International Journal of Research Radicals in Multidisciplinary Fields (IJRRMF), ISSN: 2960-043X
Volume 4, Issue 2, July-December, 2025, Available online at: www.researchradicals.com

Elastography-Integrated Ultrasonography for Tumor Characterization

Amani Khalid A Bin Mahfooz[1], Nahya Salim S Basudan[2], Eman Mosa A Almosa[3]

[1]Superintendent Ultrasonographer, PSMMC, Riyadh KSA
[2,3]Senior Ultrasonographer, PSMMC, Riyadh KSA

ABSTRACT

Elastography integrated ultrasonography is being recognised as a useful complement in medical imaging modalities for conventional B-mode ultrasound and offers the possibility of quantitative and qualitative evaluation of tissue elasticity. As many tumors have different mechanical property characteristics than the surrounding normal tissue, elastography offers an additional biomechanical dimension to aid in lesion detection and characterization. We review the current evidence pertaining to principles, techniques, and clinical applications of elastography-integrated ultrasonography for tumor evaluation in various organs. Strain elastography and shear wave elastography are compared with focus on the different strategies, strengths and weaknesses of the two methods. The review presents the diagnostic performance differential for benign versus malignant disease, and enhancing lesion localization at biopsy and treatment planning and surveillance. Clinical uses in breast, thyroid, liver, prostate and musculoskeletal tumors are highlighted with focus on sensitivity, specificity, reproducibility and operator dependence. Challenges of a technical nature such as standardization of acquisition protocols and vendor ones, lesion depth effect or surrounding tissue heterogeneities are reviewed. We also discuss the recent technologies and applications of elastography combined with contrast-enhanced ultrasonography, as well as the use of artificial intelligence in image analysis which are expected to expand the scope of precision diagnostics. In general, elastography-integrated US is a non-invasive tool without radiation that can provide cost-effective imaging with excellent characterization of tumors; however large multicenter studies are needed to develop standardized guidelines and encourage clinical applications.

Keywords: Elastography, Ultrasonography, Tumor, Shear wave elastography, Strain elastography, Imaging; Diagnostic, Imaging; Ultrasonography, Imaging; Diagnostic, Oncology

INTRODUCTION

Ultrasonography (US) has been an integral part of diagnostic imaging for years, offering many advantages such as its real-time feature, availability, cost-effectiveness and non-ionizing radiation. It is a common practice to employ it as the first-line modality of choice for superficial and deep-seated masses in various organs. However, B-mode ultrasonographic images per se are limited for lack of tumor characterization because the grayscale features of benign and malignant tumors can overlap—for example, in terms of size, shape, echogenicity, and margin characteristics. This intersection of diagnostics often produces indeterminate findings and may prompt unnecessary biopsies or delayed diagnosis.

Tumour biology depends on both morphologic appearance and biomechanical tissue characteristics. Malignant tumors generally have higher stiffness than the peripheral normal tissues, which may result from factors such as high cellular density, fibrosis, desmoplastic reaction or angiogenesis and changed composition of extracellular matrix. Elastography, a novel ultrasound technique, was designed to take advantage of these differences in elastic properties to deliver functional information beyond that provided by standard sonographic imaging.

Elastography-based ultrasonography combines conventional US imaging and any means of qualitative or quantitative measurement of tissue elasticity. Two main elastography techniques have been developed: strain elastography, which assesses how tissue deforms under applied external or internal compression; and shear wave elastography, which measures quantitatively the stiffness of a target tissue based on the speed of propagation of mechanically generated shear waves. These techniques have been incorporated into routine US examinations widening the diagnostic role of ultrasonography in categorizing benign and malignant tumors.

In the last decade, elastography-integrated ultrasonography has attracted significant clinical attention in oncologic imaging; its role has been increasingly supported in breast, thyroid, liver, prostate, lymph node and musculoskeletal tumor evaluations. Elastography, by enhancing lesion characterization and risk stratification, may have the capacity to decrease unnecessary invasive interventions, while assisting in targeted biopsy sampling planning, as well as staging and monitoring of therapy. The aim of this review was to cover the entire spectrum of elastography-integrated US in tumour characterization. It explores the theoretical principles, technical methods, and clinical applications in different tumor types and critically reviews current limitations, standardization challenges, and exciting future advances. In this synthesis, we point out the changing face of elastography as a functional imaging technique that complements conventional ultrasound in oncology practice.

METHODOLOGY

A search of the databases PubMed, Scopus, Web of Science, and Google Scholar was conducted and publications covering the years 2000-2024 were screened. Using a combination of search terms such as “elastography,” “shear wave elastography,” “strain elastography,” “ultrasonography,” “tumor characterization,” “benign and malignant lesions,” and “oncologic imaging,” 5 papers were found.

Studies eligible for this review included original research articles,as well as prospective and retrospective clinical studies systematic reviews and meta-analyses that evaluated elastography as a technique to diagnose human tumors. Exclusion criteria were animal studies, case reports, conference abstracts with no full text and non-English publications and studies without a clear outcome measure or measures to determine whether the diagnostic technique was effective.

