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The Application of Shear Wave Elastography in Clinical Practice

Yitian Cheng [+], Boqin Liu [+], Xinyi Yu, Haoran Ma, Yuanjie Chen, Jiayi Guo, Yawen Gui, Zhijun Zhang [*]

Department of Ultrasound, University-Town Hospital of Chongqing Medical University, Chongqing 401331, China

+ These authors contributed equally to this work and should be considered co-first authors.

*Corresponding Author: 297539657@qq.com

ABSTRACT

Shear wave elastography (SWE) is a novel type of ultrasound elastography technology that has emerged in recent years. It quantitatively measures the elastic modulus of tissues (represented by Young's modulus values) by detecting the propagation speed of shear waves generated in tissues under the action of acoustic radiation force. SWE technology objectively reflects the hardness characteristics of tissues as an non-invasive and highly repeatable ultrasound examination method. It has significant advantages such as quantitative measurement, simple operation, and real-time dynamic imaging. As a result, it provides an important imaging evaluation tool for the early diagnosis of clinical diseases, pathological staging, and dynamic monitoring of treatment effects. With the continuous development of ultrasound technology and in-depth exploration of clinical applications, SWE technology has shown broad application prospects and important clinical value in multiple medical fields. This article systematically reviews the development history of ultrasound elastography technology, and focuses on elaborating the basic principles of SWE technology and its application status in clinical practice. Through a comprehensive analysis of the latest research progress at home and abroad, it elaborates on the research achievements and application value of SWE technology in multiple important clinical fields such as liver fibrosis assessment, thyroid nodule differential diagnosis, breast nodule benign and malignant discrimination, myocardial hardness detection, and kidney disease assessment. The aim is to provide comprehensive reference for clinical physicians and researchers, and to envision the future development direction of this technology.

KEYWORDS

Shear wave elastography; Ultrasound examination; Clinical practice

1. INTRODUCTION

The concept of shear wave elastography (SWE) for elastography was first proposed by Ophir et al. in 1991 [1]. The core mechanism of this technology lies in using ultrasonic transducers to emit acoustic radiation pulses. By conducting continuous focusing at different tissue depths, it induces vibration displacements within the tissues, thereby exciting transverse propagating shear waves. The instrument can quantitatively calculate the Young's modulus value reflecting tissue hardness by accurately capturing the propagation characteristics of these shear waves [2]. In recent years, the application value of SWE in clinical medicine has become increasingly prominent. In the differentiation of benign and malignant tumors, the staging of tissue fibrosis, and the dynamic monitoring of therapeutic effects, SWE provides important auxiliary diagnostic information.

Especially in the field of musculoskeletal system, this technology has been widely applied in trauma assessment and pathological state analysis [3]. Moreover, SWE demonstrates unique advantages in the diagnosis of diseases in organs such as the liver, breast, and thyroid. Its non-invasive nature, real-time dynamic imaging ability, and quantitative analysis characteristics make it an important tool for the assessment of multiple organ diseases. With the deepening of clinical research, the application scope of SWE is gradually expanding to more medical fields such as the nervous system, providing new imaging support for precision medicine.

2. RESEARCH ON THE APPLICATION OF SWE IN THE DIAGNOSIS OF BREAST NODULES

In recent years, a large number of clinical studies have confirmed that shear wave elastography (SWE) demonstrates significant advantages in the differential diagnosis of benign and malignant breast masses by quantitatively detecting tissue hardness [4]. Gweon et al. conducted a clinical analysis of 153 patients with breast lesions and found that the SWE technique has good feature reproducibility. The measurement of elastic modulus by SWE can provide an objective basis for the qualitative diagnosis of breast masses. Notably, this study discovered that combining qualitative SWE with traditional B-ultrasound examination can significantly improve the specificity of biopsy recommendation decisions, thereby reducing unnecessary biopsy procedures [5].

Researchers Pillai A et al. conducted a systematic analysis of data from 87 prospective and retrospective studies (including a total of 17,810 female patients with an average age of 42.3 ± 10.4 years; 19,043 breast lesions, among which 7,623 were malignant), and confirmed that SWE has reliable diagnostic and differential diagnostic capabilities for breast cancer. Based on the diagnostic likelihood ratio analysis, this study particularly pointed out that SWE technology can effectively assist clinical decision-making and help reduce the over-treatment of BI-RADS 4a or 3 lesions [6].

