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Ultrasound Viscosity Imaging Technology: A Review of Principles, Clinical Applications and Research Progress

Fei Chen *

Baise City Youjiang Medical College for Nationalities, Baise Guangxi 533000, China
*** Corresponding author Email:** 1724831448@qq.com

Abstract: Ultrasound Viscosity imagine (UVI) is an emerging quantitative diagnostic technique that provides a functional complement to traditional ultrasound morphological examination by measuring the viscous properties of tissues. Traditional ultrasound mainly relies on tissue acoustic impedance differences to generate anatomical images, while viscoelasticity reflects the microstructure and mechanical state of tissue, which is closely related to multiple pathophysiological processes. This paper aims to systematically expound the basic physical principles, key technologies, and clinical applications of ultrasound viscosity imaging in the liver, thyroid, breast, and other organs, and to look forward to its future research and development directions. Ultrasound viscosity imaging technology provides a new imaging biomarker for early diagnosis, efficacy evaluation, and prognosis of diseases by quantifying tissue viscous parameters.

Keywords: Ultrasound Viscosity Imaging; Viscosity; Quantitative Diagnosis.

1. Introduction

1.1. Background of technological development

Ultrasound imaging technology has been applied in medical field since the beginning of 20th century, from the early one-dimensional amplitude imaging of A ultrasound to a mature system covering B ultrasound, color Doppler, elastography and other multi-dimensions. Ultrasound has also become one of the preferred imaging screening tools for clinical use because of its advantages of non-invasive, real-time, convenient and low cost. However, conventional B-mode ultrasound and color Doppler ultrasound mainly provide anatomical and hemodynamic information and are insensitive to changes in tissue microstructure and mechanical properties. A large number of studies have shown that the mechanical properties of tissues (including elasticity and viscosity) are closely related to their pathological state. For example, liver fibrosis, malignant tumors and other diseases can lead to changes in extracellular matrix composition, cell proliferation and disorder, thus significantly changing the hardness and viscosity of tissues [1]. Traditional ultrasound provides anatomical information based on tissue acoustic impedance differences, while ultrasound elastography, which emerged in the 1990s, opened a new chapter in biomechanical imaging by assessing tissue stiffness [2], The quantitative parameters of shear wave elastography (SWE) have been confirmed to be beneficial for tumor differentiation and fibrosis assessment [3, 4], With the accumulation of evidence, elastography has moved from research to clinical practice, and its value has been recognized by international guidelines and widely used in clinical diagnosis [5].

However, human tissue is not an ideal elastomer but a viscoelastic material that is both elastic and viscous. Elasticity reflects the ability of tissues to resist deformation, while viscosity describes the characteristics of deformation dissipation over time, which together determine the mechanical behavior of tissues [6]. The change in elasticity is closely related to the collagen and elastin fiber network, and the change in viscosity is closely related to collagen cross-linking density, proteoglycan content, hydration state, etc. It is closely related to the liquid composition of the tissue and the complexity of the microstructure network. Therefore, elastic modulus alone is insufficient to describe the mechanical properties of tissues comprehensively. Studies have shown that changes in tissue viscosity may occur earlier than changes in hardness when lesions occur. In the progression of diseases such as liver fibrosis, cervical maturation, and early tumors, biochemical changes in microstructure (e.g., inflammation, hydration, changes in the proportion of ECM components) will first affect the viscous response of tissues. When the disease progresses to irreversible structural remodeling (e.g., large amounts of collagen deposition), elastic hardness becomes the dominant mechanical property[7].Therefore, the quantitative detection of viscosity parameters has important clinical value, and ultrasound viscosity imaging technology has emerged.

As an important extension and deepening of elastography, ultrasound viscosity imaging can reveal microscopic information of tissues that traditional elastography cannot capture by quantifying viscosity parameters of tissues. In recent years, with the improvement of theoretical models and technology, viscous imaging has gradually moved from laboratory research to clinical application, showing great potential. This paper will systematically review the principles, applications, and progress of this technology.

The core advantage of ultrasound viscosity imaging is that it provides a completely new diagnostic dimension independent of morphology and stiffness. Compared with traditional ultrasound, it can reveal biomechanical changes in the early stages of lesions; Compared to elastography, it compensates for the diagnostic bias caused by the pure elastic hypothesis by capturing the shear wave dispersion properties. Clinical studies have confirmed that viscous parameters are highly correlated with pathological results, and that combined with conventional ultrasound or elastography can significantly improve diagnostic efficiency, especially in the differentiation of benign and malignant lesions[8,9] .In addition, this technology inherits the inherent advantages of

non-invasive, real-time, and radiation-free ultrasonography, and has a wide range of clinical application potential.