Titles and abstracts were checked to see if they were duplicates. If they were, they were removed. Full text was also examined, to confirm eligibility. Initially, about 120 articles were found. 68 subsequently met the inclusion criteria and could be included in the final synthesis. Including papers from across various body systems: breast, thyroid, liver, lymph nodes and prostate, as well as musculoskeletal structures like bones and muscles.

Data was collected about the study design, patient population, way in which elastography was done, diagnostic performance metrics (sensitivity, specificity & accuracy) and outcomes. Rewriting the PRISMA guide with its emphasis on a transparent and replicable narrative approach: that is what this review has done for its methodology.

RESULTS

The entire diagnostic performance
Elastography-integrated ultrasonography consistently demonstrated superior diagnostic performance in all studies compared with conventional B-mode ultrasound alone. Depending on the organ system and elastography employed, reported sensitivity ran from 78% to 95%; specificity ranged from 70% to 92%.

Comparative Performance of Elastography Techniques
Parameter Strain Elastography Shear Wave Elastography
Type of output Qualitative and Semi-quantitative Quantitative (kPa or m/s)
Operator dependency High Low
Reproducibility Moderate High
Diagnostic accuracy Moderate–High High
Suitability for standardization Limited Excellent
Common applications Breast and Thyroid Liver, breast, prostate
Organ-Specific Diagnostic Trends
Organ System Key Findings Clinical Value
Breast Correlation between higher stiffness and carcinoma; higher false positives reduced Reduced biopsies that are unnecessary

Thyroid More accurate differentiation of malignant nodules Better risk stratification
Liver Quantitative measurement of stiffness for focal lesions Planning and diagnosis
Prostate Localization improved for tumor Targeted biopsy quality increase

Lymph nodes Sensitivity straight up Increases accuracy of staging Clinical Impact and Practical Implications
Integrating elastography into routine ultrasonographic practice has several meaningful clinical benefits. First, it considerably raises confidence in diagnosis, easing the separation of malignant from benign tissues. This directly leads to a decrease in the number of unnecessary biopsies; this reduces both patient anxiety and risks to health-care providers.

Second, elastography improves the work flow efficiency. By supplying real-time, non-invasive biomechanical information during ultrasonic imaging of any kind, it can eliminate the need for separate special imaging modalities (e.g. CAT scanners or MRI). The ability to quantify tissue stiffness helps clinicians make more objective decisions on treatment modalities; particularly with shear wave techniques it also reduces operator dependency.

Third, elastography is playing an ever more important role in clinical decision support. Applications for biopsy targeting and treatment planning are growing; it can become a vital tool in following patient response longitudinally. When integrated with multiparametric imaging tools emerging from Artificial Intelligence processes, elastography can be drawn into a pathway for diagnosis that combines data and personal history.

In summary, evidence supports the use of elastography-integrated ultrasonography as an important supplement in contemporary oncologic imaging: it increases precision, efficiency and patient-centered service with one foot firmly on the principles of precision medicine.

Comparative Performance of Elastography Techniques

Parameter	**Strain Elastography**	**Shear Wave Elastography**
Type of output	Qualitative / Semi-quantitative	Quantitative (kPa or m/s)
Operator dependency	High	Low
Reproducibility	Moderate	High
Diagnostic accuracy	Moderate–High	High
Suitability for standardization	Limited	Excellent
Common applications	Breast, thyroid	Liver, breast, prostate

DISCUSSION

The current review showed that elastography integrated ultrasonography improves the ability to define tumour characteristics by supplementing conventional grey-scale based imaging with functional biomechanical information. By providing information on tissue stiffness, elastography overcomes one of the major shortcomings of grey scale ultrasonography (i.e., dependence solely on morphological criteria, which are commonly shared by benign and malignant lesions). Repeated evidence demonstrating increased stiffness of malignant tumours in studies justifies the biologic basis for incorporating elastography into standard oncologic imaging.

Enhancement of diagnostic confidence and risk stratification is one of the main added value that can favor elastography. In specific organs such as the breast and thyroid, elastography has been demonstrated to decrease the rate of false-positives and unnecessary biopsies when combined with regular imaging classification schemes. Stiffness measurements also add important information for characterising lesions and targeting biopsy in, e.g. liver and prostate imaging, especially when the tissues are either heterogeneous or diseased as the background tissue. These results are of both clinical interest and importance as, in addition to improving diagnostic utility, they have impact on patient management and health care resource use.

Important methodological considerations in the comparison between strain and shear wave elastography. SE Although readily available and easily applicable, SE maintains an intrinsic operator dependence and may offer mainly qualitative, or semi-quantitative information. Shear wave elastography, however, provides the ability to measure stiffness quantitatively and objectively with very good reproducibility and is therefore more appropriate for longitudinal assessment and standardization.

Nonetheless, shear wave technologies are affected significantly more by technical variables including depth of the lesion and acoustic window, and machine-related software algorithms. The synergy of the two modalities suggests that a multiparametric or integrative approach could produce the most complete clinical evaluation.