In terms of elastic parameter measurement, Shi Shanhu et al. conducted an in-depth study on 483 breast nodules in 453 female patients. All lesions were confirmed by coarse needle biopsy or surgical pathology. Study the adoption of standardized inspection schemes: First, routine two-dimensional ultrasound examination was performed, followed by SWE examination. Elastic images of radial and anti-radial sections of the lesion were collected respectively. Elastic modulus parameters (including Emean, Emax, Emin, Esd) were systematically measured, and anisotropy factors (AFmean, AFmax, AFmin, AFsd) were innovatively calculated. ROC curve analysis results show that SWE can not only accurately evaluate the hardness characteristics of breast tumors, but also effectively reflect the anisotropic characteristics of tissue structure, among which malignant tumors show more significant anisotropic characteristics [7].

From the perspective of pathophysiology, malignant breast nodules have significantly higher Young's modulus values than benign lesions due to factors such as increased collagen cross-linking in the extracellular matrix and disordered tissue structure. Multiple studies have confirmed that when 45 kPa is used as the diagnostic threshold, the sensitivity and specificity of SWE for invasive ductal carcinoma can reach 85% and 90%, respectively [8, 9]. It is worth noting that the combined application of SWE and conventional ultrasound has significant clinical significance: on the one hand, it can significantly improve diagnostic accuracy; on the other hand, it can effectively reduce unnecessary biopsy punctures. This advantage is particularly prominent in dense breast tissue or lesions with microcalcifications [8]. This multimodal imaging combined diagnostic mode provides new technical support for optimizing the diagnosis and treatment process of breast diseases.

3. RESEARCH ON THE APPLICATION OF SWE IN THE DIAGNOSIS OF THYROID NODULES

The differential diagnosis of benign and malignant thyroid nodules is always the focus and difficulty of clinical ultrasound diagnosis. Traditional ultrasonography has some limitations in the evaluation of atypical thyroid nodules. Shear wave elastography (SWE) provides a new solution to this clinical problem by quantitatively detecting nodular hardness changes. Studies have shown that the elastic modulus of malignant thyroid nodules (such as papillary carcinoma) is significantly higher than that of benign nodules due to pathological changes such as interstitial fibrosis and microcalcification. Relevant data show that the maximum Young's modulus (Emax) of malignant nodules usually exceeds 124kPa, and the diagnostic accuracy of SWE technology can be improved by about 15% compared with conventional ultrasound [8].

In the aspect of the elastic characteristics of thyroid nodules, scholars such as Lu Xin conducted a systematic analysis on 230 patients with thyroid nodules. The research results showed that there were significant statistical differences ($P < 0.05$) between malignant nodules and benign nodules in parameters such as the maximum Young's modulus (Emax), the average value (Emean), and the elastic ratio of the nodules to the surrounding normal tissues. Among them, Emax showed the most excellent diagnostic efficacy. It is worth noting that the Emean index also showed potential application value in predicting lymph node metastasis of thyroid malignancies. However, a unified elastic threshold standard has not been established for the diagnosis of thyroid diseases by SWE at present. Some studies have shown [10] that different pathological types of thyroid malignancies have characteristic elastic manifestations. For example, the SWE elastic threshold of papillary carcinoma is significantly higher than that of follicular carcinoma and medullary carcinoma, and this difference may be closely related to its specific histological structure [11].

Deng Yanfeng's team conducted a prospective study on 126 cases of thyroid space occupying lesions (51 malignant and 75 benign) to systematically evaluate the value of combined diagnosis of high frequency color Doppler ultrasound and SWE. In this study, the multi-parameter analysis method was used, and the results showed that the combined diagnosis mode had significant advantages over the single detection method, and its sensitivity (94.12%), specificity (93.3%) and accuracy (93.65%) were significantly improved, and the increases in sensitivity and accuracy were statistically significant ($P < 0.05$). The analysis of high-frequency color Doppler ultrasound parameters showed that there were significant differences in blood flow signal, resistance index (RI) and peak contraction velocity (PSV) between patients with thyroid cancer and those with benign lesions ($P < 0.05$). At the same time, SWE quantitative parameter detection showed that the indexes of Emax, Emean, Esd and Eratio in malignant group were significantly higher than those in benign group ($P < 0.05$). This study confirmed that the combined application of high-frequency color Doppler ultrasound and SWE can significantly improve the differential diagnosis of benign and malignant thyroid diseases [12].

In addition, SWE technology has shown unique value in the prognosis assessment of thyroid micropapillary carcinoma. Clinical observations have shown that the value of the elastic modulus of the nodule is associated with the invasive characteristics of the tumor (such as the risk of capsular invasion or central lymph node metastasis). When SWE elastic parameters are combined with conventional ultrasonic features (such as hypoechoic, microcalcification, etc.), diagnostic specificity can be further improved [9]. These results provide an important basis for the application of SWE in the precise diagnosis and treatment of thyroid diseases.

