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Original Article

Predictive value of conventional ultrasonographic features combined with clinical factors for capsular invasion in papillary thyroid carcinoma with Hashimoto's thyroiditis

Chengcheng Yu[1], Xiaojie Liu[2], Borui Yu[3], Jinming Zhao[1]

[1]Department of Ultrasound Medicine, Shandong Second Provincial General Hospital, Ji'nan 250022, Shandong, China; [2]Department of Ultrasound Medicine, Yantai Yeda Hospital, Yantai 264006, Shandong, China; [3]Department of Medical Imaging, The People's Hospital of Huaiyin, Ji'nan 250021, Shandong, China

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Abstract: This retrospective study aimed to investigate the predictive value of conventional ultrasonographic features combined with clinical factors for capsular invasion in patients with papillary thyroid carcinoma (PTC) with concurrent Hashimoto's thyroiditis (HT). A total of 262 patients with pathologically confirmed PTC and concurrent HT who underwent surgery at our institution from January 2018 to June 2024 were included as the training cohort. Patients were divided into capsular invasion and non-capsular invasion groups according to postoperative pathological findings. Clinical characteristics, conventional ultrasonographic features, and preoperative serum thyroid-stimulating hormone (TSH) levels were compared between the two groups. Univariate and multivariate logistic regression analyses were performed to identify independent predictors of capsular invasion, and a nomogram model was constructed based on the selected variables. The predictive performance of the model was evaluated using receiver operating characteristic curves, calibration curves, decision curve analysis, and clinical impact curves. Univariate analysis showed that age, tumor diameter, postoperative lymph node metastasis, lesion margin, and blood flow signal were significantly associated with capsular invasion. Multivariate logistic regression analysis further identified age ≥55 years, larger tumor diameter, ill-defined lesion margin, and abundant blood flow signal as independent predictors of capsular invasion. The combined nomogram model achieved an area under the curve of 0.706 in the training cohort and 0.804 in the external validation cohort, showing better predictive performance than any single factor alone. Calibration curves, decision curve analysis, and clinical impact curves suggested acceptable model calibration and potential clinical utility. These findings indicate that a nomogram incorporating age, tumor diameter, lesion margin, and blood flow signal may provide a practical preoperative tool for estimating the risk of capsular invasion in patients with PTC and HT.

Keywords: Hashimoto's thyroiditis, papillary thyroid carcinoma, prediction model, capsular invasion

Introduction

Papillary thyroid cancer (PTC) is one of the most frequent histological classifications of thyroid malignancy and tends to have a more favorable outcome than other thyroid malignancies; however, its subtypes show considerable variability in biological behavior [1, 2]. Some small tumors are associated with aggressive behaviors, for example capsular invasion within capsule wall, extra-thyroidal extent or lymph nodal spread, which are generally considered malignant [3, 4]. Capsular penetration not only indicates strong association of tumor cells' invasiveness yet might impact surgeons on decision-making for excision scope and recurrence risk assessment after operation [5]. Thus, precise preoperative estimation of capillary invasion may guide additional interventions.

Hashimoto's thyroiditis (HT) is one of the common types of autoimmune thyroid diseases, and there has been an increasing focus on this issue recently [6, 7]. With regard to co-existing HT and PTC, previous researches show that there are differences among various clinical

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manifestations at different times and vary greatly due to regional variations and individual circumstances; thus, establishing a unified diagnostic standard remains challenging [8-10]. Regarding imaging changes, although there have already been relevant studies, their specificity and clinical value require further validation before they can inform recurrence risk prediction, especially intraoperatively under ultrasound guidance.

Because it is convenient to use, non-invasive, real-time and reproducible, ultrasonic examination has been used widely for preoperative assessment of thyroid nodules and thyroid cancer [11-13]; The features displayed on ultrasound include differences in tumor margins, shapes, intratumoral echo patterns (such as homogeneous or heterogeneous), whether calcification exists within the lesion area, its size and shape ratio, along with variations in blood flow signals [14-16]. In particular during HT condition, inflammatory response and parenchymal changes may reduce the specificity of certain ultrasound features. Therefore, it cannot be guaranteed that the old-style ultrasound characteristics will have high specificity in detecting capsular invasion.

In some cases, thyroid-stimulating hormone (TSH) has also increased at times of thyroid malignancy due to nodule formation on the thyroid itself or continuous infection inside the gland. There are some studies that suggest an increase in TSH may stimulate the proliferation of thyroid follicular epithelial cells and is related to enhanced invasiveness; however, there is still no conclusive evidence linking TSH levels with capsular invasion in PTC. In addition, in patients with HT, the level of TSH is affected by prolonged low-grade inflammation or immune-mediated damage to tissues; Therefore, its application remains questionable at present.

In light of the above situation, this retrospective analysis aimed to investigate the clinical manifestations, conventional ultrasound findings and serum TSH concentrations in patients with PTC combined with HT; At the same time, identify influencing factors for capsular perforation, thereby building a preoperative predictive model. To help detect high-risk individuals early on, optimize the plan for an individualized elective operation and improve survival prediction accuracy through it.

