doi.org/10.1148/radiol.14132404>