



Review Article



Current Imaging Techniques for Thyroid Nodules and Thyroid Cancer

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Abstract

Thyroid nodules are increasingly detected in clinical practice, and accurate imaging evaluation is essential for risk stratification, treatment planning, and postoperative surveillance of thyroid cancer. Although ultrasound remains the first-line modality for thyroid nodule assessment, the roles of computed tomography (CT), spectral CT, magnetic resonance imaging (MRI), and positron emission tomography-computed tomography (PET-CT) vary across clinical scenarios, and the optimal integration of these modalities remains insufficiently standardized. In particular, existing studies often focus on individual imaging techniques, while practical guidance on modality selection for initial screening, preoperative anatomical assessment, recurrence monitoring, and high-risk disease evaluation remains limited. This narrative review summarizes the imaging principles, clinical indications, diagnostic value, advantages, and limitations of ultrasound, CT, spectral CT, MRI, and PET-CT in the evaluation of thyroid nodules and thyroid cancer. Future advances should focus on standardized multimodal imaging strategies, quantitative functional imaging, radiomics, and carefully validated artificial intelligence-assisted approaches to improve individualized diagnosis and management of thyroid nodules and thyroid cancer.

Introduction

The thyroid gland is an important endocrine gland in the body, and the incidence of thyroid cancer has increased over the last few years in many countries.¹ The incidence of incidental thyroid nodules is also increasing, especially in middle-aged women.² Relevant surveys have shown that the proportion of malignant thyroid nodules is about 5% to 15%.³ The increasing incidence of thyroid cancer has caused a substantial medical burden in the United States, China, Europe, and other countries.⁴ Based on these epidemiological data, the increase in the incidence of thyroid cancer may be due to a true increase in disease incidence, or it may be due to the corresponding increase in the detection of occult thyroid cancer with advances in diagnostic testing.⁵

As a malignant tumor, thyroid cancer often grows slowly, and

its biological behavior is mostly indolent. With reasonable and standardized treatment, its prognosis is usually good.⁶ Thyroid cancer is more likely to be complicated by cervical lymph node metastasis, especially central lymph node metastasis, and the corresponding surgery is more complicated. Injuries to the recurrent laryngeal nerve, superior laryngeal nerve, and parathyroid gland are common during surgery, which seriously affect patients' quality of life.⁷ Therefore, the most critical issue is the diagnosis and evaluation of malignant thyroid nodules and early standardized treatment of thyroid diseases. Accurate and effective diagnostic methods for detecting malignant thyroid nodules are essential for early standardized diagnosis and treatment.⁸

This narrative review aims to systematically summarize the imaging principles, clinical indications, diagnostic performance, advantages, and limitations of the aforementioned imaging techniques and to propose a stratified selection strategy based on clinical scenarios to guide precision imaging diagnosis of thyroid nodules and thyroid cancer.

Commonly used imaging techniques for thyroid disease

Currently, imaging diagnostic methods for thyroid-related diseases mainly include ultrasound,⁹ computed tomography (CT), positron emission tomography-computed tomography (PET-CT), spectral CT, and magnetic resonance imaging (MRI) (Table 1). In traditional clinical practice, radiologists visually interpret images and

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Table 1. Comparison of commonly used imaging techniques for thyroid nodules

