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Enhancing recurrent laryngeal nerve localization during transoral endoscopic thyroid surgery using augmented reality: a proof-of-concept study

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Purpose: During transoral endoscopic thyroidectomy, preserving the recurrent laryngeal nerve (RLN) is a major challenge because visualization of this nerve is often obstructed by the thyroid itself, increasing the risk of serious complications. This study explores the application of an augmented reality (AR) system to facilitate easier identification of the RLN during transoral endoscopic thyroidectomy.
Methods: Three patients scheduled for transoral endoscopic thyroidectomy were enrolled in this proof-of-concept study. Preoperative computed tomography scans were used to create an AR model that included the thyroid, trachea, veins, arteries, and RLN. The model was overlaid onto real-time endoscopic camera images during live surgeries. Manual registration of the AR model was performed using a customized controller. The model was aligned with surgical landmarks such as the trachea and common carotid artery. Manual registration accuracy was assessed using the Dice similarity coefficient (DSC) to evaluate the alignment between the real RLN and the RLN of the AR model.
Results: The 3 patients included were female (mean age, 33.3 ± 15.7 years), and the mean tumor size was 1.0 ± 0.3 cm. All patients underwent transoral endoscopic thyroidectomy of the right lobe. Final histopathological diagnoses comprised 2 papillary thyroid carcinomas and one follicular adenoma. The manual registration accuracy was 0.60, 0.70, and 0.57 for patients 1, 2, and 3, respectively, with a mean value of 0.6 ± 0.1.
Conclusion: The application of an AR system during transoral endoscopic thyroidectomy proved feasible and demonstrated potential for improving the localization of anatomical structures, particularly the RLN, as indicated by a moderate DSC.
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Key Words: Augmented reality, Endoscopy, Recurrent laryngeal nerve, Thyroidectomy

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INTRODUCTION

Thyroid surgery is commonly performed to treat a broad range of thyroid conditions including benign nodules, hyperthyroidism, and thyroid cancer [1]. Preserving the function of the recurrent laryngeal nerve (RLN) during thyroid surgery is crucial because injury to this structure can lead to serious consequences such as vocal cord palsy, aspiration, and decreased quality of life [2].

Identifying and preserving the RLN during surgery is challenging because of its anatomical location behind the thyroid which makes it difficult to visualize, thus increasing the risk of injury [3]. Although the recent development of endoscopic thyroid surgery has minimized the invasiveness of thyroid surgery and improved cosmetic outcomes, the risk of nerve damage persists due to limited direct visualization of the RLN [4]. Hence, improvements in equipment or the development of new technologies are necessary for safer surgeries.

For safe surgery, it is essential to accurately identify the anatomical structures in order to distinguish between tissue that needs to be resected and that which needs to be preserved. Surgeons usually rely on CT or MRI scans to understand and assess the structure of a lesion prior to surgery. However, these imaging modalities produce 2-dimensional images which limit the surgeon's precise understanding of the anatomical location of organs within the 3-dimensional surgical field [5]. Recent advances in engineering are actively overcoming this limitation, and augmented reality (AR) technology is emerging as a potential method for safer surgery when integrated into surgical imaging [6]. Previous studies have explored the application of an AR system into robotic thyroid surgery for localizing important anatomical structures during surgery [7,8].

In this proof-of-concept study, we evaluated the feasibility of using an AR model to assist surgeons in localizing key anatomical structures, in particular the RLN, during transoral endoscopic thyroidectomy.

METHODS

Patient selection

The Institutional Review Board of Seoul Metropolitan Government-Seoul National University Boramae Medical Center (No. 10-2023-69) approved this prospective proof-of-concept study. All methods were conducted following regulations and institutional guidelines. The study included 3 patients who underwent transoral endoscopic thyroidectomy from May to June 2024. Patients were counseled on the use of the AR system and informed consent was acquired from each patient before surgery.