Methods and materials

Research participants

This retrospective study was conducted at the Department of Ultrasound Medicine, Shandong Second Provincial General Hospital. A total of 262 patients with papillary thyroid carcinoma (PTC) in the background of Hashimoto's thyroiditis (HT), who underwent surgery between January 2018 and June 2024, were enrolled as the training cohort. All patients met the pathological criteria for PTC according to their postoperative paraffin-embedded tissues. According to whether there was capsule invasion in postoperative pathology, divided the patients into two groups: capsule-invasive group (n=149) and non-capsule-invasive group (n=113).

An independent external validation cohort of 100 patients was collected from the Department of Ultrasound Medicine, Yantai Yeda Hospital, between January 2024 and June 2025. The training cohort was used for model development, and the external validation cohort was used to evaluate the predictive performance and generalizability of the model.

Inclusion criteria: (1) Thyroid nodules suspected in patients undergoing preoperative clinical, biochemical and imaging examination, accompanied by HT; (2) Received thyroid surgery with available complete postoperative paraffin section report; (3) Completed pretreatment routine physical examination, including conventional thyroid ultrasound and serum TSH measurement; and (4) Obtained all related medical history information.

The exclusion items were as follows: (1) Presence of other types of thyroid malignancy or malignant tumors in other systems; (2) Previous thyroid surgery, radiotherapy or related anti-tumor treatment; (3) Severe impairment of major organs such as the heart, liver and kidney; And lack of clinical data, lab indicator or ultrasound image for subsequent statistics disqualified participants.

This study was approved by the Ethics Committee of Shandong Second Provincial General Hospital (Approval No. 2026-030-01; approval date: March 27, 2026). As this was a retrospective study based on anonymized clinical data, the requirement for informed consent was waived by the Ethics Committee of Shandong

Second Provincial General Hospital. All patient information was anonymized before analysis, and patient confidentiality was strictly protected throughout the study.

Study method

All participants were preoperatively subjected to standard-thyroidular-US examinations. A high-frequency linear-array probe was employed for multiple planar scans covering the thyroid gland and adjacent areas in the neck; lesions' shapes, margins, largest diameter, aspect ratio, intralobular blood vessel distribution characteristics were observed. Ultrasound examination results from all subjects were assessed by two skilled and non-investigating radiologists separately to avoid bias. When there is inconsistency, a third senior sonographer re-reviewed the data to reach a final decision.

Lesion shape was divided into regular or irregular shapes; The lesion margin status was categorized as clear or indistinct margins; Maximum tumor volume size is divided into <1 cm and ≥1 cm; Aspect Ratio, it can be divided into <1 or ≥1; And the grade of blood flow signals was evaluated with conventional gradings from 0-1 to 2-3 points. All patients were tested for preoperative serum thyroid-stimulating hormone (TSH) in parallel; thus, TSH levels were stratified for subsequent analysis.

The paraffin sections obtained post-operation served as the reference for pathologist examinations. Based on whether or not there was capsule invasion according to pathological examination, the patients were classified as having capsular-invasive or non-capsular invasive disease. Collect general clinical data and relevant observation indicators such as gender, age, tumor size, location of the tumor, multifocal lesions, postoperative lymph node metastasis, co-existence of nodular goiter, ultrasound manifestations, serum TSH level after surgery, etc.

Observation indicators and model construction

Comparisons of general clinical characteristics, ultrasound manifestations and serum TSH values between the two groups to identify risk factors associated with capsular invasion in papillary thyroid carcinomas accompanied by Hashimoto's thyroiditis. Preoperative serum thyroid-stimulating hormone (TSH) levels were collected for all patients. TSH was categorized according to the laboratory reference interval and the distribution of TSH values in the study population. The categories were defined as <0.35, 0.35-1.88, >1.88-3.42, >3.42-4.94, and >4.94 mIU/L. These categories were used for group comparison to explore the association between TSH levels and capsular invasion. Firstly, univariate analysis screening of the correlation between clinical and imaging parameters with capsular invasion. Variables that showed statistical significance were included in the multivariate logistic regression model to determine which ones had an impact on capsular invasion independently.

Based on this foundation, a combination of clinical and ultrasonic variable predictions was used to establish a prediction model; At that time, a nomogram was drawn up for presentation purposes. Again, the Receiver Operating Characteristic (ROC) curve analysis was performed to assess the diagnostic performance for all indicators, which include age, tumor diameter; Margin status; Blood flow signal; Finally, according to predictive outcomes to decide whether there is an intact capsule. The area under the curve (AUC) and corresponding sensitivities/specificities/Youden's Index were all evaluated. By using calibration curves to determine which extent they match the actual risk situations. Applied decision curve analysis (DCA) and clinical impact curves (CIC) to assess the clinical effectiveness, cost-effectiveness, and robustness of the model in practice.

