International Journal of Biology and Life Sciences
ISSN: 2957-9511 | Vol. 17, No. 1, 2026

Advances in Artificial Intelligence for the Ultrasound Diagnosis of Thyroid Nodules

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Abstract: The increasing detection of thyroid nodules and thyroid cancer has made timely malignancy detection and the avoidance of unnecessary biopsy, surgery, and overtreatment important clinical priorities. Ultrasound is a convenient, real-time, inexpensive, easy-to-obtain and repeated non-invasive imaging method for screening and risk assessment of thyroid nodules. The diagnostic results of human operators and equipment settings can affect the sensitivity of image interpretation. Recently, with the development of artificial intelligence (AI), machine learning and deep learning have been applied to thyroid disease diagnosis. Segmentation of images, feature extraction, differentiation of benign and malignant nodules, risk stratification, biopsy decision support, cytological examination, contrast-enhanced ultrasound video analysis, and prediction of lymph node metastasis are all included. Research has shown that, at present, AI support can improve the precision and uniformity of diagnosis independently of operator experience. It will also be convenient for new doctors and health workers in primary care to use. Review of the technical foundations, current applications, advantages and disadvantages, and future directions of artificial intelligence in ultrasound diagnosis of benign and malignant thyroid tumors. To provide information on the clinical application and use of these technologies in personalised diagnosis and treatment.

Keywords: Artificial Intelligence; Thyroid Nodules; Thyroid Cancer; Ultrasound Diagnosis; Deep Learning; Machine Learning.

1. Introduction

Thyroid cancer is a type of common endocrine disease. In 2020, more than 580,000 new cases occurred around the world, with about 449,000 in women and 137,000 in men; thyroid cancer caused about 44,000 deaths [1]. With the spread of high-resolution ultrasound and routine health check-ups, many more thyroid nodules and cases of thyroid cancer have been identified. Despite this rise in incidence, overall thyroid cancer mortality has remained relatively low. Therefore, some low-risk or indolent lesions may have been overdiagnosed and unnecessarily treated. Therefore, the main clinical goal is to improve the differentiation between benign and malignant nodules and promptly detect malignancy. High-precision diagnosis can help reduce the need for unnecessary fine-needle aspiration biopsy and surgery [2].

Ultrasound is a general-purpose tool for the initial examination of thyroid nodules and is non-ionising, inexpensive, and easy to obtain. Composition, echogenicity, shape and margin irregularity; calcification; and blood vessel changes are all factors related to cancer. Interpreters' experience and equipment conditions will also affect the quality of the image. Physicians may have different assessments of nodule margins, echogenicity and TI-RADS classifications for thyroid lesions [2]. Artificial intelligence (AI) can automatically or semi-automatically extract high-dimensional features from large medical imaging data and use these features to build diagnostic prediction models. These models can perform lesion detection, classification, risk assessment and clinical decision-making [3]. Research on AI for thyroid ultrasound has developed rapidly in recent years. Recently, research has begun to address the problem of multi-source data integration for dynamic tumour and lymph node metastasis prediction in contrast-enhanced ultrasound (CEUS) videos.

2. Ultrasound Diagnosis of Thyroid Nodules

A thyroid nodule is a localised abnormality in the structure or sonography of the adjacent normal thyroid tissue. Nodules can be caused by nodular goiter, adenoma, inflammation or cancer. Most are asymptomatic, can be detected through a physical examination, neck imaging or self-palpation, etc. Their main clinical roles are to detect potential cancers and decide whether to monitor[4], biopsy or operate based on the risk assessment [5].

TI-RADS is a system to assess the risk of thyroid nodules. Standardise the terminology, scoring criteria and management recommendations to improve the consistency of assessment for benign and malignant nodules. Although the Scoring methods and divisions of categories for the TI-RADS systems differ, they generally consider composition, echogenicity, shape, margins, and calcification. Automation of the recognition and quantification of these features can enhance the consistency of TI-RADS evaluation and offer more objective support for clinical decisions [4].

3. Technical Foundations of Artificial Intelligence

A subfield of artificial intelligence that learns from data to recognise patterns and make predictions or classifications of new data is machine learning. The first type of feature extraction used by traditional machine learning is manual feature engineering. Support Vector Machines, Random Forests, K-Nearest Neighbors, Artificial Neural Networks[6-9], and other classifiers are used to carry out diagnosis [10] based on the extracted features. Deep learning (DL) is a type

of multilayer neural network used to learn high-level features directly from the data. Convolutional Neural Networks (CNNs) extract local and gradually more abstract features of image pixels. They are now frequently used instruments for the diagnosis of diseases via ultrasound, CT and MRI [11], etc [12].