Three-dimensional thyroid segmentation and virtual thyroid model reconstruction

Preoperative CT scans were performed in all 3 patients, and DICOM (Digital Imaging and Communications in Medicine) images were obtained from 70-second portal phase scans. We segmented the major anatomical structures, including the thyroid gland and the surrounding structures (trachea, common carotid artery, internal jugular vein, and RLN), and reconstructed them in a 3-dimensional (3D) model using the "Total Segmentator" which is an artificial intelligence (AI)-based extension of 3D Slicer ver. 5.7.0, an open-source 3D segmentation software (Fig. 1). As the RLN is not visible on CT, an AR image of the RLN was manually constructed in its

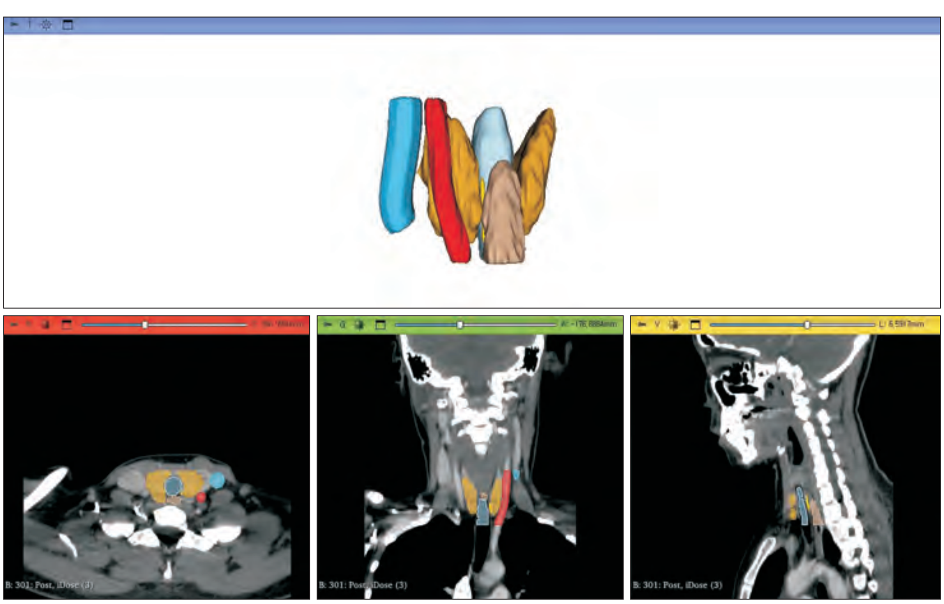

Fig. 1. Segmentation. The thyroid gland and surrounding structures (trachea, common carotid artery, internal jugular vein, and recurrent laryngeal nerve) were segmented from preoperative CT scans.

expected location between the trachea and esophagus, based on expert clinical advice from the operating surgeon (YJC).

Application of the augmented reality software onto the real-time endoscopic image

A series of digital interface (SDI) image signal 1:2 splitters (NEXT-SDI0102SP, NEXTU) were connected to the recording storage device of the endoscope (Precision Ideal Eyes 10 mm 30° HD autoclavable telescope, Stryker) to duplicate the input video while maintaining image signals between the laparoscope and the monitor. The video was streamed to the personal computer (PC) via an SDI-to-HDMI converter (NEXT 122SDHC, NEXTU). During surgery, the virtual thyroid AR model was overlaid in real-time onto the endoscopic camera monitor using Unity (Unity Technologies), a visualization software.

Controller

To facilitate one-handed manual registration of the virtual thyroid AR model, we developed a controller utilizing a customized keyboard (Razer Tartarus Pros R707-0311, Razer Inc.). The controller offers various functions for interacting with the model, such as zooming in and out, translating in multiple directions (right, left, up, and down), and rotating the model in clockwise and counterclockwise directions along roll, pitch, and yaw axes (Fig. 2).

Application of the augmented reality software onto the real-time endoscopic image

An SDI image signal 1:2 splitter (NEXT-SDI0102SP) was connected to the recording storage of the endoscope (Stryker Precision Ideal Eyes 10 mm 30° HD autoclavable telescope) to duplicate the input video while maintaining the image signal between the endoscope and the monitor. The video was streamed to the PC via an SDI-to-HDMI converter (NEXT 122SDHC). During surgery, the AR model was superimposed on the endoscopic view in real-time using the visualization software, Unity game engine 2022.3.21f1. The image was displayed on the monitor of a laptop PC (GP76 Leopard 11UH, MSI).