Imaging technique	Imaging principle	Primary clinical indications	Key advantages	Main limitations	Radiation exposure	Cost level
Ultrasound	High-frequency sound wave reflection	Initial nodule screening, TI-RADS classification, FNA biopsy guidance, follow-up monitoring	Noninvasive, no radiation, real-time, low cost, high resolution	Operator-dependent, limited visualization in retrosternal/obese patients	None	Low
CT	X-ray computed tomography	Evaluating retrosternal extension, lymph node metastasis, tumor invasion extent, postoperative assessment	High spatial resolution, clear anatomical delineation, fast scanning	Involves radiation, requires iodine contrast, lower sensitivity for microcalcifications	Yes	Medium
PET-CT	Metabolic (FDG) and anatomical fusion imaging	Staging in high-risk patients, recurrence monitoring, distant metastasis evaluation, adjunctive assessment in iodine scan-negative cases	Whole-body imaging, provides functional/metabolic information, high negative predictive value	Expensive, high radiation dose, false positives possible (e.g., thyroiditis)	Yes	High
Spectral CT	Dual-energy/Multi-energy X-ray imaging	Nodule characterization, iodine quantification, detection of small lesions, reduced contrast dose requirement	Multi-parametric quantification, relatively lower radiation, iodine maps aid benign/malignant differentiation	Equipment not widely available, protocols need standardization, complex post-processing	Yes (lower than conventional CT)	Medium-High
MRI	Magnetic fields and radiofrequency pulses	Evaluating soft tissue invasion, neurovascular relationships, postoperative residual disease/recurrence, alternative for patients with contrast allergy	No radiation, excellent soft-tissue contrast, multi-planar imaging	Long scan time, high cost, insensitive to calcifications, contraindications (metal implants/clostraphobia)	None	High

CT, computed tomography; FDG, fluorodeoxyglucose; FNA, fine-needle aspiration; MRI, magnetic resonance imaging; PET-CT, positron emission tomography-computed tomography; TI-RADS, Thyroid Imaging Reporting and Data System.

analyze and diagnose the features contained in the images based on the diameter, morphological characteristics, boundaries, density, echoes, or signals of the lesions. In recent years, with the advancement of science and technology, radiomics has gradually become an important area of medical research. It mainly includes four steps: image acquisition, region of interest segmentation, region of interest texture feature extraction, and further data analysis. From texture analysis to computer-aided diagnosis to traditional machine learning models and deep learning, by extracting and mining a large amount of potential quantitative information from medical images, imaging information can be maximized to assist clinical work.

Diagnostic ultrasound

At present, in the clinical application of examination methods for the diagnosis of thyroid diseases, it is recommended that all patients with suspicious thyroid gland nodules should initially undergo ultrasound examination.¹⁰ Ultrasound technology is highly dependent on the operator's level of expertise, and accurate diagnosis needs to be performed by physicians during image acquisition. The ultrasound diagnosis of thyroid nodules is often based on morphology (the shape, aspect ratio, and size), nodule margins, echo characteristics, and the presence or absence of calcifications on ultrasound images as the basis for malignant diagnosis.¹¹ Usually, benign nodules are mostly cystic on ultrasound, or the proportion of cystic components is high. Sometimes, the cystic component may account for more than 50% of the nodule volume, and some may show sponge-like changes with relatively clear boundaries. Malignant nodules are irregular in shape, lack a halo, and

often show fine punctate calcifications or clustered calcifications with irregular borders. In clinical practice, the Thyroid Imaging Reporting and Data System (TI-RADS) is usually used to score and quantify thyroid nodules based on ultrasound image characteristics and then refine the classification to determine the likelihood of malignancy.¹² In addition to traditional ultrasound diagnostic technology, the relatively new ultrasound superb microvascular imaging (SMI) technique has gradually entered clinical practice. It can compensate for the shortcomings of conventional ultrasound imaging in differentiating benign and malignant nodules and help physicians quickly and easily monitor the distribution of microvessels in tumors noninvasively and evaluate the characteristics of microvascular perfusion. Benign and malignant thyroid nodules can be distinguished based on changes in blood flow and vascular morphology within the nodules.¹³ Two-dimensional shear-wave elastography can quantitatively evaluate malignant thyroid nodules through real-time transverse wave propagation based on rapid sequence recording. Ultrasound shear-wave elastography (SWE) can provide qualitative and quantitative information about nodule stiffness. The clinical application of the above ultrasound technologies has greatly improved the diagnostic efficiency for thyroid nodules.