Out-of-sample test

Evaluate the generalizability and robustness of the built model by performing external validation on a separate dataset. The external validation cohort was composed of another group of patients at the same stage as that used to build the models, and their inclusion conditions were identical; However, such data did not participate in building the model.

Based on the built regression model and its related coefficients in this experiment, calculate the predicted probability values for each patient in an external dataset. To evaluate the discriminative power of the model through an ROC curve analysis. Draw a calibration curve to check how well-predicted the probability is consistent with reality. Additionally, based on DCA,

Table 1. Comparisons of baseline features in the two groups

Clinicopathological characteristic	Category	Capsular invasion (n=149)	No capsular invasion (n=113)	χ^2	P
Sex	Male	34	27	0.046	0.831
	Female	115	86		
Age (years)	<55	98	92	8.220	0.004
	≥55	51	21		
Tumor diameter (cm)	<1	45	49	4.918	0.027
	≥1	104	64		
Tumor location	Unilateral	97	80	1.107	0.313
	Bilateral	52	33		
Multifocality	Yes	60	45	0.006	0.953
	No	89	68		
Postoperative lymph node metastasis (number)	<5	120	102	5.099	0.024
	≥5	29	11		

determine which cases will be considered positive at what specific probability thresholds. By using these methods in total, this paper verified the stability and usability of the Model.

Statistics analysis

Statistical analyses were performed using SPSS 26.0. After testing for normality, continuous data are presented with means ± standard deviation (SD), and pairwise comparisons between groups were performed using independent-samples T-tests. The distribution of categorical data is frequency and percentage; Then conduct inter-group comparison by applying chi-squared test.

Using univariate and multivariate logistic regression analysis to find risk factors for capsular invasions; Calculate the odds ratio (OR) and its corresponding 95% confidence interval (CI). ROC curve analysis was used to evaluate the discriminative ability of the model, calibration curves were used to assess model fit, and DCA and CIC were used to evaluate the net clinical benefit of the model. Two-tailed *p*-value less than 0.05 was considered statistically significant.

Results

Basic attributes

The final number of patients selected was 262; among them, there were 149 cases with capsular invasion and 113 without. There was no significant difference between the two groups in sex, tumor location, multiple involvement, or co-occurrence of nodule goiters (all P>0.05). However, considerable discrepancies were found in ages, tumor diameters, and numbers of post-operative lymph node metastases between the two groups (all P<0.05).

Especially, the proportion of capsule invasion among older people ≥55 was notably greater than that for the young population under 35 (P<0.01); Tumor size showed an inverse correlation with capsular invasion; it was positively associated with tumor area ≤1 cm (P=0.027). Furthermore, among patients with more than five postoperative metastasis lymph nodes, the proportion of capsules involved was significantly higher compared to those with less than five lymph node metastases (P=0.024). The details are shown in **Table 1**.

Ultrasonic characteristics

A total of 260 patients met the criteria for image-based features. No statistically significant difference was found among these two groups regarding tumor shape and aspect ratio in all cases (P>0.05). There were substantial disparities among the lesions' margins and blood flow signals of each group (all P<0.05). In particular, lesions with poorly defined boundaries had a higher likelihood of presenting as capsular infiltration compared to those with clear boundary (P=0.020); Lesions showing blood flow grade 2-3 had increased chances of being classified as capsules infiltration than those in blood flow grades 0-1 (P<0.001). Based on this study's results, changes in lesion margin definition, tumor size and blood flow signals can all impact capsule invasion differently. The details are shown in **Table 2.**

Table 2. Comparison of ultrasonic features in the two groups

Variable	Category	Capsular invasion (n=149)	No capsular invasion (n=113)	χ^2	*P*
Shape	Regular	22	21	0.697	0.404
	Irregular	127	92		
Margin	Well-defined	30	37	5.431	0.020
	Ill-defined	119	76		
Aspect ratio	<1	60	41	0.415	0.519
	≥1	89	72		
Blood flow signal (grade)	0-1	38	54	14.616	<0.001
	2-3	111	58		

Table 3. Comparison of serum TSH concentration in different groups

TSH (mIU/L)	Capsular invasion (n=149)	No capsular invasion (n=113)	X^2	*P*
<0.35	4	2	29.922	<0.001
0.35-1.88	47	73		
>1.88-3.42	60	20		
>3.42-4.94	22	8		
>4.94	16	10		

Note: Thyroid-Stimulating Hormone.

TSH levels

The distribution of preoperative serum thyroid-stimulating hormone (TSH) levels differed significantly between the capsular invasion and non-capsular invasion groups according to the chi-square test (χ^2=29.922, P<0.001). Patients with capsular invasion were more frequently distributed in higher TSH categories, particularly the >1.88-3.42 mIU/L category, whereas patients without capsular invasion were mainly concentrated in the 0.35-1.88 mIU/L category. However, this result only indicates a between-group difference in TSH distribution. In the univariate logistic regression analysis, TSH categories were not significantly associated with capsular invasion, and therefore TSH was not included in the multivariate logistic regression model. These findings suggest that TSH may reflect differences in thyroid functional status between groups, but it should not be interpreted as an independent predictor of capsular invasion. The details are shown in **Table 3**.