Protocol

Before applying the AR software during surgery, the surgeon received brief training on operating the controller and performing manual registration. Prior to surgery, the controller was wrapped in sterile plastic for use within the sterile surgical environment. All surgeries were carried out by a single surgeon (YJC) with 12 years of experience in endocrine surgeries. Manual registration of the AR model was performed before and after thyroid resection. The virtual thyroid AR model was superimposed on the laptop PC monitor with replicated endoscopic images. Using the controller, the surgeon manually aligned the AR model image by adjusting the position, rotation, size, and deformation of the virtual thyroid AR model to align with the trachea, common carotid artery, and internal jugular vein (landmarks with minimal relative movement during surgery) until the surgeon determined that alignment was satisfactory (Fig. 3). An assistant captured monitor images during the procedure for documentation.

Outcome measurement

The Dice similarity coefficient (DSC) is a statistical tool used to validate the accuracy and reliability of image segmentation by comparing the overlap between the predicted segmentation

Fig. 2. Controller. The controller designed to allow one-handed manipulation of the augmented reality thyroid model using a custom wireless keypad, with functions for zooming, translation in different directions, and rotation in roll, pitch, and yaw.

Fig. 3. Intraoperative use of the controller. The controller was encased in aseptic vinyl for sterile surgical field use, allowing the operator to manually register the augmented reality thyroid model on the endoscopic image on the laptop monitor using one hand.

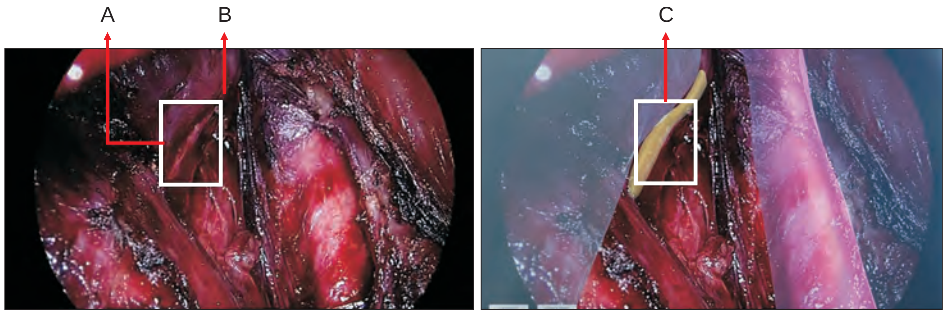

Fig. 4. Region of interest (ROI) of the recurrent laryngeal nerve (RLN). The visually identifiable area was designated as the ROI and used for the evaluation of the Dice similarity coefficient. A, RLN visible area; B, RLN invisible area; C, ROI or the designated area used for evaluation, based on A.

and the actual image [9]. Manual registration accuracy was evaluated using the DSC employing the following formula: DSC = 2 × |A ∩ B| / |A| + |B|. The DSC value ranges from 0 to 1, with a DSC of 0 signifying no overlap between the predicted segmentation and the actual image, and a DSC of 1 representing perfect overlap, where the predicted segmentation precisely matches the actual image [9,10]. We measured the similarity between the actual RLN and the aligned RLN of the AR model image post-registration after thyroidectomy.

To enhance the accuracy and objectivity of the experiment, the actual RLN location was identified through consultation with an experienced clinician, based on which binary mask images were generated. The visually identifiable portion of the RLN was then evaluated by extracting only the region of interest from both ground-truth images and registered 3D AR RLN model images using window techniques. The DSC was measured by using the ImageJ software (ver. 1.8.0, National Institutes of Health) with the TNTPFNFP plugin, a widely used tool in biomedical image analysis. This approach provided a quantitative assessment of the registration accuracy of the AI model (Fig. 4).

RESULTS

Three patients were included in this study. All were female, with a mean age of 33.3 ± 15.7 years. The mean tumor size was 1.0 ± 0.3 cm. All patients underwent transoral endoscopic thyroidectomy of the right thyroid lobe via the vestibular approach. The final histopathological diagnoses were 2 cases of papillary thyroid carcinoma and one case of follicular adenoma.

The manual registration accuracy, as measured by the DSC, was 0.60, 0.70, and 0.57 for patients 1, 2, and 3, respectively, with a mean value of 0.6 ± 0.1 (Table 1). Figs. 5–7 display images of the surgical field during transoral endoscopic thyroidectomy for each patient, before and after manual registration of the AR model, following flap dissection prior to thyroidectomy, as well as after thyroidectomy.

Table 1. Patient characteristics and outcomes

Characteristic	Patient 1	Patient 2	Patient 3
Age (yr)	21	28	51
Sex	Female	Female	Female
Location	Right	Right	Right
Tumor size (cm)	0.9	0.7	1.3
Diagnosis	PTC	PTC	FA
Dice similarity coefficient	0.60	0.70	0.57

PTC, papillary thyroid carcinoma, FA, follicular adenoma.