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2. Basic Principle of ultrasound viscosity imaging

2.1. Viscoelastic Model of Biological Tissue

Biological tissues can be modeled as viscoelastic materials, and their mechanical behavior is often simulated by a combination of springs (representing elastic elements) and dampers (representing viscous elements). The simplest model is the Kelvin-Voigt model, which connects a spring and a damper in parallel. In this model, the mechanical response of the tissue is described by two key parameters: one is the modulus of elasticity (μ_1, Usually written as G′), which represents the stiffness of the spring in kilopascals (kPa). It describes the "hard" nature of tissues, i.e., the ability to instantaneously deform and recover. The second is the viscosity modulus (μ_2, Usually written as G″), which represents the viscosity of the damper, and the unit is Pa·s. It describes the "soft" properties of tissues, i.e., deformation delays over time and energy dissipation. When tissue deforms, the elastic part stores energy, while the viscous part converts mechanical energy into thermal energy and dissipates it. This energy dissipation directly affects the propagation behavior of shear waves in tissues[10–12].

2.2. Propagation of Shear Waves in Viscoelastic Media

The core of ultrasound viscosity imagine is based on shear wave propagation. Unlike compressional waves, which are used in conventional ultrasound, shear waves involve particle motion perpendicular to the direction of wave propagation. In a purely elastic medium, the propagation velocity of shear waves (c) is constant and depends only on the elastic modulus (E) and density (ρ) of the tissue, following the formula $E \approx 3\rho c^2$. Wave velocity is independent of frequency, and dispersion (i.e., the wave velocity of different frequency components is the same) and attenuation do not occur during the propagation of the waveform. However, the situation becomes more complicated in viscoelastic media. Due to viscous energy dissipation, shear waves are attenuated (amplitude decreases) and dispersed (wave velocity varies with frequency) during propagation. The higher the frequency, the faster the attenuation and the shorter the propagation distance.[12–14]

3. Technical Classification of viscosity imaging

Viscosity imagine uses the dispersion and attenuation characteristics of shear wave to deduce the viscous modulus of tissue. The current mainstream technology path is mainly based on the following methods:

3.1. Viscosity imaging based on external mechanical excitation

This method is in direct contact with the tissue surface through a probe or external device to apply mechanical excitation and is similar to quantitative palpation. Static excitation refers to the application of slow compression to the tissue, measuring its strain, and is mainly used to estimate the elasticity of the organization. Dynamic excitation is the generation of shear waves that travel within the tissue by vibration or transient excitation on the surface of the tissue. Ultrasonic probes capture tissue motion at very high frame rates and infer viscoelastic parameters by monitoring the propagation velocity or attenuation of shear waves [15,16].By analyzing the wave velocity of different frequency components, the dispersion curve can be fitted and the viscosity can be calculated[17,18].

3.2. Viscous imaging based on acoustic radiation excitation

At its core, the method is excited using the sound radiation generated by the focused ultrasound emitted by the imaging probe itself. Short pulses of acoustic radiation cause local micron-level displacements in the tissue, which then generate transient shear waves that propagate to the periphery. By tracking the propagation of the shear wave through the ultra-high-speed imaging sequence, and analyzing its wave velocity (related to elasticity) and dispersion characteristics (related to viscosity), the elastic modulus and viscosity modulus of the tissue can be quantitatively calculated at the same time [19,20].

4. Progress in the clinical application of ultrasound viscosity imaging

4.1. diagnosis of breast diseases

The viscous properties of breast tissue are closely related to the type of pathology, and ultrasound viscosity imaging has shown clear value in the differentiation of benign and malignant breast masses. The relevant research is relatively mature. The prospective multicenter study carried out by Professor Zhou Jianqiao's team at Ruijin Hospital Affiliated to Shanghai Jiao Tong University School of Medicine is an important achievement in this field. In this study, 639 patients with breast masses were enrolled, and the viscosity parameters were detected by the Mindray Resona 9 system. The pathological results were used as the gold standard, and it was found that the diagnostic efficacy of the viscosity coefficient calculated by the Voigt model was significantly better than that of the dispersion coefficient. Among them, the maximum viscosity value (A'-S2-Vmax) in the 2 mm area around the mass was the best diagnostic parameter, and the diagnostic AUC increased from 0.85 to 0.90 ($P < 0.001$) when the boundary value was 9.97 Pa·s[8].A prospective study (2023–2024) included 184 solid breast lesions, and the results showed that the mean maximum viscosity coefficient of malignant lesions (7.56 ± 3.63 Pa·s) was significantly higher than that of benign lesions (4.52 ± 2.33 Pa·s). With 5.39 Pa·s as the critical value, the diagnostic AUC of viscosity imaging reached 0.763, and the AUC further increased to 0.787 after combining with shear wave elastography, confirming the diagnostic advantages of multi-parameter fusion[9].