CNNs can identify the location and degree of malignancy of thyroid nodules in medical images. ResNet uses residual connections to alleviate the problem of vanishing gradients during training and is widely applied in transfer learning and image classification. U-Net is an encoder-decoder structure with skip connections that can be used to segment the boundaries of nodules and regions of interest (ROIs). Transformers and the corresponding architectures use self-attention for global image dependency learning. Multimodal integration, 3D image analysis and recognition of complex lesions are all popular applications of them. Deep learning can learn high-dimensional features of large medical image datasets to address the problems of traditional machine learning. However, it needs more training data and computational power for parameter optimisation, and interpretability is still lacking.

4. Current Applications in Thyroid Ultrasound

4.1. Differentiating Benign and Malignant Thyroid Nodules

AI-assisted diagnostic models learn morphological and textural features of ultrasound images to detect thyroid nodules and classify the malignancy of these nodules. Some models have reached the risk stratification performance of the TI-RADS system and are even better. AI assistance can improve the accuracy and consistency of diagnosis for less experienced doctors [1-3]. Xu et al. carried out a multicenter study in routine clinical practice to evaluate an AI system with physicians of different experience levels. Therefore [13-16], the results showed that AI assistance enhanced the diagnostic ability of junior doctors. Li et al. developed deep CNN models on ultrasound images from multiple cohorts []. The models for detecting thyroid cancer had the sensitivity of experienced ultrasound doctors and were more specific. Wang and others developed an all-in-one AI model to improve the detection rate of suspicious nodules and report known risk factors. It will be more feasible for clinicians to apply.

4.2. Subcentimetre Thyroid Nodules

Thyroid nodules less than 1 cm are relatively small, and information about the boundaries and internal structure of lesions cannot be obtained. Therefore, both conventional ultrasound diagnosis and AI recognition are limited. Feng et al. [13] Used retrospectively collected multicenter ultrasound data to develop TNT-Net, a dual-channel DL model. Separate Transverse and Longitudinal images were provided to improve the learning of features from different imaging planes. The results showed better differentiation of benign and malignant subcentimetre nodules, and a new way of managing them was proposed. Rho et al. [17] have developed a ResNet101-based deep CNN for thyroid nodules of 10 mm or more. Nodules smaller than 10 mm in size were performed as well by the model and by radiologists. The Specificity for nodules $\leq$ 5 mm was relatively high. Therefore, AI can be used to reduce unnecessary biopsies and improve the risk assessment of very small nodules.

4.3. Assisting Fine-Needle Aspiration Cytology

Ultrasound-guided fine-needle aspiration biopsy (FNAB) is a typical method for preoperative diagnosis of thyroid nodules. However, there are also problems of sampling bias, slide preparation and pathologist experience in the results, and some specimens show indeterminate or non-diagnostic findings [18]. Lee et al. [19] built an AI model based on digitised thyroid fine-needle aspiration (FNA) images from several centres. The model has good accuracy and specificity, and the diagnostic agreement of pathologists using it is improved. Hirokawa et al. [20] have shown the applications of DL in auxiliary support for thyroid FNA cytology. Elliott Range et al. [21] studied malignancy prediction in thyroid cytopathology, and Alabrak et al. [22] investigated the subclassification of Bethesda category IV follicular neoplasms. Both studies have identified some applications of AI in cytology.

4.4. Contrast-enhanced Ultrasound, Lymph Node Metastasis, and Rare Subtypes

CEUS can show microvascular perfusion of thyroid nodules and help distinguish between benign and malignant lesions. Artificial intelligence models can automatically extract time-intensity curves, perfusion distributions and enhancement heterogeneity from dynamic CEUS images. Add these functions to the existing two-dimensional ultrasound and colour Doppler imaging/elastography for improved diagnostic efficiency. Liu et al. [23] developed a multimodal DL model combining conventional two-dimensional ultrasound with CEUS videos to predict occult lymph node metastasis in papillary thyroid carcinoma preoperatively. Wan et al. [24] and Chen et al. [25] investigated temporal feature modelling for nodule segmentation, dynamic perfusion representation, and joint segmentation and differential diagnosis. Their work offers a method for automated analysis of CEUS videos.