DISCUSSION

Identifying hidden anatomical structures during thyroidectomy poses considerable challenges, especially during transoral endoscopic thyroidectomy owing to the limited operative field, difficulties in maneuvering endoscopic instruments and the camera in the confined space, and a lack of tactile feedback [11]. Identifying the RLN is the most time-intensive step in thyroid surgery, and it is especially difficult during transoral endoscopic procedures [12]. RLN injury can result in serious complications such as vocal cord paralysis, aspiration, and, in severe cases, can be fatal [2]. Additionally, injury to other anatomical structures, including the trachea, common carotid artery, and jugular vein, can lead to severe complications [13]. Therefore, the surgeon's ability to precisely locate these critical structures is crucial. To facilitate this important step, we developed an AR system that superimposes important anatomical structures onto the endoscopic camera view during transoral endoscopic thyroidectomy. Our findings indicate that the manual registration accuracy of the AR system, as measured by the DSC, is within a moderate range. This suggests that the AR system is feasible and may assist surgeons by enhancing the visualization of anatomical structures, thereby helping prevent RLN injury during thyroidectomy.

The DSC is a simple statistical validation metric used to assess the reliability or reproducibility of image segmentation by measuring spatial overlap [9]. In clinical practice, interpretation of a DSC value may vary depending on the specific application and context. Some studies have proposed

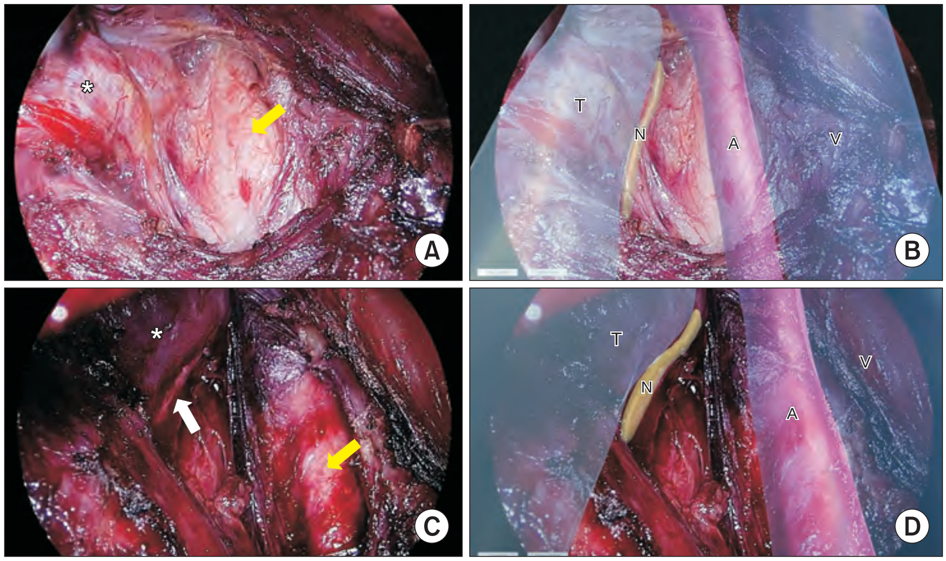

Fig. 5. Patient 1. (A) Endoscopic surgical field before recurrent laryngeal nerve identification (asterisk, thyroid gland; yellow arrow, common carotid artery). (B) Augmented reality (AR) model application before recurrent laryngeal nerve identification (T, thyroid gland; N, recurrent laryngeal nerve; A, common carotid artery; V, internal jugular vein). (C) Endoscopic surgical field after recurrent laryngeal nerve identification (asterisk, thyroid gland; yellow arrow, common carotid artery; white arrow, recurrent laryngeal nerve). (D) AR model application after recurrent laryngeal nerve identification (T, thyroid gland; N, recurrent laryngeal nerve; A, common carotid artery; V, internal jugular vein).