While conventional ultrasound provides excellent morphological characterization, advanced ultrasound techniques offer functional and hemodynamic information that can further refine diagnostic accuracy, particularly for indeterminate nodules or those with overlapping features. SMI is an advanced Doppler technique that uses a unique algorithm to separate low-velocity microvascular flow from tissue motion artifacts without the need for contrast agents. SMI provides superior visualization of intranodular

microvascular architecture compared with conventional color or power Doppler. SMI has demonstrated improved sensitivity for detecting microvessels in small nodules and can aid in distinguishing benign from malignant lesions, especially when conventional Doppler is inconclusive. SWE is a real-time quantitative technique that measures tissue stiffness by tracking the propagation velocity of shear waves induced by acoustic radiation force. SWE is particularly useful for nodules with indeterminate cytology on prior fine-needle aspiration (FNA) or for reducing unnecessary biopsies in low-suspicion nodules. Contrast-enhanced ultrasound (CEUS) involves intravenous administration of microbubble contrast agents to evaluate macro- and microvascular perfusion in real time. CEUS enables dynamic assessment of enhancement patterns, including the degree, homogeneity, and wash-in/wash-out kinetics. Malignant nodules often exhibit heterogeneous hypoenhancement with rapid washout, whereas benign nodules typically demonstrate homogeneous hyperenhancement or isoenhancement with slow washout. Although CEUS is not routinely performed for all thyroid nodules, it serves as a valuable problem-solving tool for nodules with discordant grayscale ultrasound and SMI findings or for evaluating cervical lymph node metastases when conventional ultrasound is equivocal.

Ultrasound is currently the preferred noninvasive screening tool for thyroid nodules, offering significant advantages such as real-time imaging, absence of radiation, relatively low cost, and the ability to guide biopsy procedures. Its high-frequency probes provide excellent resolution for superficial structures, clearly depicting internal microcalcifications, margin morphology, and blood flow distribution within nodules. When combined with the TI-RADS classification system, it substantially enhances diagnostic standardization. However, ultrasound diagnosis is highly operator-dependent, has limited visualization of retrosternal thyroid tissue or thyroid tissue in obese patients, and the interpretation of subtle malignant features remains somewhat subjective.

CT

Compared with ultrasound, traditional CT examination technology has better spatial and density resolution, which can clearly show cervical lymph nodes and retrosternal lesions and has unique advantages for visualizing intralesional calcification. The basis for judging benign and malignant signs based on CT mainly includes lesion location, diameter, number of nodules, morphological characteristics, boundary features, calcification, hemorrhage, cystic changes, necrotic enhancement, and local and distant lymph node metastasis (Fig. 1). Malignant thyroid nodules mainly present as lobulated nodules with irregular soft-tissue density and are rarely accompanied by bilateral or unilateral thyroid tissue enlargement. Signs such as poorly defined boundaries, absence of a capsule, or incomplete continuity of the capsule are considered malignant signs. In addition, lymph node metastasis around the anterior jugular muscle group and vein invasion often occur during tumor infiltrative growth. Calcifications are often a key factor in the diagnosis of thyroid nodules, with microcalcifications often suggesting a malignant thyroid nodule and coarse calcifications suggesting a high likelihood of benign nodules. Among them, the morphology of calcified foci in papillary thyroid carcinoma often appears sandy. CT can also provide information for further surgical treatment, which is of great significance for malignant cases such as retrosternal goiter, and is often used for preoperative comprehensive evaluation, postoperative efficacy prediction, and case follow-up.¹⁴

CT offers excellent spatial and density resolution, enabling clear visualization of the anatomical relationships between the

thyroid and surrounding cervical structures (such as the trachea, esophagus, blood vessels, and lymph nodes). It is particularly valuable for assessing retrosternal thyroid lesions, lymph node metastasis, and the extent of tumor invasion, providing crucial information for surgical planning. However, CT involves exposure to ionizing radiation, and iodine-based contrast agents may trigger allergic reactions or interfere with thyroid function. Furthermore, its sensitivity for detecting microcalcifications is lower than that of high-frequency ultrasound.

PET-CT

PET-CT has reached clinical maturity in the diagnosis of nodules.¹⁵ Generally, the standardized uptake value is an important quantitative index, and increased uptake of fluorodeoxyglucose (FDG) usually represents a higher risk of malignancy. Patients with thyroid cancer can be staged based on PET-CT to detect potential metastatic lesions in the neck and evaluate treatment effects and prognosis in patients with distant metastatic lesions.¹⁶ PET-CT can also be used to further identify sonographically suspicious and scintigraphically hypofunctional thyroid nodules.¹⁷ However, the high cost of PET-CT also affects its application in the diagnosis of thyroid nodules.