4. THE APPLICATION VALUE OF SWE IN THE DIAGNOSIS OF LIVER DISEASES

Ultrasonic shear wave elastography (SWE) has become an important imaging tool for the evaluation of diffuse liver diseases due to its advantages of non-invasiveness, simple operation and good repeatability. Through quantitative measurement of liver hardness, this technique provides an objective basis for the graded diagnosis of liver fibrosis, treatment monitoring of chronic liver disease and prognosis assessment [13]. Studies have shown that with the aggravation of liver fibrosis, tissue hardness presents a progressive increase. SWE achieves the noninvasive stage of liver fibrosis by detecting shear wave velocity (SWV) or Young's modulus value (e.g., >10kPa indicates significant fibrosis), and its diagnostic sensitivity and specificity for early liver fibrosis (stage F1-F2) are both over 80%, which is significantly better than traditional serological markers [8].

In terms of the diagnosis of liver space-occupying lesions, Zhao Jia and other scholars conducted a systematic study on 68 patients with liver tumors. The results showed that the diagnostic accuracy (86.76%), sensitivity (81.08%) and specificity (93.55%) of SWE examination were significantly higher than those of conventional ultrasound examination (60.29%, 51.35%, 70.97%), and the differences were statistically significant ($P<0.05$). Further analysis showed that the consistency of SWE examination results and postoperative pathological results was good (Kappa=0.711), while the consistency of conventional ultrasound was only moderate (Kappa=0.582). It is worth noting that the elastic modulus of the malignant tumor group was significantly higher than that of the benign tumor group ($P<0.05$) [14].

Congestive liver disease (CH) is an important complication of heart failure, and its pathological mechanism is closely related to passive hepatic congestion caused by elevated hepatic venous pressure. Long-term hepatic venous hypertension can lead to liver fibrosis and even cirrhosis [15]. CH has characteristic manifestations in ultrasound examination, including hepatic venous dilation with low collapse rate, portal hypertension signs (hepatomegaly, ascites, splenomegaly, etc.), and characteristic hemodynamic changes (tachytachysis, decreased velocity of venous system, increased hepatic arterial resistance, etc.). Emerging ultrasound techniques, such as elastic imaging and contra-ultrasound, provide a new perspective for the diagnosis of CH [16].

Song Yi's team conducted a special study on the value of SWE in the differential diagnosis of focal liver lesions (FLLs). The study included 122 patients with FLLs (122 lesions), of which 65 were benign (47 hemangiomas, 10 hepatocellular adenomas, 8 focal nodular hyperplasia) and 57 were malignant (38 hepatocellular carcinomas, 19 metastatic hepatocellular carcinomas). According to ROC curve analysis, when the critical value of Young's mean modulus (Emean) was set to 16.300 kPa, the diagnostic sensitivity was 68.9%, the specificity was 54.4%, and the area under ROC curve was 63.3%. Although the diagnostic efficiency is at a moderate level, SWE can still be used as an effective auxiliary means to enhance contrast-enhanced ultrasound (CEUS) in the diagnosis of benign and malignant FLLs [17].

5. INNOVATIVE APPLICATION OF SWE IN THE EVALUATION OF HEART DISEASE

Shear Wave Elastography (SWE), as an emerging ultrasound technology, can achieve non-invasive quantitative evaluation of myocardial hardness by detecting the mechanical wave propagation velocity in myocardial tissue, thus providing a new dimension for traditional echocardiography to diagnose myocardial diseases [18]. The core principle of this technique is to capture the instantaneous shear waves of the myocardium wall using high frame rate ultrasound and convert their propagation characteristics into the corresponding tissue elastic parameters. However, due to the unique thin-wall geometry of the heart and complex material properties, the propagation of shear waves may be interfered by many factors, which to some extent limits its standardized application in clinical practice [19].

In the diagnosis of heart disease, diastolic Myocardial Stiffness (MS) has become an important indicator for assessing congenital or acquired heart disease. Recent studies have shown that the SWE technique can effectively quantify MS, but its measurement results may be affected by external factors such as left ventricular geometry. For example, a study of 60 healthy volunteers showed that diastolic MS increased linearly with age, and that age had a more significant effect on MS than myocardial geometry. However, because the ventricular geometry may interfere with the measurement of Shear Wave Velocity (SWV), future studies need to further clarify the standardization boundaries of its clinical application [20].