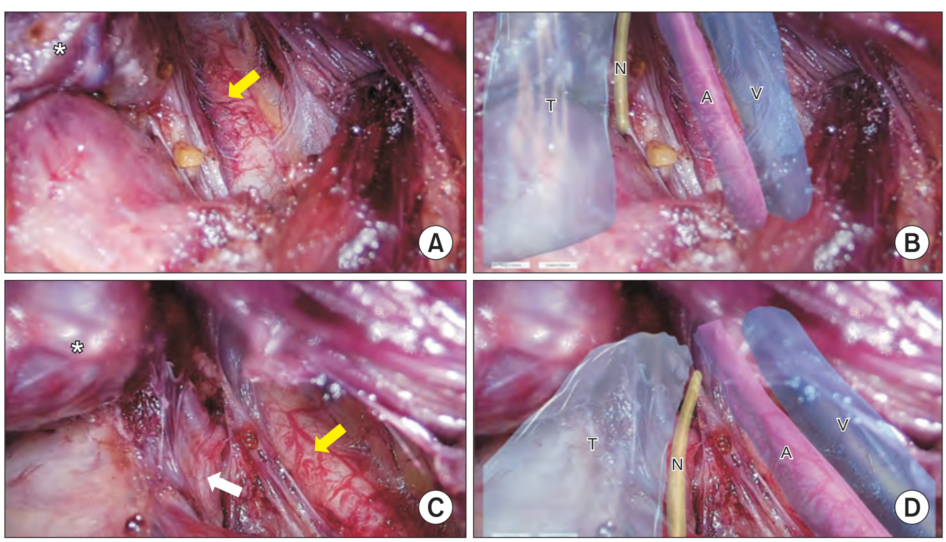

Fig. 6. Patient 2. (A) Endoscopic surgical field before recurrent laryngeal nerve identification (asterisk, thyroid gland; yellow arrow, common carotid artery). (B) Augmented reality (AR) model application before recurrent laryngeal nerve identification (T, thyroid gland; N, recurrent laryngeal nerve; A, common carotid artery; V, internal jugular vein). (C) Endoscopic surgical field after recurrent laryngeal nerve identification (asterisk, thyroid gland; yellow arrow, common carotid artery; white arrow, recurrent laryngeal nerve). (D) AR model application after recurrent laryngeal nerve identification (T, thyroid gland; N, recurrent laryngeal nerve; A, common carotid artery; V, internal jugular vein).

that a DSC value above 0.7 indicates strong agreement [14,15]. The mean DSC value of 0.6 resulting from the application of AR during our 3 cases indicates a reasonable but not ideal overlap between the predicted and actual structures. Thus, there is significant room for improvement. The reason for this moderate performance is likely because the RLN is very thin, which means that any small deviation could have a significant impact on the DSC value. Nevertheless, the significance of this application lies in providing an approximate location of the nerve rather than pinpoint accuracy. The use of the AR system may enable the surgeon to perform dissection more quickly in areas where the nerve is likely to be absent and to exercise