Cervical lymph node metastasis affects the planning of treatment and prognosis in thyroid cancer [26]. Lee and others developed an ultrasound-based computer-assisted diagnosis system for the localisation and diagnosis of metastatic lymph nodes. Han et al. [27-28] combined ultrasound radiomic features with clinical data to predict central compartment lymph node metastasis in solitary papillary thyroid microcarcinoma. Esce et al. [29] and Zhang et al. [30] have investigated nodal metastasis prediction based on visual information from primary tumors and ultrasound video keyframes, respectively. Dai et al. [31] used text-guided diffusion models to generate additional training data for rare thyroid cancer subtypes to address the problem of limited samples. Therefore, generative AI may be used to help improve the diagnosis of rare histological subtypes.

4.5. Recent Research in China

Recently, more research in China has been conducted on the application of algorithms in clinical practice. The main contents are the evaluation of locally developed AI systems and their integration with the Chinese Thyroid Imaging Reporting and Data System (C-TIRADS) or multimodal ultrasound. Training for junior doctors, recognition of particular types of thyroid tumors, and transfer learning are also included. Guo et al. [32] Used AI-SONIC Thyroid 5.3.3.0 to evaluate the preoperative malignancy risk and supported the application of AI-SONIC. Zhang et al [33-34]. [2024]

compared C-TIRADS with an AI-assisted diagnostic system and found similar overall diagnostic performance. The AI system also increased the value of some nodules with complex ultrasound features. Zeng and others (2023) have studied the application of AI in ultrasound image recognition to improve the efficiency and speed of diagnosis.

Bo et al. [35] developed and validated an all-in-one AI system for automatic thyroid nodule segmentation and classification. Therefore, according to the above results, the tasks can reduce ROI delineation variability. Yang et al. [36] studied the application of AI in quality-improvement activities for junior ultrasound physicians' training. Jiang et al. [37] evaluated AI-assisted diagnosis of medullary thyroid carcinoma and pointed out the need to improve performance for rare histological types. Song et al. [38] have studied AI-assisted multimodal ultrasound combined with serum thyroid-stimulating hormone measurement for thyroid nodule characterisation. Zou et al. [39] developed an ultrasound-based transfer learning model for estimating the malignancy probability of mixed cystic-solid nodules. Together, these studies have promoted the development of automatic segmentation, multi-source data integration, transfer learning and clinical workflow optimisation.

5. Advantages, Challenges, and Future Directions

The same input image is given to the AI-assisted system for analysis to reduce subjective bias. Help less experienced doctors and healthcare workers in primary care recognise the signs of malignancy, standardise reporting, and reduce missed diagnoses. With the development of thyroid ultrasound pathology and follow-up databases, AI may also be used to predict the progression of disease and recurrence risk.

Some Problems Still Exist in Clinical Translation. Reliable models need high-quality data, but the acquisition of images is influenced by equipment, transducer frequency, gain settings, imaging plane and operator. Image quality in the different centres may vary. The Standards for ROI division, nodule boundary annotation, TI-RADS classification and matching images with pathological diagnoses are also inconsistent. Many models have achieved good results in single-center or retrospective studies, but their accuracy has decreased when applied to data from other hospitals or devices due to domain shift. DL models are also often considered to be black boxes, and the reasons for diagnosis cannot be understood by clinicians. Class Activation Maps and attention heatmaps show the regions in an image that are used for prediction. However [40], the connection between these explanations and the basic causes of disease [41] has not been proven. Other problems in the application of this system include the protection of patient information and data security.

In the future, high-quality, standardised multicentre thyroid ultrasound databases will be constructed according to unified acquisition protocols, annotation methods, pathological reference standards and follow-up records. Multimodal models need to integrate 2D ultrasound, colour Doppler imaging, elastography, CEUS, clinical data, lab results, molecular tests and pathological information. Explainable AI and Clinician-AI Collaboration are also worth exploring. The decision-support system will provide risk assessment and rationale, etc., but the doctor will make the final decision. Prospective clinical trials and real-world studies need to be conducted to determine whether AI can improve diagnostic accuracy and reduce unnecessary biopsies and costs for patients' health [42].

6. Conclusion

Artificial intelligence is now being used to improve the methods and tools for diagnosing thyroid nodules. Current research has shown the applications of automated nodule detection, malignancy classification, risk stratification, subcentimetre nodule assessment, FNAB cytology, CEUS video analysis and prediction of lymph node metastasis. Multimodal Analysis can extend the applications further. Artificial intelligence can enhance the precision and consistency of diagnosis in some areas and help alleviate the work pressure of doctors. Clinical translation will need multi-centre collaboration, standardised databases, prospective validation, multimodal integration, etc., and interpretable algorithms. Coordinated attention to data, algorithm development, clinical application and ethics will be required to advance these technologies from experimental research to routine medical treatment. Artificial intelligence can enhance the diagnostic accuracy and personalised treatment of thyroid diseases for patients through ultrasound.

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