To further validate the clinical applicability of SWE, Zhuo et al. conducted a prospective study comparing and analyzing the basal segment SWV of the ventricular septum in 16 healthy volunteers and 5 patients with hypertrophic cardiomyopathy (HCM). Research results confirm that SWE technology can effectively distinguish the difference in stiffness between normal myocardium and HCM myocardium, indicating that it has potential application value in the diagnosis of myocardial diseases [21]. In addition, Song et al. developed a novel SWE technology based on pulse inversion harmonic imaging and time-aligned sequential tracking to meet the needs of evaluating chemotherapy-related cardiotoxicity in children with cancer. This technology achieves quantitative measurement of myocardial hardness by detecting transient shear waves in end-diastolic myocardium. It was found that both long-axis and short-axis imaging of the parasternal interventricular septum could be used for myocardial assessment in children, but SWV in the short-axis direction was significantly higher than that in the long-axis direction due to the presence of myocardial anisotropy ($p<0.01$). This result provides an important reference for non-invasive detection of myocardial stiffness in children, and emphasizes the key role of imaging axial selection in SWE technology [22].

In terms of technical optimization, Song's team further verified the repeatability of SWE and the effect of myocardial anisotropy. Through multiple measurements of 10 healthy volunteers, the study found that the diastolic hardness measurement of the basal ventricular septum and the left ventricular free wall had high repeatability (70%) under the short-axis view. Notably, there was a significant difference between the short and long axis SWV of the same myotome (e.g. Basal interventricular septum: 1.82 m/s vs. 1.29 m/s), further confirming the influence of myocardial anisotropy on the measurement results. This study not only initially established the normal reference range of left ventricular diastolic stiffness, but also provided an important methodological basis for the clinical application of SWE technology [23].

6. RESEARCH PROGRESS OF SWE IN THE EVALUATION OF KIDNEY DISEASE

A study of 50 healthy volunteers and 42 patients with chronic kidney disease (CKD) by Grosu et al. showed that the SWE technique had a high success rate in kidney assessment (94% for right kidney, 90.2% for left kidney) and good reproducibility (ICC: 0.96 for right kidney, 0.91 for left kidney). It was found that the transverse wave velocity of renal parenchyma in CKD patients was significantly lower than that in healthy people. When the critical value was set to 1.47m/s, the diagnostic specificity and sensitivity of SWE for CKD reached 76.9% and 89.2%, respectively [24].

In terms of the evaluation of diabetic nephropathy, Yuksekkaya et al. 's study on 108 patients with type 2 diabetes and 17 healthy controls showed that the renal SWE value in the diabetic group was significantly increased (10.156±1.75kPa vs. 8.241±1.40kPa). It is suggested that SWE may be a useful supplement for the early diagnosis of diabetic nephropathy [25]. However, the study of Kenichiro Asano's team pointed out that the decrease of SWV may be related to the decrease of blood flow caused by renal arterial sclerosis, rather than simply reflecting the degree of renal fibrosis, which reminds us that multiple influencing factors should be taken into consideration when interpreting the results of renal SWE [26].

7. CLINICAL APPLICATION OF SWE IN MUSCULOSKELETAL DISEASES

SWE can objectively reflect the physiological characteristics and structural integrity of muscles by dynamically monitoring the changes of biomechanical parameters in different functional states such as stretching and loading. Compared with traditional muscle assessment methods (such as palpation, electromyography detection, etc.), SWE breaks through the limitation of strong subjective dependence and realizes real-time quantitative analysis of mechanical characteristics of specific muscle groups, showing unique advantages in the field of muscle tension monitoring [27].

In the diagnosis and treatment system of muscle disease, the quantitative analysis of biomechanical parameters is of great clinical value. Taking knee osteoarthritis as an example, this technique provides an objective basis for disease staging and rehabilitation efficacy evaluation by quantifying the changes in elastic characteristics of quadriceps and other muscle groups [28]. Studies have confirmed that the dynamic change of muscle hardness after treatment intervention can effectively reflect the treatment effect. For example, Gao team [29] found that the shear wave velocity of the psoas major muscle decreased significantly after spinal manipulation, revealing the regulatory effect of mechanical treatment on deep muscle groups.

For the assessment of the tendon system, SWE can not only achieve bilateral contrast scan, but also capture the difference in elastic characteristics in different functional states. Due to the complexity of tendon fiber tracking, it is necessary to avoid anisotropic artifact interference by multi-angle scanning during detection. Relevant studies [30] have shown that the shear wave conduction velocity of healthy tendons under contraction is about 30% higher than that of diseased tendons, which provides a new index for the quantitative diagnosis of tendon injury.