4.2. Diagnosis of thyroid disease

The high incidence of thyroid nodules makes it difficult for conventional ultrasound to characterize some small or atypical nodules, and ultrasound viscosity provides a new tool for their differential diagnosis. The study by the Cangzhou Central Hospital team included 437 patients with thyroid nodules, systematically analyzed the diagnostic value of viscosity parameters in different regions, and found that the maximum viscosity value (S1-Vmax) around 1 mm nodules had the best diagnostic efficacy, with an AUC of 0.831. The diagnostic AUC of large nodules (>1 cm in diameter) and small nodules (≤1 cm in diameter) was 0.893 and 0.851, respectively, which improved the diagnostic accuracy of small nodules [21].This finding is of great clinical significance because the differentiation of benign and malignant thyroid nodules is a clinical challenge, and ultrasound viscosity imaging can compensate for the limitations of conventional ultrasound in showing the characteristics of small lesions by capturing the viscosity changes around the nodule, thereby reducing missed diagnoses and misdiagnoses.

4.3. Liver disease assessment

As a typical viscoelastic organ, the liver's viscoelastic changes are closely related to the degree of fibrosis and the nature of focal lesions, and the application of ultrasound viscosity imaging in liver diseases is gradually deepening.

Liver fibrosis is a common pathological process in chronic liver disease, and accurate staging is crucial for treatment decision-making. Traditional elastography has been used to assess liver fibrosis, but it ignores viscosity, which may lead to insufficient accuracy in early staging. Studies have shown that the liver viscosity coefficient gradually increases with the progression of fibrosis and changes significantly in stage F2 (moderate fibrosis), which precedes the change in elastic parameters and can be used as a sensitive indicator of early liver fibrosis. When 2D-SWE technology is combined with viscosity imaging, the overall accuracy of liver fibrosis staging increases from 78% to 86%, especially for stages F1–F2[22] .The AUC value of 2D-SWE combined with viscosity parameters in the detection of fibrosis at stage F2 and above reached 0.89, which was significantly better than the method using elastic parameters alone[23].

There are many types of focal lesions (FLLs) of the liver, and the phenomenon of "homologous and heterologous disease" is common, making it difficult to characterize them with traditional ultrasound. Ultrasound viscosity imaging studies showed that the viscosity coefficient of hepatocellular carcinoma was significantly higher than that of hepatic hemangioma and liver abscess, while the viscosity value of metastatic liver cancer was intermediate. A study of 120 patients with FLL showed that the AUC of viscosity imaging to distinguish benign and malignant lesions was 0.82, and the AUC increased to 0.91 after combining ultrasound contrast, providing a new option for non-invasive diagnosis. [24]

Shear wave dispersion slope (SWDS) has certain diagnostic value in assessing both liver fibrosis and necrotic inflammatory activity[25].However, the shear wave dispersion slope is not as good as the shear wave velocity in predicting the degree of fibrosis [26,27].Nevertheless, the dispersion slope is more useful than the shear wave velocity in predicting the degree of necrotic inflammation. Since liver transplant patients have a higher stage of fibrotic and necrotic inflammatory activity during allograft injury, the shear wave dispersion slope provides good diagnostic performance in detecting allograft injury and is better than the liver stiffness parameter [27].

4.4. Detection of acute radiation dermatitis after radiotherapy

The viscosity parameters could effectively distinguish between normal and abnormal breast skin, and there were significant differences in the mean, maximum, minimum, and standard deviation of skin viscoelasticity (SVE) between the two groups ($p < 0.01$), which could capture the skin viscosity changes caused by radiotherapy. At the 20 Gy radiotherapy dose threshold, the mean and maximum values of abnormal skin viscoelasticity (Ab-SVE) were significantly higher in the >20 Gy group, which could sensitively reflect the dose-related degree of skin damage. The standard deviation of normal skin viscoelasticity could be used as an auxiliary parameter to provide a quantitative basis for the evaluation of radiation dermatitis (RD). The multimodal model constructed by combining viscous parameters with photoacoustic imaging (PA) and acoustic tactile elastography (STE) performed well in RD detection (AUC = 0.90, accuracy 87.23%), significantly better than the traditional subjective Radiation Therapy Oncology Group (RTOG) criteria (accuracy rate 57.58%), confirming that viscous parameters were significantly better than objective measures. It is of great value to accurately assess the skin viscosity changes induced by radiotherapy and distinguish between normal and abnormal breast tissues, providing a reliable quantitative tool for the early detection and severity assessment of acute radiation dermatitis.[28].

