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Original Article

Effects of endoscopic transnasal orbital decompression on anterior segment ocular blood flow and clinical outcome in thyroid-associated ophthalmopathy: a retrospective study

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Abstract: Background: Thyroid-associated ophthalmopathy (TAO) is characterized by orbital inflammation and elevated intraorbital pressure, which may compromise anterior segment microcirculation. While endoscopic transnasal orbital decompression (ETOD) effectively alleviates proptosis and improves vision, its effect on microcirculation remains underexplored. Objective: This study aimed to evaluate the effect of ETOD on anterior segment microcirculation in TAO using SS-OCTA and to correlate these changes with clinical outcome. Methods: This retrospective study included 45 TAO patients undergoing ETOD and 45 matched healthy controls. SS-OCTA measures (superficial, deep, and small vessel density; blood flow area) and clinical measures (exophthalmos, intraocular pressure, best-corrected visual acuity) were assessed preoperatively and 3 months postoperatively. Results: Preoperatively, SVD was significantly higher in TAO patients than in healthy controls (50.63 ± 1.98% vs. 48.53 ± 2.78%, P < 0.001), whereas DVD showed no significant difference (47.93 ± 1.59% vs. 47.30 ± 2.57%, P = 0.169). In contrast, BFA was significantly lower (2.07 ± 0.31 vs. 2.49 ± 0.27 mm^2, P < 0.001), whereas SmiVD showed no significant difference (P = 0.939). Three months after ETOD, SVD and DVD decreased significantly (temporal quadrant SVD: from 51.53 ± 2.26% to 43.37 ± 1.78%, -15.8%, P < 0.001; temporal DVD: from 47.81 ± 2.49% to 38.66 ± 2.70%, -19.1%, P < 0.001), whereas BFA increased significantly (temporal BFA: from 2.08 ± 0.49 mm^2 to 2.34 ± 0.45 mm^2, +12.5%, P < 0.001). SmiVD remained unchanged (P > 0.05). BCVA showed no significant change (LogMAR 0.05 ± 0.06 to 0.04 ± 0.07, P = 0.290). Exophthalmos reduction showed a significant positive correlation with SVD reduction (r = 0.346, P = 0.020), and postoperative IOP was not significantly correlated with postoperative SmiVD (r = 0.024, P = 0.875). Conclusions: ETOD effectively reduced exophthalmos and IOP and restored anterior segment hemodynamics by decreasing pathologically elevated vessel densities toward normal levels. SS-OCTA provides a valuable noninvasive tool for monitoring microcirculatory changes after orbital decompression in TAO.

Keywords: Thyroid-associated ophthalmopathy, orbital decompression, anterior segment microcirculation, SS-OCTA, vessel density

Introduction

Thyroid-associated ophthalmopathy (TAO) is the most common extrathyroidal manifestation of Graves' disease [1]. Its pathogenesis involves autoimmune-mediated activation of orbital fibroblasts, deposition of glycosaminoglycans, inflammatory cell infiltration, and tissue edema, which increase orbital content and progressively elevate intraorbital pressure [2]. These pathologic changes not only result in characteristic clinical features such as proptosis, eyelid retraction, and extraocular muscle enlargement but also may cause compressive optic neuropathy due to optic nerve compression or exposure keratopathy secondary to severe proptosis and lagophthalmos. Both of these can severely impair visual function and quality of life [3-5].

Elevated intraorbital pressure is a central mechanism in the pathophysiologic cascade of

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TAO [6, 7]. Persistently increased orbital pressure exerts direct mechanical compression on the optic nerve and globe and may also impair microcirculation in both the orbit and the anterior segment of the eye. Anterior segment ischemia is recognized as a significant contributor to vision loss in TAO patients, primarily resulting from compression, vasospasm, or inflammatory damage to vessels supplying the anterior segment - particularly the anterior ciliary arteries [8-11]. However, conventional clinical examinations cannot objectively or quantitatively assess these microcirculatory alterations [12, 13].

For patients with moderate-to-severe, inactive (stable-phase) TAO who respond poorly to medical therapy, surgical orbital decompression is a critical intervention for improving appearance and preserving visual function [3, 14, 15]. Among various decompression techniques, endoscopic transnasal orbital decompression (ETOD) has emerged as one of the mainstream approaches due to its advantages, including excellent endoscopic visualization and precise expansion of bony orbital walls. It also allows simultaneous management of concurrent sinus pathology and avoids visible facial scarring [16, 17]. By effectively enlarging orbital volume and partially removing orbital fat, ETOD directly and significantly reduces intraorbital pressure, yielding well-documented clinical benefits in terms of globe repositioning and relief of optic nerve compression [18]. However, the effect of this surgery on anterior segment microcirculation in TAO patients - particularly the dynamic patterns of postoperative perfusion changes and their relationship to visual function improvement - remains insufficiently characterized by systematic and in-depth research [19].