Although SWE has a broad application prospect in the biomechanical evaluation of musculoskeletal system, the current research still has limitations such as insufficient sample representation and lack of detection standardization. In the future, it is necessary to establish a unified detection specification through multi-center collaboration to verify its reliability in disease dynamic monitoring, making SWE an important technical support in the precision rehabilitation medicine system.

8. ANALYSIS OF TECHNICAL CHARACTERISTICS OF SHEAR WAVE ELASTIC IMAGING

8.1. Clinical Conversion Value of Technical Advantages

The core advantage of shear wave elastography (SWE) is the non-invasive quantitative evaluation of tissue mechanical properties. Compared with traditional biopsy techniques, SWE can significantly reduce the risk of diagnosis and treatment by measuring the value of Young's modulus, which is particularly prominent in the stage of liver fibrosis. The existing meta-analysis data show that when 7.1kPa is set as the diagnostic threshold, the diagnostic accuracy of SWE for significant liver fibrosis can reach more than 85%, making it an important alternative to liver biopsy [31]. The real-time imaging capability of this technology is due to its unique physics principle: by actively exciting shear waves, dynamic elastic maps can be generated at millisecond time resolution. This real-time feature not only visualizes the hardness distribution of the lesion area, but also provides important real-time feedback during interventional therapy. It is worth noting that the objectivity of SWE is significantly superior to traditional palpation methods, and its physical measurement method based on shear wave velocity enables the consistency coefficient (ICC) of measurement results between different operators to reach 0.95, which greatly reduces the influence of human factors [32]. The continuous expansion of clinical applications is another important feature of SWE. From the initial liver disease assessment to the current coverage of thyroid, breast, prostate and other organ systems, the breadth of application of SWE continues to expand. Especially in the field of treatment monitoring, this technology can dynamically track the evolution of fibrosis in patients with chronic liver disease and the change of tissue hardness after tumor ablation treatment, providing an objective basis for efficacy evaluation.

8.2. Technical Limitations and Improvement Direction

SWE still faces several technical challenges in clinical application. Tissue depth dependence is one of the most prominent limiting factors. Studies have shown that in obese patients, when the depth of the target area exceeds 8 cm, the detection failure rate of SWE can reach 20% [33]. The solution to this problem depends on the development of a new generation of high-frequency composite probes, as well as the optimization of respiratory gating techniques or rapid imaging sequences (such as ultra-high speed ultrasound) [34].

The standardization problem also restricts the wide application of SWE. At present, there are significant differences in the excitation frequency range (50-500Hz), algorithm model (time/frequency domain analysis) and probe design of devices from different manufacturers, which makes it difficult to directly compare measurement results. The establishment of unified quality control standards and diagnostic thresholds has become a key problem to be solved urgently.

9. THE TECHNOLOGICAL PATH OF FUTURE DEVELOPMENT

Technological innovation will focus on three key directions: First, through the development of wide-band composite array probes, the effective detection depth is expected to be increased to more than 10 cm, while maintaining adequate spatial resolution [35]; Secondly, the introduction of artificial intelligence technology will realize automatic artifact identification and intelligent optimization of the measurement area, significantly improving the detection success rate; Finally, multimodal image fusion techniques, such as SWE-CEUS combined imaging, are expected to provide more comprehensive diagnostic information. Standardization construction requires large-scale multi-center research, focusing on two core issues: the establishment of an organ-specific diagnostic threshold system and the formulation of a standardized process for cross-calibration between devices [36]. This work will involve data from at least 5,000 prospective multi-disease studies.

10. CONCLUSION AND PROSPECT

Shear wave elastography provides a new dimension for clinical diagnosis by quantitatively measuring tissue mechanics parameters. Its non-invasive, quantifiable and reproducible characteristics make it unique in early disease screening, accurate staging and treatment monitoring. However, technical bottlenecks such as limited deep tissue detection and insufficient standardization still need to be overcome. Future development directions should include: (1) Establishing organ-specific diagnostic criteria based on Chinese population; (2) Develop high-performance probes with independent intellectual property rights; (3) Construct a multi-modal intelligent diagnosis system. With the gradual resolution of these technical challenges, SWE is expected to become an important tool in routine clinical practice to provide more reliable imaging support for precision medicine. Especially in the field of early tumor diagnosis and chronic disease management, this technology has broad clinical application prospects.

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