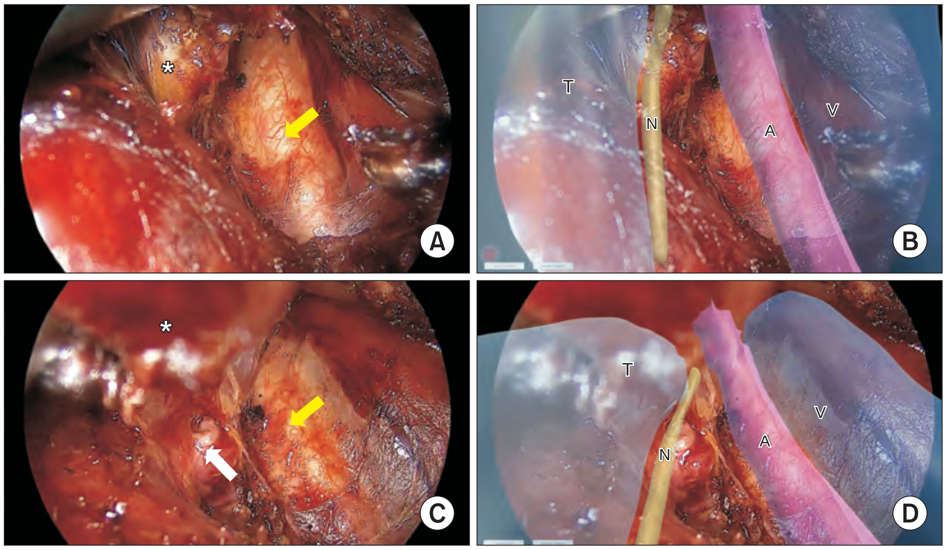

Fig. 7. Patient 3. (A) Endoscopic surgical field before recurrent laryngeal nerve identification (asterisk, thyroid gland; yellow arrow, common carotid artery). (B) Augmented reality (AR) model application before recurrent laryngeal nerve identification (T, thyroid gland; N, recurrent laryngeal nerve; A, common carotid artery; V, internal jugular vein). (C) Endoscopic surgical field after recurrent laryngeal nerve identification (asterisk, thyroid gland; yellow arrow, common carotid artery; white arrow, recurrent laryngeal nerve). (D) AR model application after recurrent laryngeal nerve identification (T, thyroid gland; N, recurrent laryngeal nerve; A, common carotid artery; V, internal jugular vein).

greater caution in areas where the nerve is likely to be present.

Intraoperative neuromonitoring (IONM) is commonly used to locate the RLN during thyroid surgeries. While IONM is valuable for identifying and assessing the integrity of the RLN, there is ongoing debate about its effectiveness in reducing the rate of RLN injury [16]. IONM can sometimes fail due to issues such as endotracheal tube misplacement, tissue thickness around the RLN, problems with the IONM equipment, or interactions with medications like neuromuscular blockade agents [17,18]. Furthermore, while IONM can detect nerve signals from the RLN, it does not provide direct imaging, requiring surgeons to infer the nerve's location from signal detection alone [19]. Additionally, using IONM is expensive, with costs ranging from 250 to 700 US dollars depending on the country. Also, differences in insurance systems across countries result in varying availability, making it impractical for universal use among all patients. Although our AR system may not surpass or replace IONM in RLN localization, it has the potential to complement IONM by providing additional visualization of the RLN and other key anatomical structures.

Integrating the AR system into surgical practice involved addressing several technical and practical challenges. Precise alignment of the AR model with the real-time endoscopic camera images is crucial for accuracy. Misalignment could lead to incorrect localization of anatomical structures, potentially increasing the risk of complications. Although the RLN and blood vessels in the neck are generally fixed, they can deform due to traction during surgery [20,21], which has the potential to affect the accuracy of the AR. Additionally, as the RLN is not visible on preoperative CT scans, the AR model of the RLN was based on its expected location relative to other anatomical structures. This also has the potential to impact accuracy if the RLN in the AR model does not match its actual position. We believe that if the nerve location could be identified preoperatively using CT or ultrasound images, the accuracy of AR alignment could be enhanced, allowing for more precise identification of the RLN during surgery [22]. The manual registration process introduces a degree of subjectivity and the potential for human error which also has the potential to affect AR image alignment accuracy [23].

Currently, automatic tracking is not possible with this system and thus the AR model does not follow camera movement and must be manually re-registered following significant endoscope movements. Research on automatic registration and tracking of AR models in other surgeries is ongoing [24-27], and similar advancements are anticipated for transoral endoscopic thyroidectomy. Furthermore, during manual registration, the alignment of the AR model was based on the location of the trachea and the blood vessels in particular, possibly requiring more exposure of the blood vessels than is typical during transoral endoscopic thyroidectomy [28]. Therefore, ongoing improvements in the development of AR software and hardware, along with comprehensive surgeon training, are essential for the successful implementation of this tool.

Our study has limitations. The limited sample size limits the generalizability of our results. However, because the 3 cases presented were able to demonstrate that the AR system can successfully be used for RLN localization, we believe this study serves sufficiently as a proof of concept. Nevertheless, larger, multicenter studies are necessary to validate the effectiveness and reliability of the AR system across various clinical settings. This study does not have a comparative arm which limits our ability to compare outcomes between surgeries using AR and those that do not. Future comparative studies will be essential to better understand the impact of AR technology on surgical outcomes. Despite these limitations, our study lays the groundwork for using AR in transoral endoscopic thyroidectomy and paves the way for further research in this field.

In conclusion, this study demonstrated the feasibility of the application of an AR system during transoral endoscopic thyroidectomy and showed its potential for improving the localization of anatomical structures, particularly the RLN, as indicated by an acceptable DSC. Further comparative studies with larger sample sizes are necessary to validate these findings and optimize AR technology for broader clinical applications.

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Conflict of Interest

Young Jun Chai, serving as an member of the Editorial Board of *Annals of Surgical Treatment and Research*, did not participate in the review process of this article. No other potential conflicts of interest pertinent to this article were reported.

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Methodology: TJ
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