In recent years, ophthalmic imaging has witnessed remarkable advances [20]. Swept-source optical coherence tomography angiography (SS-OCTA) is a noninvasive, high-resolution, and repeatable imaging modality capable of visualizing the layered microvascular networks of both the retina and the anterior segment, while enabling precise quantification of measures such as vessel density and perfusion area [21-24]. This technology provides a powerful tool for *in vivo*, dynamic assessment of ocular microcirculation and has been widely applied in hemodynamic studies of conditions like glaucoma and diabetic retinopathy [25, 26]. Nevertheless, its application in TAO - especially in evaluating the therapeutic effects of orbital decompression surgery - remains underexplored [15].

Therefore, this retrospective study used SS-OCTA to investigate systematically the changes in microvascular density and blood flow area in the anterior segment of TAO patients before and after ETOD. By comparing these measures between the surgical group and a healthy control group, we sought to explore the beneficial effects of surgical intervention on anterior segment microcirculation. Furthermore, we aimed to explore the intrinsic associations between such microcirculatory improvements and key clinical outcomes - including reduction in proptosis, changes in intraocular pressure (IOP), and gains in best-corrected visual acuity (BCVA) - thereby providing novel hemodynamic evidence for assessing ETOD efficacy and deepening our understanding of the mechanisms underlying surgical treatment in TAO.

Materials and methods

Study design

This was a single-center, retrospective cohort study designed to evaluate the impact of endoscopic transnasal orbital decompression (ETOD) on anterior segment microcirculation in patients with thyroid-associated ophthalmopathy (TAO). The study protocol was reviewed and approved by the Ethics Committee of Mianyang City Central Hospital. All procedures adhered to the principles of the Declaration of Helsinki. The participant selection flowchart is shown in **Figure 1**.

Study population

Surgical group (TAO group): Consecutive patients diagnosed with TAO who underwent ETOD at Mianyang City Central Hospital between January 2023 and June 2025 were enrolled.

Inclusion criteria: Diagnosis confirmed according to Bartley's clinical diagnostic criteria; Presence of surgical indications (e.g., compressive optic neuropathy, severe proptosis unresponsive to medical therapy, or exposure keratopathy); Availability of complete SS-OCTA imaging

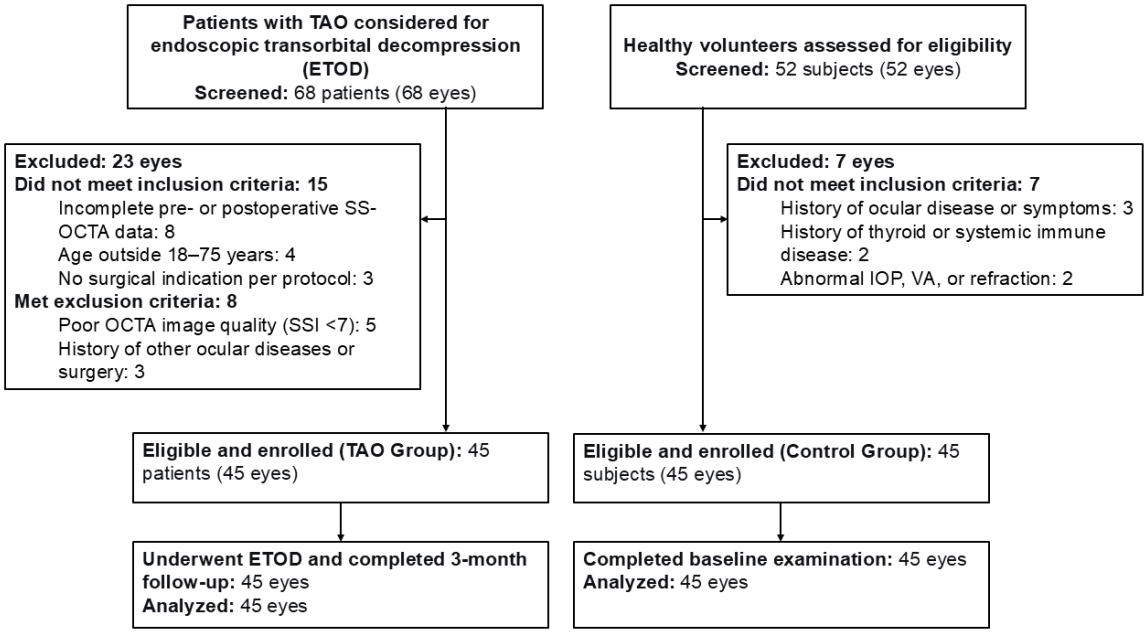

Figure 1. Participant enrollment and allocation flowchart.