Univariate analysis

Univariate logistic regression was conducted to examine the correlated variables with capsules in this study (**Table 4**). The results indicated that there was a significant association between age, tumor diameter, post-operative lymph-node metastasis, lesion margin and blood flow signal at present and capsular invasion (P<0.05). In particular, the risk of capsular invasion was significantly higher in older individuals (≥55 years) compared to younger ones (<55 years; OR=2.39, 95% CI: 1.33-4.32, P=0.004). Tumor size > or equal to 1 cm was also found to be significantly related with an increase in the risk of capsular invasion (OR= 1.80, 95% CI: 1.08-3.00; P=0.025).

Additionally, the number of postsurgical metastatic lymph nodes in patients was positively correlated with capsular invasion [odds ratio (OR)=2.46; 95% CI: 1.15-5.30; P=0.021]. Lesions with ill-defined borders were more prone to be accompanied by capsular invasion than those with a clearly defined border (odds ratio [OR]=1.96, 95% CI: 1.12-3.43, P=0.019); Lesions with blood flow grades 2-3 had higher likelihood of being accompanied by capsular invasion compared with those with blood flow grades 0-1 ([OR]=2.63, 95% CI: 1.56-4.42, P< 0.001). In comparison, sex, tum our location, shape, aspect ratio and TSH level were not significantly related to capsular invasion in the univariate logistic regression analysis (all P>0.05).

Multivariate analysis

A multivariate logistic model was constructed to determine which variables are independent of capsules in infection (**Table 5**). According to the result of this study, age, tumor diameter, lesion margin and blood flow signals

Table 4. Results of univariate logistic regression analysis

Variables	β	S.E	Z	*P*	OR (95% CI)
Sex					
0					1.00 (Reference)
1	0.07	0.29	0.24	0.808	1.07 (0.60-1.91)
Age					
0					1.00 (Reference)
1	0.87	0.30	2.90	0.004	2.39 (1.33-4.32)
Tumor diameter					
0					1.00 (Reference)
1	0.59	0.26	2.25	0.025	1.80 (1.08-3.00)
Tumor location					
0					1.00 (Reference)
1	0.26	0.27	0.97	0.332	1.30 (0.76-2.21)
Postoperative lymph node metastasis					
0					1.00 (Reference)
1	0.90	0.39	2.31	0.021	2.46 (1.15-5.30)
Shape					
0					1.00 (Reference)
1	0.29	0.33	0.86	0.391	1.33 (0.69-2.57)
Margin					
0					1.00 (Reference)
1	0.67	0.29	2.34	0.019	1.96 (1.12-3.43)
Aspect ratio					
0					1.00 (Reference)
1	-0.15	0.26	-0.60	0.548	0.86 (0.52-1.42)
Blood flow signal					
0					1.00 (Reference)
1	0.97	0.27	3.64	<.001	2.63 (1.56-4.42)
TSH					
0					1.00 (Reference)
1	1.13	0.89	1.28	0.201	3.11 (0.55-17.64)
2	-0.41	0.90	-0.45	0.654	0.67 (0.11-3.92)
3	-0.50	0.97	-0.51	0.608	0.61 (0.09-4.06)
4	0.18	0.96	0.19	0.850	1.20 (0.18-7.93)

Note: Thyroid-Stimulating Hormone.

are all independent risk factors of capsular invasion (all P<0.05). Patients over the age of 55 were significantly more likely to have capsule invasion compared with those under 55 years old (OR=2.60, 95% CI: 1.37-4.92, P=0.003). Similarly, a tumor size greater than or equal to 1 cm was found to have been significantly related to an increased incidence of capsular involvement (OR=1.86; 95% CI: 1.07-3.23; P=0.028).

Imaging feature-wise, the lesion showed lack of clear boundary relative to other lesions that demonstrated distinct contour (OR=2.50; 95% CI: 1.35-4.63; P=0.004). Grades 2-3 blood flow was found to have a higher likelihood of capsular invasiveness compared to grade I-II; OR=3.22, 95% CI: 1.82-5.69, P<0.001. Post-operative lymph node metastasis showed a trend towards being associated with an increased risk (OR=1.88) but failed to achieve statistical significance after adjustment in the multivariable model (P=0.131).