4.5. Other areas of application

In addition to the above organs, some progress has been made in the research of ultrasound viscosity imaging in other fields. For example, in the evaluation of kidney transplantation and chronic kidney disease (CKD), ultrasound viscosity imaging distinguishes healthy from diseased tissue by measuring viscous parameters. These parameters have been shown to be significantly associated with decreased renal function, interstitial fibrosis, and inflammatory cell infiltration [29,30].Ultrasound viscosity imaging was able to clearly distinguish the structure and composition of atherosclerotic plaques in a hypercholesterolemia porcine model and verify its accuracy by histochemistry[31].

5. Challenges

Although ultrasound viscosity imaging has shown great potential, it still faces many technical challenges that limit its widespread clinical application. Different manufacturers' equipment, different probes, and different measurement settings (e.g., drive frequency, depth) can affect viscous measurement results. Establishing unified technical operating practices and quality control standards is key to promoting their widespread clinical applications. Most current ultrasonic viscosity imaging methods only provide the shear energy storage modulus (G') and cannot directly measure the loss modulus (G") or viscous properties, which limits their application in complex tissue characterization[32].In some complex pathological conditions (such as polycystic nephropathy or chronic kidney disease), the viscous composition of the tissue can change significantly, and existing ultrasound viscosity imaging methods may not

accurately capture these changes. In addition, heterogeneity within tissues, such as fibrosis and vascular lesions, may also affect the reliability of imaging results [33] .Although ultrasound viscosity imaging can provide high-resolution mapping of viscoelastic parameters, its sensitivity to small-scale (e.g., submillimeter-level) changes is limited, and the resolution and sensitivity of existing techniques may not be sufficient to provide reliable diagnostic information when detecting small lesions or early pathological changes[34].In multi-parameter monitoring, ultrasound viscosity imaging may still need to be used in conjunction with other imaging techniques, such as elastography and Doppler ultrasound, to provide a more comprehensive assessment of tissue properties. However, data integration and interpretation between different technologies can be challenging. Clinical validation Despite the large number of encouraging studies, most are still in the single-center, small-sample stage. Large-scale, multicenter prospective clinical trials are needed to finally establish the diagnostic cut-offs, sensitivity, and specificity of ultrasound viscosity imaging for different diseases and to demonstrate its value in improving patient outcomes.

6. Research Prospects

The Kelvin-Voigt model is fundamental but may be oversimplified for some complex organizations. Researchers are exploring more complex models (e.g., standard linear solid models, fractional derivative models) to more accurately describe the mechanical behavior of tissues. Most current viscosity measurements are based on the assumption of a one-dimensional propagation path, but two-dimensional or even three-dimensional viscosity imaging can be developed, which can more comprehensively assess the heterogeneity of mechanical properties in the region of interest and is more valuable for evaluating heterogeneous lesions (such as tumors). It can also integrate viscous imaging with multimodal imaging, combining technologies such as contrast ultrasound and diffusion-weighted magnetic resonance imaging to comprehensively evaluate lesions from multiple perspectives, including blood flow perfusion, cell density, and mechanical properties, thereby achieving accurate diagnosis at the level of Using deep learning algorithms, deep features related to viscoelasticity can be extracted directly from ultrasonic RF data or B-mode images, and even end-to-end viscosity parameter estimation can be realized. This approach is expected to overcome the dependence of traditional methods on beamforming and signal quality and improve the repeatability of measurements.

In the future, ultrasound viscosity imaging is expected to achieve breakthroughs in the following fields: standardization of early diagnosis—establishing a database of viscosity parameter and diagnostic thresholds for different organ diseases, and forming industry standards; treatment efficacy monitoring—evaluating the effects of chemotherapy and targeted therapy by dynamically monitoring tumor viscosity changes, and achieving individualized treatment guidance.

7. Conclusion

As a revolutionary biomechanical imaging technique, ultrasound viscosity imaging opens up new perspectives for disease diagnosis by quantitatively detecting tissue viscosity characteristics. Clinical studies in breast, thyroid, liver, and other organ diseases have confirmed that viscous parameters can significantly improve diagnostic accuracy, especially in differentiating benign and malignant diseases. Although it currently faces challenges such as limited detection depth and lack of standardization, these problems will be gradually solved with the continuous development of coded excitation technology, multimodal fusion, and artificial intelligence.

In the future, with the maturity of technology and the accumulation of clinical evidence, ultrasound viscosity imaging is expected to move from scientific research to routine clinical application, becoming an indispensable part of ultrasound medicine and providing strong support for early diagnosis, efficacy evaluation, and individualized treatment of diseases.

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