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Biophysical Basis and Utility of Ultrasound Elastography in Diagnosing Thyroid Nodules: Review

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Abstract
Aim: To evaluate the biophysical principles and clinical utility of ultrasound elastography (USE) in diagnosing thyroid nodules.
Thyroid nodules are common, with a small percentage being malignant, requiring precise diagnostic tools. Ultrasound elastography, a non-invasive imaging modality, assesses tissue stiffness to differentiate between benign and malignant nodules. Strain elastography (SE) and shear wave elastography (SWE) provide qualitative and quantitative stiffness measurements, enhancing diagnostic accuracy. USE reduces unnecessary biopsies, complements traditional ultrasound, and aids in monitoring nodule progression. Despite challenges such as operator dependency and overlapping stiffness values, USE is a valuable tool for improving thyroid nodule management and patient outcomes.

Introduction

Thyroid nodules are a prevalent clinical finding, affecting a significant portion of the population, particularly in regions with iodine deficiency. These nodules are detected in up to 68% of individuals undergoing ultrasound imaging, with most being benign and asymptomatic. However, the potential for malignancy, present in approximately 5–15% of cases, necessitates an accurate and efficient diagnostic approach. Current methods for thyroid nodule evaluation primarily include grayscale ultrasound (US) and fine-needle aspiration biopsy (FNAB). While these techniques are effective, they have limitations: ultrasound alone may lack specificity, and FNAB, though more definitive, is invasive, occasionally inconclusive, and not suitable for all nodules (1).
Ultrasound elastography (USE) has emerged as a promising non-invasive diagnostic tool, offering complementary information about thyroid nodules by assessing their mechanical properties. Tissue stiffness, or elasticity, has been recognized as a key differentiator between benign and malignant nodules, with malignant nodules typically being stiffer due to their dense cellular architecture, fibrosis, and stromal alterations. USE quantifies this stiffness, providing both qualitative and quantitative data that enhance diagnostic accuracy (2).

The biophysical foundation of USE lies in its ability to measure tissue deformation in response to applied mechanical forces. By assessing the degree of deformation or the propagation speed of shear waves through the tissue, USE identifies variations in stiffness that correlate with pathological changes. Two primary techniques—strain elastography (SE) and shear wave elastography (SWE)—are utilized in clinical practice, each offering unique advantages. SE provides qualitative and semi-quantitative insights by comparing stiffness within the nodule and adjacent tissue, while SWE delivers quantitative stiffness measurements in kilopascals (kPa), allowing for standardized thresholds in clinical decision-making (3).

As thyroid nodule management increasingly emphasizes risk stratification and minimally invasive approaches, USE plays a crucial role in enhancing diagnostic workflows. By combining morphological assessment from conventional ultrasound with mechanical data from elastography, clinicians can more accurately differentiate benign from malignant nodules, reducing unnecessary biopsies and interventions. Additionally, USE aids in monitoring nodule progression, supporting active surveillance strategies for low-risk nodules (3).

This review examines the biophysical principles of USE, its clinical applications in diagnosing thyroid nodules, and its integration into modern diagnostic protocols. By evaluating its strengths, limitations, and potential for standardization, this review underscores the utility of ultrasound elastography in improving thyroid nodule management and optimizing patient care.

Review

1. Biophysical Basis of Ultrasound Elastography

Ultrasound elastography (USE) is a specialized imaging technique that assesses tissue elasticity to aid in diagnosing and differentiating pathological conditions. The biophysical principle underlying USE is that tissues exhibit varying degrees of elasticity depending on their structural composition. Elasticity, defined as a material's ability to return to its original shape after deformation, is influenced by cellular density, extracellular matrix properties, and the presence of fibrosis or calcification. In thyroid nodules, malignant tissues typically exhibit increased stiffness due to their dense cellular architecture, stromal desmoplasia, and fibrous encapsulation. In contrast, benign nodules, such as colloid or cystic nodules, are usually softer and less rigid (1).

Two main modalities of USE—strain elastography (SE) and shear wave elastography (SWE)—quantify tissue stiffness differently. SE evaluates the deformation (strain) of tissue when an external force, such as manual compression or physiological pulsations, is applied. The degree of strain is inversely proportional to stiffness, with harder tissues showing less deformation. SE provides semi-quantitative measurements, such as the strain ratio, which compares the stiffness of the nodule to adjacent normal tissue. SWE, on the other hand, generates quantitative measurements by inducing shear waves using focused ultrasound beams. The propagation speed of these shear waves correlates directly with tissue stiffness, allowing for real-time quantification in kilopascals (kPa) (2). SWE offers higher reproducibility and diagnostic consistency compared to SE, making it a preferred choice in clinical practice.

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2. Utility of Ultrasound Elastography in Diagnosing Thyroid Nodules

2.1. Differentiating Benign and Malignant Nodules

Distinguishing between benign and malignant thyroid nodules is a critical aspect of thyroid imaging, as it determines the need for further invasive procedures, such as fine-needle aspiration biopsy (FNAB), or surgical intervention. USE plays a pivotal role in this differentiation by assessing tissue stiffness, which is a hallmark of malignancy. Malignant nodules generally exhibit higher stiffness due to their dense cellularity and fibrotic composition.