and clinical data both preoperatively and at the 3-month postoperative follow-up; Age between 18 and 75 years.

Exclusion criteria: Coexisting ocular diseases (e.g., glaucoma, uveitis, retinopathy); History of ocular trauma or intraocular surgery; Severe systemic comorbidities (e.g., uncontrolled hypertension, diabetes mellitus, or other autoimmune disorders); Receipt of other ocular treatments during the perioperative period that could potentially affect ocular blood flow (e.g., radiotherapy); Poor-quality OCTA images (signal strength < 7).

Control group: Age- and sex-matched healthy individuals undergoing routine health examinations during the same period were recruited as controls.

Inclusion criteria: No history or symptoms of ocular disease; No history of thyroid disease or other systemic autoimmune conditions; Normal intraocular pressure, visual acuity, and refractive status.

Ultimately, 45 participants (45 eyes) were included in each group.

Surgical procedure

All surgeries were performed jointly by the same team of experienced otolaryngologists and ophthalmologists. ETOD (Endoscopic Transnasal Orbital Decompression) was performed through an endoscopic transnasal approach to decompress the medial and/or inferior walls of the orbit. The bony window extended from the anterior orbital apex to the infraorbital foramen. Depending on the indications, a portion of the orbital fat was removed, with a total volume of 2-4 ml. The extent of decompression was tailored to each patient based on preoperative imaging and intraoperative findings.

Data collection

Demographic and clinical data: Information on age and gender was recorded. Clinical measurements included: best-corrected visual acuity (BCVA, converted to LogMAR values), intraocular pressure (IOP) measured by a non-contact tonometer, and exophthalmometry readings using a Hertel exophthalmometer (in millimeters with a fixed orbital distance).

Anterior segment OCTA parameters: All measurements were obtained using an Intalight device in anterior segment mode, operated by the same experienced technician under standardized conditions. The scanning area was 12×12 mm, centered on the limbus. The device operated at a central wavelength of 1060 nm and an A-scan rate of 100,000 scans/s. The

analysis software allowed for the selection of a 3×3 mm region of interest within the scanned area and automatically generated the following measures:

Superficial Vessel Density (SVD, %): Percentage of vessel area within a defined depth range from the corneal limbus.

Deep Vessel Density (DVD, %): Percentage of vessel area in the deeper stromal vascular network.

Small Vessel Density (SmiVD, %): Defined as the density of vessels with diameters less than 20 μm.

Blood Flow Area (BFA, mm^2): Total area in the image where blood flow signals were detected.

To provide a comprehensive evaluation, SVD, DVD, SmiVD, and BFA were recorded separately for both the temporal and nasal quadrants.

Quality control and data management

All data were entered and verified by two independent researchers to ensure accuracy and consistency. OCTA images were independently assessed by two senior ophthalmologists, and any images deemed to be of poor quality were excluded. A data monitoring mechanism was established during the study to ensure the integrity and reliability of the data. To assess inter-observer agreement (i.e., reproducibility), two experienced ophthalmologists independently analyzed 10 randomly selected OCTA images. The intraclass correlation coefficients (ICC) for all measured parameters exceeded 0.85, indicating excellent inter-observer agreement.