PET-CT, by reflecting tissue glucose metabolic activity (e.g., FDG uptake), holds unique value in staging thyroid cancer, monitoring recurrence, and evaluating distant metastasis. This is especially true for postoperative patients with elevated thyroglobulin levels but negative iodine scans. Its whole-body imaging capability aids in detecting unsuspected distant metastases. Nonetheless, PET-CT is expensive, delivers a high radiation dose, and can yield false-positive results because some benign conditions (e.g., thyroiditis) may also exhibit high FDG uptake. Therefore, it is not recommended as a routine initial screening tool for thyroid nodules.

Spectral CT

Spectral CT is based on conventional CT and obtains iodine maps and energy spectrum curves through a single scan. It acquires dual-energy data by switching energy resolution and then analyzes the energy spectrum in the digital domain.¹⁸ The advantages of this scanning technology are that it can effectively reduce the radiation dose, shorten the scanning time, reduce vascular artifacts, and clearly display lesion information.¹⁹ Single-energy imaging, material decomposition, and energy spectrum curves are often used for spectral CT analysis of benign and malignant thyroid nodules. Single-energy imaging involves instantaneous switching between high and low energy values, determining the attenuation coefficient within a fixed voxel range according to the specific energy values obtained, and then generating single-energy images for analysis.²⁰ Some studies have analyzed data from different phases (arterial phase, venous phase, etc.) to obtain the corresponding optimal energy level and found that the detection rate of thyroid microcarcinoma increases at this level. Material decomposition imaging, which analyzes corresponding attenuation effects through substance separation, can achieve a relatively high detection rate for small and multiple lesions. Because thyroid tissue is rich in iodine, when thyroid follicular epithelial cells are damaged, the iodine content decreases correspondingly, and the iodine content in the lesion area is reduced compared with adjacent normal tissue.²¹ Similarly, iodine-based images of thyroid scans in the arterial phase have been found to be the most helpful for diagnosing the nature of thyroid nodules.

Spectral CT, based on dual-energy or multi-energy imaging, provides various quantitative parameters such as iodine concentra-