ROC curve analysis

ROC curve analysis was used to evaluate the predictive value of individual factors and the

Table 5. Multivariate logistic regression analysis of factors associated with capsular invasion

Variables	β	S.E	Z	P	OR (95% CI)
Intercept	-2.44	0.49	-4.98	<0.001	0.09 (0.03-0.23)
Age					
0					1.00 (Reference)
1	0.96	0.33	2.94	0.003	2.60 (1.37-4.92)
Tumor diameter					
0					1.00 (Reference)
1	0.62	0.28	2.19	0.028	1.86 (1.07-3.23)
Postoperative lymph node metastasis					
0					1.00 (Reference)
1	0.63	0.42	1.51	0.131	1.88 (0.83-4.25)
Margin					
0					1.00 (Reference)
1	0.92	0.31	2.91	0.004	2.50 (1.35-4.63)
Blood flow signal					
0					1.00 (Reference)
1	1.17	0.29	4.01	<0.001	3.22 (1.82-5.69)

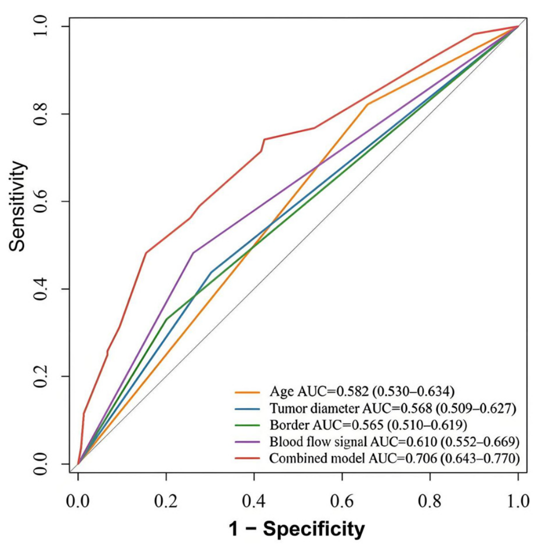

Figure 1. ROC curve of age, tumor diameter, lesion margin, vascularity and the combined model to predict Capsule Invasion in Papillary thyroid cancer with Hashimoto's thyroiditis.

combined model for capsular invasion. The results show that each individual predictor showed relatively weak discriminative ability. The AUC values of age, tumor diameter, margin status and blood flow signal were 0.582 (95% CI: 0.530-0.634), 0.568 (95% CI: 0.509-0.627), 0.565 (95% CI: 0.510-0.619) and 0.610 (95% CI: 0.552-0.669), respectively. Among them, the blood flow signal presented relatively good predictive performance but had an average discriminating capability.

Compared to the single model, the integrated one has shown more robust predictive power; The AUC is 0.706 (95% CI: 0.643-0.770). At the optimal cut-off point of 0.522, the specificity was 0.482, the sensitivity was 0.846, and the Youden index was 0.328. The above results indicate that the combination model has a higher recognition accuracy than any single individual model; therefore, it may provide some references for clinical work. See **Figure 1** and **Table 6**.

Construction of the nomogram to predict risk of capsular invasion

Predicted nomograms for capsular invasion include patient age multiplied by individual factors from tissue lesions, such as tumor size, disease-free boundary distance, and blood flow signals. Each score for a certain factor was proportional to its regression coefficient; blood flow signals had the largest weight, then lesion margins and age were ranked second and third respectively. Using the sum of the scores from all relevant factors to determine an individualized probability that a given patient has undergone capsular invasion. See **Figure 2**.

Calibration ability and clinical benefit assessment of the prediction model

Calibration Curve showed that the predicted probabilities were in close agreement with the observed ones for capsules invasion. The bias-

Table 6. ROC curve analysis of clinical characteristics, individual ultrasonic features, and combined models to diagnose capsular invasion

Variable	AUC	95% CI	Optimal cutoff	Specificity	Sensitivity	Youden index
Age	0.582	0.53-0.634	0.5	0.821	0.342	0.164
Tumor diameter	0.568	0.509-0.627	0.5	0.438	0.698	0.135
Margin	0.565	0.51-0.619	0.5	0.33	0.799	0.129
Blood flow signal	0.61	0.552-0.669	0.5	0.482	0.738	0.22
Combined model	0.706	0.643-0.77	0.522	0.482	0.846	0.328

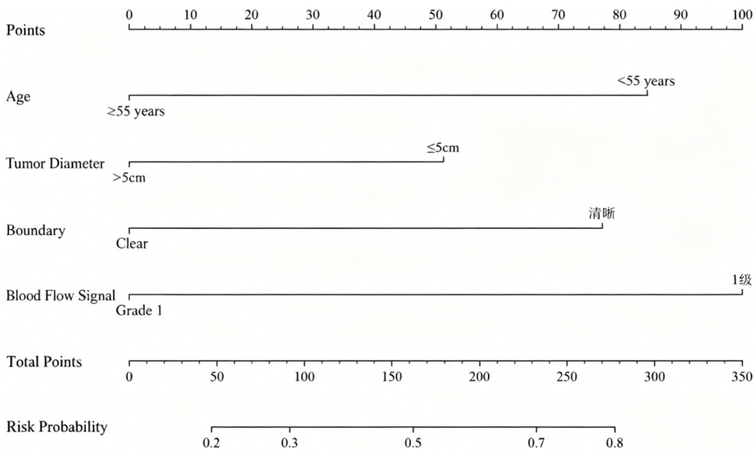

Figure 2. Nomogram for predicting the risk of capsular invasion in papillary thyroid carcinoma (PTC) in the background of Hashimoto's thyroiditis (HT).