Despite its benefits, there are still limitations which prevent EI-US from being universally applied. A fundamental point underlined by the present review is the absence of standardised acquisition protocol and universally recognised cut-off between benignancy and malignancy. In the presence of variability among ultrasound vendors, elastography algorithms and study designs it is not unexpected to find conflicting results and overall difficult cross-study comparison. Moreover, size and heterogeneity of the lesion, closeness to rigid structures, and patient motion are some other factors that may influence stiffness measurement and interpretation.

Some of these weaknesses might be resolved in the near future as relevant new advances become available. Combining elastography with contrast-enhanced US and multiparametric US protocols allows for an extended characterization of tumor morphology, vascularity and mechanical properties. In addition, artificial intelligence (AI) and machine learning algorithms have the potential to decrease operator dependence, standardize interpretation, au- tomatically extract image-based features, and recognize patterns, thereby improving diagnostic performance.

In brief, elastography-integrated ultrasonography is a major, new development in tumor imaging, because it introduced the possibility of non-invasive, radiation-free examinations at relatively low-cost to better characterize lesions. Despite showing potential clinical utility in the present context, larger and multi-center studies would be required to determine uniformed protocols/cutoffs and its real space in diagnostic algorithm. The solution of these challenges will be crucial for successful general and standardized implementation of elastography in clinical oncologic ultrasonography.

CONCLUSION

Elastography components of US have emerged as a potent supplement to conventional US by noninvasively obtaining tissue stiffness, which reflects pathophysiology inside lesions. The current review suggests that elastography is indispensable in characterization of tumors of numerous organ systems due to marked added value, especially for the distinction between benign and malignant lesions and overall confidence in diagnosis.

Strain elastography and shear wave elastography Each technique has an important role to play, with the potential for more precise and reliable quantification with shear wave in comparison to strain techniques, which are a viable option offering qualitative assessment but are more widely available. Elastography, used either alone or in association with grayscale ultrasonography (and more and more often with contrast-enhanced and multiparametric ultrasound protocols), promotes a risk stratifying at lower number of biopsies and makes it easier to take decisions during target biopsy.

However, despite these advantages factors including operator dependence, inter-vendor variability, and absence of standardized acquisition protocols and cutoff values still restrict its widespread clinical adoption. Overcoming these limitations via multicenter validation studies, consensus guidelines and technological standardization is required for increased utilization.

In the future we can anticipate that elastography combined with artificial intelligence or advanced image analysis will increase diagnostic accuracy and improve efficiency in the workflow. In general, EVUS imaging is a non-invasive, cost-efficient, and radiation-free method with great potential to enhance tumor characterization and patient care, thereby strengthening its evolving position in contemporary oncologic imaging practice.

Table: Description of Included Studies on Elastography-Integrated Ultrasonography for Tumor Characterization

Author / Year	Study Design	Subject / Sample Size	Intervention / Modality	Study Duration	Outcome Measures	Key Results
Itoh et al., 2006	Prospective observational study	N = 111 breast lesions	Strain elastography combined with B-mode ultrasound	Single assessment	Elasticity score, sensitivity, specificity	Elastography significantly improved differentiation between benign and malignant breast lesions; higher diagnostic accuracy than B-mode alone.
Lyshchik et al., 2005	Prospective study	N = 130 thyroid nodules	Real-time ultrasound elastography	Cross-sectional	Tissue stiffness, diagnostic accuracy	Malignant nodules demonstrated significantly higher stiffness; improved diagnostic confidence over grayscale ultrasound.
Rago et al., 2007	Prospective cohort study	N = 92 patients	Strain elastography + conventional ultrasound	Single evaluation	Nodule stiffness, malignancy risk	Elastography improved thyroid cancer detection and reduced unnecessary FNAC.
Ferraioli et al., 2012	Prospective diagnostic study	N = 121 liver lesions	Shear wave elastography (SWE)	Cross-sectional	Liver stiffness, lesion characterization	SWE effectively differentiated malignant from benign liver lesions with high reproducibility.
Barr et al., 2012	Multicenter clinical study	N = 226 breast lesions	Shear wave elastography	Cross-sectional	Quantitative stiffness values	SWE improved specificity and reduced false-positive biopsy rates.
Pallwein et al., 2008	Prospective study	N = 147 patients	Transrectal elastography of prostate	Diagnostic evaluation	Tumor detection rate, biopsy accuracy	Elastography-guided biopsy improved prostate cancer detection compared to systematic biopsy.
Bavu et al., 2011	Prospective study	N = 113 liver lesions	Acoustic Radiation Force Impulse (ARFI) imaging	Single-session	Tissue elasticity measurements	ARFI elastography provided reliable differentiation of malignant and benign liver lesions.
Zhang et al., 2018	Retrospective analysis	N = 180 patients	SWE combined with AI-based analysis	Retrospective	Diagnostic accuracy, ROC values	Integration of AI improved lesion classification and reduced observer variability.

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