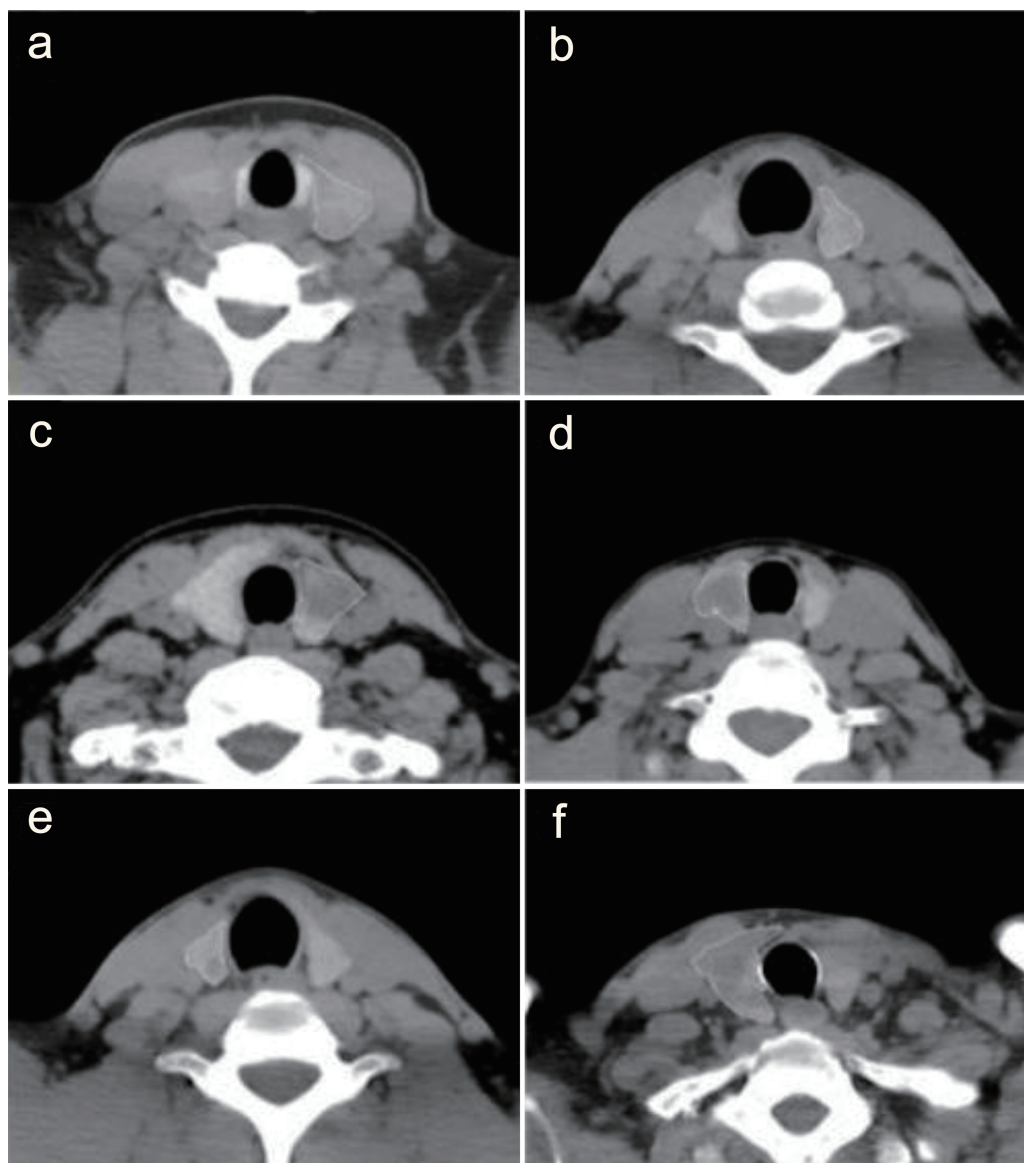


Fig. 1. Computed tomography images of benign and malignant thyroid tissue. (a, b) Normal thyroid tissue. (c, d) Benign thyroid nodules. (e, f) Malignant thyroid nodules. The representative images of typical thyroid diseases shown in Fig. 1 were obtained from the hospital where the corresponding author received postgraduate training. These images were collected by the corresponding author and previously included in the corresponding author's degree thesis. The images contain no personal identifiers or information that could be used to identify individual patients, and are used solely to illustrate the imaging features of thyroid diseases.

tion maps, virtual non-contrast images, and spectral curves, aiding in distinguishing benign from malignant nodules. It demonstrates relatively high sensitivity, particularly in detecting small and multiple lesions. This technology can potentially reduce radiation dose, decrease contrast agent volume, and minimize vascular artifacts. However, the equipment is not yet widely available, scanning protocols and diagnostic criteria need further standardization, and the technique requires greater operational and post-processing expertise.

MRI

MRI is also a commonly used examination method for evaluating thyroid diseases. It can not only provide better soft tissue infor-

mation but also display anatomical details in multiple directions and planes.²² Generally, the signal characteristics of most malignant thyroid nodules on MRI are similar to or lower than those of normal thyroid tissue on T1-weighted images, whereas the signal characteristics on T2-weighted images are mostly high.

MRI offers superior soft tissue contrast and multi-planar imaging capabilities without ionizing radiation. It can clearly display the anatomical relationships between the thyroid and surrounding nerves and blood vessels, holding significant value in assessing tumor invasion, postoperative residual disease, or recurrence. Functional sequences such as dynamic contrast-enhanced and diffusion-weighted imaging can provide additional tissue characterization information. However, MRI involves

longer scan times, higher costs, is insensitive to calcifications, and is not suitable for patients with certain metallic implants or claustrophobia.