Statistical analysis

Statistical analyses were performed using SPSS version 26.0. Continuous variables were tested for normality using the Shapiro-Wilk test. Normally distributed data were presented as mean ± standard deviation (SD), while non-normally distributed data were reported as median (interquartile range, IQR). Categorical variables were expressed as frequencies (percentages). Within-group comparisons (preoperative vs. 3-month postoperative values in the surgical group) were conducted using paired-samples t-tests for normally distributed data or Wilcoxon signed-rank tests for non-normally distributed data. Between-group comparisons (surgical group preoperatively vs. control group; surgical group postoperatively vs. control group) were performed using independent-samples t-tests for normally distributed data or Mann-Whitney U tests for non-normally distributed data. Additionally, subgroup analyses were carried out based on preoperative exophthalmos, baseline perfusion levels, and age. Correlations between variables were assessed using Pearson correlation coefficients for normally distributed data or Spearman's rank correlation coefficients for non-normally distributed data. All statistical tests were two-tailed, and a *P*-value < 0.05 was considered significant. The Shapiro-Wilk test confirmed that all paired differences were normally distributed (P > 0.05). To control for type I error due to multiple comparisons, the Bonferroni correction was applied. The significance threshold was adjusted to P < 0.00625 (0.05/8). Bonferroni correction was applied for the three comparisons in **Table 1**, setting the significance level at P < 0.0167. All originally significant *P* values (< 0.001) remained significant after correction. For subgroup analysis based on preoperative perfusion (SVD), the cutoff value of 49.40% was defined as the median of the preoperative SVD distribution in the TAO group.

Results

Baseline characteristics

The surgical group (TAO group) and the control group were well matched in terms of age (42.9 ± 11.4 years vs. 44.5 ± 11.4 years, P = 0.507) and sex distribution (male: 21 cases, 46.7% vs. 27 cases, 60.0%, P = 0.344), with no significant differences (**Table 1**). Preoperatively, SVD was significantly higher in TAO patients than in healthy controls (P < 0.001), whereas DVD showed no significant difference (P = 0.169). BFA was significantly lower (P < 0.001; **Table 1**). Small vessel density (SmiVD) did not differ significantly among groups (P = 0.939). Three months after ETOD, both SVD and DVD decreased significantly compared to preoperative values (both P < 0.001), whereas BFA increased significantly (P < 0.001). SmiVD remained statistically unchanged across all three groups (P > 0.05, **Table 1**; **Figure 2**).

Table 1. Baseline characteristics of the study population

Characteristic	Control (n = 45)	TAO Pre-op (n = 45)	TAO Post-op (n = 45)	P1 (Pre-op vs. Control)	P2 (Post-op vs. Control)	P3 (Pre-op vs. Post-op)
Age (years)	44.5 ± 11.4	42.9 ± 11.4	-	0.514	0.272	-
Gender (n, %)				0.291	0.291	1.000
Male	27 (60.0%)	21 (46.7%)	21 (46.7%)			
Female	18 (40.0%)	24 (53.3%)	24 (53.3%)			
Exophthalmos (mm)	15.24 ± 1.80	21.68 ± 2.32	16.99 ± 2.09	< 0.001	< 0.001	< 0.001
Intraocular pressure (mmHg)	14.17 ± 1.97	16.51 ± 2.59	12.71 ± 2.30	< 0.001	0.002	< 0.001
Best corrected visual acuity (LogMAR)	0.02 ± 0.07	0.05 ± 0.06	0.04 ± 0.07	0.021	0.262	0.290
Superficial vascular density (%)	48.53 ± 2.78	50.63 ± 1.98	43.30 ± 1.48	< 0.001	< 0.001	< 0.001
Deep vascular density (%)	47.30 ± 2.57	47.93 ± 1.59	39.88 ± 1.83	0.169	< 0.001	< 0.001
Small vessel density (%)	28.58 ± 2.59	28.62 ± 2.17	28.74 ± 2.26	0.933	0.742	0.272
Blood flow area (mm^2)	2.49 ± 0.27	2.07 ± 0.31	2.32 ± 0.29	< 0.001	0.005	< 0.001

Data are presented as mean ± standard deviation unless otherwise indicated. P1: independent t-test (Welch) between TAO Pre-op and Control. P2: independent t-test (Welch) between TAO Post-op and Control. P3: paired t-test between TAO Pre-op and Post-op. Significance level after Bonferroni correction for multiple comparisons: P < 0.0167. Abbreviation: TAO, thyroid-associated orbitopathy; Pre-op, preoperative; Post-op, postoperative; IOP, intraocular pressure; BCVA, best corrected visual acuity; AS-OCTA, anterior segment optical coherence tomography angiography.