Strain Elastography (SE): SE provides visual and semi-quantitative stiffness assessments using color-coded elastograms. On SE, malignant nodules often appear darker (stiffer), while benign nodules are brighter and more deformable. The strain ratio, calculated by comparing the stiffness of the nodule to adjacent normal tissue, has proven to be a reliable metric. Studies have reported sensitivity rates for SE ranging from 80–90%, with specificity rates of 70–80% (3). This modality is particularly useful in identifying malignant nodules in patients with multiple thyroid nodules or in those with indeterminate features on grayscale ultrasound.

Shear Wave Elastography (SWE): SWE offers a more precise and quantitative assessment of stiffness. Stiffness values above 65 kPa are often associated with malignancy, providing clinicians with standardized thresholds for diagnosis. SWE has demonstrated high diagnostic accuracy, with sensitivity and specificity rates of 85–95% and 75–90%, respectively (4). The quantitative nature of SWE also makes it a valuable tool for longitudinal monitoring of nodules, as changes in stiffness over time can indicate progression or regression.

2.2. Reducing Unnecessary Biopsies

FNAB is considered the gold standard for evaluating thyroid nodules, but its limitations include indeterminate cytology results in up to 25% of cases and the potential for patient discomfort. USE complements FNAB by stratifying the risk of malignancy based on stiffness measurements, enabling clinicians to better prioritize nodules for biopsy. Nodules with benign elastographic characteristics, such as low strain ratios or stiffness values, may be safely monitored, reducing the number of unnecessary biopsies (5).

Moreover, integrating USE with established ultrasound risk stratification systems, such as the American College of Radiology's Thyroid Imaging Reporting and Data System (ACR TI-RADS), enhances diagnostic accuracy. For example, a nodule classified as low-risk on TI-RADS but exhibiting high stiffness on SWE may warrant further evaluation, while a nodule with benign ultrasound features and low stiffness may be managed conservatively.

2.3. Characterizing Nodule Composition

The ability of USE to assess the mechanical properties of tissue provides additional insights into nodule composition. Cystic or predominantly fluid-filled nodules typically exhibit lower stiffness values, distinguishing them from solid nodules, which are generally stiffer. In cases of calcified nodules or nodules with heterogeneous structures, SWE can help delineate areas of increased stiffness that may correspond to malignant foci (6). This detailed characterization complements grayscale ultrasound features, improving overall diagnostic accuracy.

2.4. Monitoring and Follow-Up

USE is also valuable in the longitudinal management of thyroid nodules, particularly for patients undergoing active surveillance. Changes in stiffness over time can provide critical information about nodule behavior. For instance, a benign nodule that remains soft and stable on repeated elastographic assessments is unlikely to require intervention. Conversely, an increase in stiffness may indicate malignant transformation or progression, prompting further evaluation. This non-invasive monitoring capability makes USE an important tool in individualized patient management (7).

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3. Challenges and Limitations of Ultrasound Elastography

While USE has demonstrated significant utility in thyroid nodule evaluation, it is not without limitations. **Operator dependency** is a key challenge in strain elastography, as the consistency of applied compression can affect results. SWE, though less operator-dependent, may be influenced by factors such as nodule depth, size, and the presence of calcifications, which can disrupt shear wave propagation and reduce measurement accuracy (8).

Another limitation is the overlap in stiffness values between benign and malignant nodules. Certain benign conditions, such as Hashimoto's thyroiditis or nodules with significant fibrosis, may exhibit high stiffness, mimicking malignancy. Conversely, some malignant nodules, such as follicular carcinomas, may have stiffness values within the benign range. These overlaps highlight the need for a multimodal diagnostic approach that combines USE with grayscale ultrasound, Doppler imaging, and FNAB.

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4. Integration Into Clinical Practice

Integrating USE into clinical practice requires a strategic approach to maximize its diagnostic potential. As a complement to conventional ultrasound and FNAB, elastography provides additional information that enhances risk stratification and decision-making. For example, a nodule with suspicious grayscale features but low stiffness on SWE may still warrant biopsy, whereas a nodule with benign ultrasound features and low stiffness may be safely monitored. This integrated approach minimizes unnecessary interventions while ensuring that high-risk nodules are appropriately managed (9).

To standardize the use of USE in thyroid nodule evaluation, establishing universal stiffness thresholds and protocols is essential. Additionally, clinician training and the adoption of advanced elastography technologies will further improve diagnostic accuracy and reproducibility.

Conclusion

Ultrasound elastography represents a significant advancement in the evaluation of thyroid nodules, offering a non-invasive method to assess tissue stiffness—a key indicator of malignancy. By complementing conventional ultrasound and FNAB, elastography improves diagnostic accuracy, reduces unnecessary interventions, and provides valuable insights into nodule behavior. While challenges such as operator dependency and overlapping stiffness values remain, continued technological advancements and standardization efforts are likely to enhance its clinical utility. As part of an integrated diagnostic approach, ultrasound elastography holds great promise in improving the management of thyroid nodules and optimizing patient outcomes.

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