Optimal clinical scenarios

Ultrasound is best suited for initial screening of thyroid nodules, TI-RADS-based risk stratification, real-time guidance for FNA biopsy, and longitudinal follow-up of benign nodules. It is ideal for outpatients, pregnant women, and repeated examinations due to its lack of radiation, low cost, and wide availability. CT is indicated for preoperative assessment of patients with confirmed or suspected malignant nodules, particularly when retrosternal goiter, extensive cervical lymph node metastasis, or invasion of the trachea, esophagus, or major vessels is clinically suspected. It is also valuable for postoperative evaluation when deep-seated recurrence is not well visualized by ultrasound. PET-CT is recommended for staging and restaging of high-risk thyroid cancer patients, especially those with elevated thyroglobulin levels but negative iodine scans. It is also useful for detecting distant metastases and monitoring treatment response. PET-CT is not indicated for routine screening of thyroid nodules. Spectral CT serves as a problem-solving tool for small (≤ 1 cm) or multifocal thyroid nodules when conventional imaging yields indeterminate or discordant findings. It provides quantitative iodine mapping to help differentiate benign from malignant nodules and is particularly useful when a lower contrast dose is required due to patient comorbidities. MRI is preferred for evaluating soft tissue invasion when CT findings are equivocal. It is also the modality of choice for patients with contraindications to iodinated contrast agents, such as severe allergy or renal impairment, and offers the advantage of no ionizing radiation exposure.

Comparison and selection strategies of thyroid imaging techniques

Initial screening and risk assessment: Ultrasound should be used as the preferred examination method for thyroid nodules, combined with TI-RADS classification for risk stratification and guidance regarding the need for needle biopsy.

Preoperative assessment and staging: For patients with high-risk ultrasound findings or confirmed malignant nodules, especially those with clinical suspicion of retrosternal extension, lymph node metastasis, or local invasion, enhanced CT is recommended to clarify the anatomical extent and assist in surgical planning. MRI can be used as an alternative or supplement to CT, especially for assessing soft tissue invasion or when patients have contraindications to iodine contrast agents.

Recurrence and metastasis monitoring: PET-CT is of great value for patients after thyroid cancer surgery if serological indicators are elevated and iodine scans are negative, or if distant metastases are clinically suspected.

Technological complementarity and multimodal integration: In difficult cases, quantitative iodine maps from spectral CT or MRI functional sequences (e.g., diffusion-weighted imaging, dynamic enhancement) can be combined to provide auxiliary information. The integration of radiomics and artificial intelligence technology is expected to further improve differential diagnosis and prognosis prediction.

Individualized and evidence-based selection: The final imaging strategy should be individualized based on the patient's specific condition, nodule characteristics, medical resource availability, economic factors, and evidence-based guidelines.

Future directions

Future advances should focus on standardized multimodal imaging strategies, quantitative functional imaging, radiomics, and carefully validated artificial intelligence-assisted approaches to improve individualized diagnosis and management of thyroid nodules and thyroid cancer.

Limitations

This narrative review, while providing a comprehensive overview of current imaging techniques for thyroid cancer, has several limitations that should be acknowledged. As a narrative rather than a systematic review, this article did not employ a predefined, reproducible search strategy or a structured quality assessment of the included literature. Consequently, the selection and interpretation of studies may be subject to selection bias, and the level of evidence supporting various imaging modalities was not systematically graded. This review did not include a formal meta-analysis or pooled data analysis due to its narrative design, and it did not explore potential publication bias across the cited studies. Future systematic reviews with quantitative synthesis and standardized reporting would help overcome these limitations and provide more definitive guidance for clinical practice.

Conclusions

Multiple imaging modalities play complementary roles in the screening and examination of thyroid nodules and thyroid cancer. Ultrasound is used for initial screening and TI-RADS-based risk stratification. CT or MRI is performed for preoperative anatomical evaluation and assessment of local invasion. Spectral CT is helpful for differentiating small or multifocal nodules that are difficult to characterize. PET-CT is reserved for high-risk cases.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization (SY, X Yao), investigation (SY, WL), writing – original draft (SY, X Yao), writing – review & editing (SY, WL, DC, HL), visualization (X Yin), supervision (MZ). All authors have approved the final version and publication of the manuscript.

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