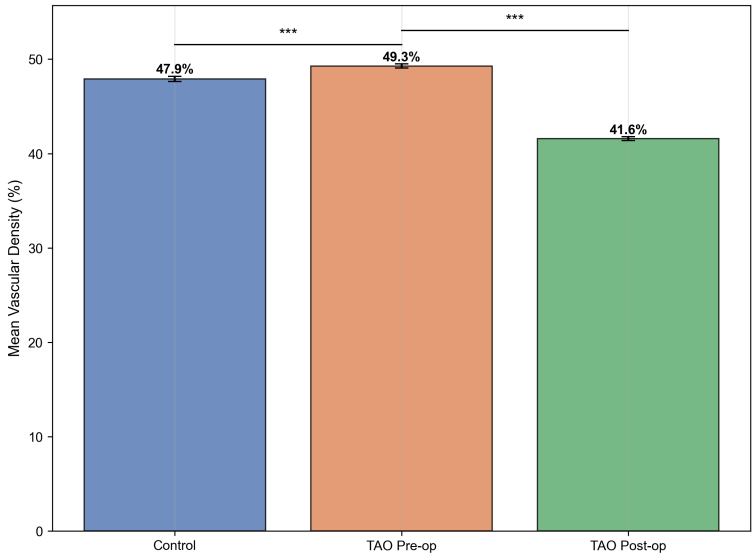

Figure 2. Comparison of anterior segment vascular density among groups. Data are mean ± SD. ***P < 0.001 for Control vs. TAO Preoperative and for TAO Preoperative vs. TAO Postoperative (independent and paired t-tests, respectively). TAO Postoperative vs. Control also showed P < 0.001. Abbreviation: SVD, superficial vascular density; DVD, deep vascular density.

Changes in clinical indicators

Preoperatively, the TAO group exhibited significantly higher exophthalmos and IOP compared to controls (both P < 0.001), while BCVA showed a trend toward worse values in the TAO group, but this difference did not reach statistical significance after Bonferroni correction (uncorrected P = 0.021). As shown in **Table 3** and **Figure 4**, three months after ETOD, exophthalmos and IOP decreased significantly (both P < 0.001). Postoperative IOP was significantly lower than that of controls (P = 0.002). BCVA remained stable postoperatively and did not differ significantly from preoperative values (P = 0.290) or from controls (P = 0.262).

Changes in anterior segment OCTA measures

As shown in **Table 2** and **Figure 3**, at the 3-month postoperative follow-up, vessel densities (SVD and DVD) in both the temporal and nasal quadrants decreased significantly compared to preoperative values, whereas blood flow area (BFA) increased significantly. In contrast, small vessel density (SmiVD) showed minimal, non-significant changes. BFA increased significantly in both quadrants (both P < 0.001).

Subgroup analysis

Subgroup analyses based on preoperative exophthalmos, vascular density, and age are summarized in **Table 4**. Patients with higher preoperative exophthalmos (≥ 21.4 mm) exhibited a significantly greater reduction in SVD compared to those with lower exophthalmos (P = 0.001). Preoperative vascular density and age did not significantly influence the extent of SVD reduction (P = 0.093 and P = 0.211, respectively).

Table 2. Changes in anterior segment blood flow measures after surgery

Measure	Pre-op	Post-op (3 months)	Change	Improvement (%)	*P*-value
Temporal SVD (%)	51.53 ± 2.26	43.37 ± 1.78	-8.16	-15.8%	< 0.001
Nasal SVD (%)	49.71 ± 2.45	43.23 ± 1.90	-6.49	-13.0%	< 0.001
Temporal DVD (%)	47.81 ± 2.49	38.66 ± 2.70	-9.15	-19.1%	< 0.001
Nasal DVD (%)	48.05 ± 2.37	41.09 ± 2.69	-6.95	-14.5%	< 0.001
Temporal SmiVD (%)	29.23 ± 3.56	29.30 ± 3.85	0.07	0.2%	0.553
Nasal SmiVD (%)	28.02 ± 3.49	28.18 ± 3.86	0.16	0.6%	0.362
Temporal BFA (mm^2)	2.08 ± 0.49	2.34 ± 0.45	0.26	12.5%	< 0.001
Nasal BFA (mm^2)	2.06 ± 0.42	2.31 ± 0.38	0.25	12.3%	< 0.001

Data are presented as mean ± standard deviation. All *P* values were calculated using paired t-tests. After Bonferroni correction for eight comparisons, a *P* value < 0.00625 was considered statistically significant. The six parameters with *P* < 0.001 remained significant after correction, whereas the two SmiVD parameters (P = 0.553 and P = 0.362) remained non-significant. Abbreviation: Pre-op, preoperative; Post-op, postoperative; SVD, superficial vascular density; DVD, deep vascular density; SmiVD, small vessel density; BFA, blood flow area.