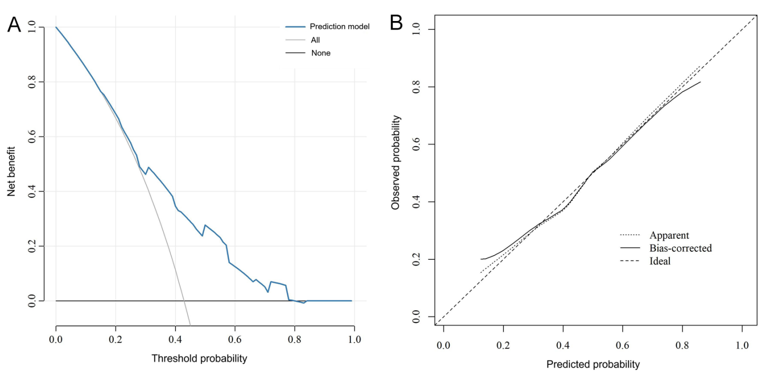

Figure 3. Decisive curve analysis and calibration curves for capsule invasion predicted by papillary thyroid cancer patients with Hashimoto's thyroiditis. A. Decisive curve analysis of the prediction model. B. Calibration curves for predicted model.

corrected curve was close to the ideal reference line and thus indicated that the model had good calibration performance with little problem of overfitting. Meanwhile, the apparent curve exhibited a tendency consistent with the bias-corrected curve; thus, it verified that the model is both stable and reliable.

Based on decision curve analysis, in most cases where the cut-off probability was set between 0.2 and 0.7, this prediction model provided more overall gain compared to both "treat all" and "no treatment at all", indicating that it is clinically worthwhile for use in decisions. See **Figure 3**.

External validation

Evaluate the generalizability and robustness of the built model by conducting an external validation with another set of data. A total of 100 patients from an outside group were selected for validation; among them, 65 had capsule invasiveness and 35 did not.

The ROC curves of each indicator also showed low prediction performance in the outside test set separately. The AUC values of the variables age, tumor size, margin status and blood flow signal intensity were 0.610, 0.647, 0.652 and 0.642, respectively; These results show that these factors have weak discriminant power. The combined model obtained an AUC of 0.804 (95% CI: 0.713-0.895), which was higher than that of any individual prediction; therefore, it can be considered to have good generalization ability in multiple groups of people.

At the optimal cut-off value of 0.522, the model had a sensitivity of 0.482 and a specificity of

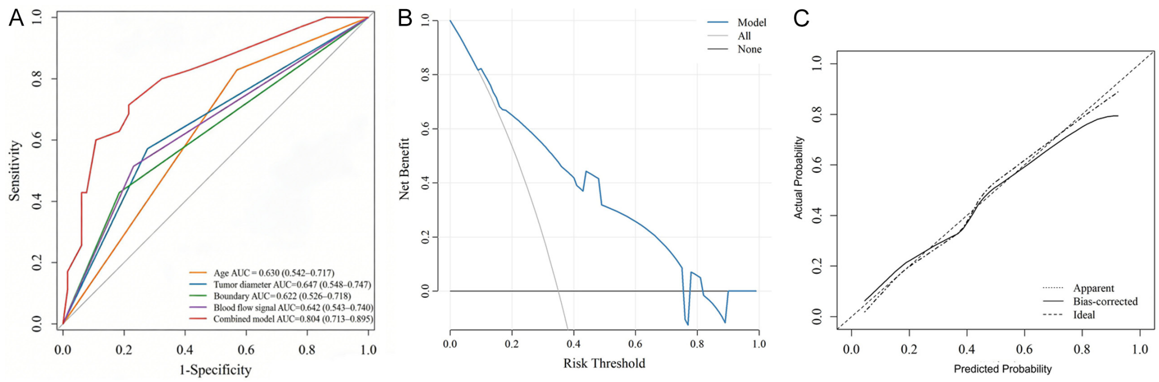

Figure 4. ROC curve. A. ROC curves of individual predictors and the combined model for predicting capsular invasion. B. Decision curve analysis showing the clinical net benefit of the combined model. C. Calibration curve showing the agreement between predicted and actual probabilities.

0.846; The Youden index was at this time: 0.328 which shows relatively higher specificity. Further decision-curve analysis showed that, in a range of approximately 0.09-0.77 probabilities, the net benefit of the model remained consistently greater than those of "treat-all" or "treat-none", indicating relatively stable clinical applicability across a broad area; Especially within the middle-risk area (approximately 0.2%-0.7%), it was more pronounced.

The AUC in the external validation group was slightly higher than that in the training set, but it still showed acceptable discrimination; therefore, the model had excellent generalization properties. Overall, the combined model of age, tumor diameter, margin status and blood flow signal showed good prediction accuracy and some application value on the external test set (**Figure 4**).

Discussion

Based on this, we aimed to predict capsular invasion in PTC patients with HT before operation. According to the obtained data analysis, age ≥55 years old, tumor size greater than or equal to 1 cm, ill-defined margin and abundant blood flow signals are all related to capsules; Also identified as independent risks of capsular invasions in combination with other variables. In the ROC analysis, none of them can discriminate well, and therefore we combine their results to obtain a multivariate logistic-regression prediction model that performs significantly better in terms of discrimination. Therefore, based on this combination of clinical data and imaging findings can help us predict capsular invasion more accurately in patients who have been diagnosed with PTC accompanied by HT.

Age differed significantly between the capsular invasion and non-capsular invasion groups. Patients aged ≥55 years had a higher risk of capsular invasion, suggesting that older age may be associated with increased local invasiveness in patients with PTC and HT. There may also be associations with the decline of the immune surveillance system during ageing, changes in the tumor microenvironment, or a longer course of disease; previous studies have reported an inverse correlation between HT onset and tumor invasiveness in patients with PTH-related thyroiditis (PTTI); The number of capsules infiltrated by young people is smaller than that of elderly people aged more than 50, indicating that Age has some regulatory impact on the behavior of HT-associated tumors. In clinical practice, age primarily functions as both risk predictors for all patients but varies from person to person in its likelihood of locally invasive cancer based on their characteristics. As can be seen from our results, more preoperative attention should be paid to older PTC patients with HT.

Tumor size is generally used to evaluate the likelihood of capsular invasion based on earlier studies [17]; The selected cut-off point at 1 cm for measuring tumor volume showed that people whose cancer mass was ≥1 cm had significantly higher risk compared to those who were <1 cm, and this trend was statistically supported ($P<0.05$). Since the volume of tumor increases, so does the distance between it and the thyroid capsule; Therefore, the probability of cancer cell penetration outside locally restrictive tissue components also rises accordingly. Therefore, in the construction of HT, if the lesion area exceeds 1 centimeter, more attention should be paid to whether it has an invasive nature. Vikneson et al. found in their study that there is a positive correlation between tumor volume (TV) and lymphovascular invasions in differentiated thyroid cancer (<2 cm), as TV increased, so were LVI rate [18]; however, TD >1 cm was not significantly associated with it. In the above study, it was found that some tumors with diameters of 10 mm were larger in size compared to those with similar Ds but greater in volume; thus, the accuracy of simply assessing the degree of lesion based on its diameter needs verification. Unlike the present study, that analysis also included patients undergoing hemithyroidectomy and patients with follicular thyroid cancer or oncocytic thyroid carcinoma, who have a different biological behavior and metastatic pattern compared to PTC. Therefore, these results indicate that volume parameters might offer additional details about tumor aggressiveness; However, they cannot deny the actual effectiveness of using the size of PTC to predict whether it will have capsular invasion.

Among the test scores, an ill-defined margin is considered to have been determined separately by this study. Generally speaking, clearly demarcated areas of lesion are regarded as localized diseases however, if the boundaries are blurred or unclear, it may indicate an uncertain border with surrounding normal thyroid tissue, which suggests infiltration growth [19]. Particularly in cases where HT exists, there is diffuse inflammatory infiltration and fibrosis within the thyroid parenchyma, thereby increasing background complexity on ultrasound it becomes challenging to judge the edge precisely [it can] still find a close link between poorly delineated edges and capsular invasion, indicating that this feature retains clinical utility even in such complex settings [20]. Patients whose preoperative-ultrasound-lesion-borders are indistinct or who are close to the thyroid-capsule may be rated as having higher risk.

Blood flow signal scored first in terms of predictor values for this research. According to the results, compared with grade 0-1 blood flow grades 2 and 3 were more prone to capsular invasion in patients. Increased intratumoral and peritumoral vasculature generally indicates active angiogenesis as a significant biological foundation for tumor growth, invasiveness, metastasis [21]; angiogenesis and abnormal vascularization are closely related to the proliferation of tumor cells [22]. Moreover, different blood flow patterns at various sizes of lesions have been observed in previous studies; larger lesions tend to exhibit richer and more disorderly internal vessels. The results aligns with the findings of Fukuoka et al. showing that lesions with higher vascular density tended to grow more rapidly [23]. This continuity suggests that vascular characteristics are related to both blood supply states of tumors as well as their levels of growth activity and invasiveness to a certain degree. Abundant blood flow indicates that cancer cells have more vigorous metabolism and are moving to the highest extent locally. Therefore, in the construction of HT, although there is a blood flow signal supplementing the evaluation result with more detail on PTC's malignancy degree; Specifically, in cases where there is an ill-defined margin, large volume, or close relationship with the thyroid capsule of a lesion, it needs more caution during clinical diagnosis.

TSH may also provide useful information in the assessment of capsular invasion. In this study, the distribution of TSH levels differed significantly between patients with and without capsular invasion, suggesting that thyroid functional status may vary between the two groups. However, TSH categories were not significantly associated with capsular invasion in the univariate logistic regression analysis and were not retained in the final predictive model. This apparent inconsistency can be explained by the different purposes of the statistical tests. The chi-square test evaluates whether the distribution of TSH categories differs between groups, whereas logistic regression assesses whether TSH contributes to the risk of capsular invasion as a predictive factor. Therefore, TSH should be interpreted as a variable showing a group-level distributional difference rather than an independent predictor of capsular invasion. In patients with PTC and HT, serum TSH levels may be influenced by autoimmune inflammation, thyroid functional impairment, and individual treatment status. Thus, TSH may reflect the background thyroid functional and inflammatory status rather than directly indicate local tumor invasiveness. For this reason, TSH was not included in the final nomogram model, which was constructed using age, tumor diameter, lesion margin, and blood flow signal. This finding may be explained by several factors. First, TSH levels in patients with Hashimoto's thyroiditis may be influenced by autoimmune inflammation, thyroid functional impairment, and individual treatment status. Second, the relationship between TSH and capsular invasion may not be strictly linear. Third, categorization of TSH may have reduced statistical stability, especially when the number of patients in some subgroups was limited. Therefore, TSH may reflect the background thyroid functional and inflammatory status rather than directly serve as an independent predictor of capsular invasion.

The further ROC analysis found that the AUC values of single factors were as follows: Age was 0.582; Tumor Diameter was 0.568; Margin was 0.565; Blood Flow Signal was 0.610; The AUC values of the individual predictors were around 0.6, indicating limited discriminative ability. The combined model achieved an AUC of 0.706 and had some specific recognition; that is to say, integrating multiple factors would improve the detection accuracy more effectively than using them alone individually. Calibration curves, decision curves and clinical impact curves show that the model has a high degree of fitting and is stable; In terms of net benefits to clinical practice at large, there is an expected positive effect. For patients whose preoperative decision-making on expanding surgery scope, strengthening centre-lymph-node evaluation and close post-operative observation is needed, based on this mode of management it would offer assistance.

This study has several limitations. First, although an external validation cohort was included, the training cohort was retrospectively collected from a single institution, which may have introduced selection bias. Therefore, the generalizability of the model should be further validated in larger multicenter prospective studies. Second, the model was based mainly on conventional ultrasonographic features and clinical variables. Advanced imaging techniques, such as ultrasound elastography, contrast-enhanced ultrasound, radiomics, and deep learning-based image analysis, were not incorporated, which may partly explain the moderate predictive performance of the model. Third, although the combined model performed better than individual predictors, the AUC of 0.706 indicates acceptable but not excellent discrimination. Thus, this nomogram should be regarded as a preliminary risk stratification tool rather than a definitive diagnostic method. Fourth, TSH was analyzed as a categorical variable in this study, and its potential nonlinear association with capsular invasion was not fully explored. Finally, thyroid function and immune-related indicators, such as FT3, FT4, thyroid peroxidase antibody, and thyroglobulin antibody, were not fully integrated into the model. Future studies should combine multimodal ultrasound, laboratory indicators, and artificial intelligence-based methods to improve predictive accuracy and clinical applicability.

Therefore, based on the above findings: In settings of Hashimoto's thyroiditis, age, tumor size, lesion margin and blood flow signals are among the key predictors for capsular invasion in papillary thyroid cancer. Based on the above variables, a combined model that showed superior prediction accuracy to all individual predictors separately. These findings suggest that integrating clinical characteristics with conventional ultrasonographic features may improve individualized preoperative risk stratification for patients with PTC and HT, helping clinicians identify patients who require closer evaluation of capsular invasion and more careful surgical planning before surgery. Although recent radiomics, contrast-enhanced ultrasound, elastography, and artificial intelligence-based models have shown higher predictive performance in thyroid cancer risk assessment, these techniques are not always available in routine clinical practice, especially in primary or resource-limited medical settings. This study does not aim to replace advanced imaging or machine-learning models. Instead, it aimed to develop a simple, accessible, and low-cost preliminary risk stratification tool based on routinely available clinical and conventional ultrasonographic features. Therefore, the AUC value of 0.706 should be interpreted as acceptable but not excellent discrimination. This nomogram may provide auxiliary information for preoperative risk assessment, but it should not be used as a definitive diagnostic tool. Future studies incorporating multimodal ultrasound, radiomics, and deep learning methods are needed to further improve predictive accuracy and clinical applicability.

Conclusion

Age ≥55 years, larger tumor diameter, ill-defined lesion margin, and abundant blood flow signal were independent predictors of capsular invasion in patients with PTC and HT. The nomogram based on these routinely available clinical and ultrasonographic factors showed acceptable predictive performance, suggesting it may serve as a practical auxiliary tool for preoperative risk stratification.

Disclosure of conflict of interest

None.

Address correspondence to: Jinming Zhao, Department of Ultrasound Medicine, Shandong Second Provincial General Hospital, No. 4 Duanxing West Road, Huaing District, Ji'nan 250022, Shandong, China. Tel: +86-18764086330; E-mail: zhaojinming120225@163.com

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