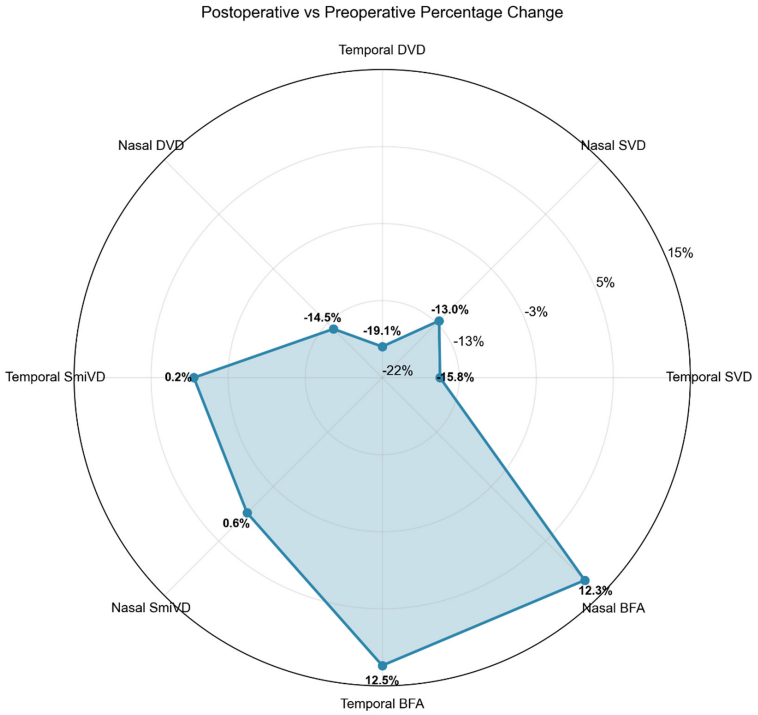

Figure 3. Percentage change of various measures after surgery. Data are presented as percentage change from preoperative to 3-month postoperative values. All changes were assessed by paired t-tests; see **Table 2** for exact values and *P*-values (with Bonferroni correction for multiple comparisons). Abbreviation: SVD, superficial vascular density; DVD, deep vascular density; SmiVD, small vessel density; BFA, blood flow area.

Correlation analysis revealed a significant positive correlation between the amount of exophthalmos reduction and the reduction in superficial vascular density (r = 0.346, P = 0.020, **Figure 5A**). No significant correlation was found between postoperative IOP and postoperative small vessel density (r = 0.024, P = 0.875, **Figure 5B**).

Discussion

This is the first study to evaluate systematically the effect of ETOD on anterior segment microcirculation in TAO using SS-OCTA. Key findings include: 1) Preoperatively, TAO patients exhibited paradoxically elevated superficial vessel density compared to healthy controls, while deep vessel density showed no significant difference. 2) ETOD significantly reduced these elevated vessel densities toward normal levels, while simultaneously increasing blood flow area. 3) These microcirculatory changes paralleled improvements in clinical indicators (exophthalmos and IOP).

The preoperative elevation of SVD and DVD is consistent with venous congestion and compensatory arteriolar dilation within the confined orbital compartment. In TAO, increased orbital soft tissue volume elevates intraorbital pressure, compressing thin-walled venous structures and impairing venous outflow. This venous stasis leads to capillary engorgement and reflex dilation of upstream arterioles, manifesting as

Table 3. Clinical outcomes and comparison with controls

Clinical Index	Control	TAO Pre-op	TAO Post-op	P1 (Pre-op vs. Control)	P2 (Post-op vs. Pre-op)	P3 (Post-op vs. Control)
Exophthalmos (mm)	15.24 ± 1.80	21.68 ± 2.32	16.99 ± 2.09	< 0.001	< 0.001	< 0.001
Intraocular pressure (mmHg)	14.17 ± 1.97	16.51 ± 2.59	12.71 ± 2.30	< 0.001	< 0.001	0.002
BCVA (LogMAR)	0.02 ± 0.07	0.05 ± 0.06	0.04 ± 0.07	0.021	0.290	0.262

Data are presented as mean ± standard deviation. P1: comparison between TAO preoperative group and controls (unpaired t-test). P2: comparison between TAO preoperative and postoperative groups (paired t-test). P3: comparison between TAO postoperative group and controls (unpaired t-test). Abbreviation: TAO, thyroid-associated orbitopathy; Pre-op, preoperative; Post-op, postoperative; IOP, intraocular pressure; BCVA, best corrected visual acuity.

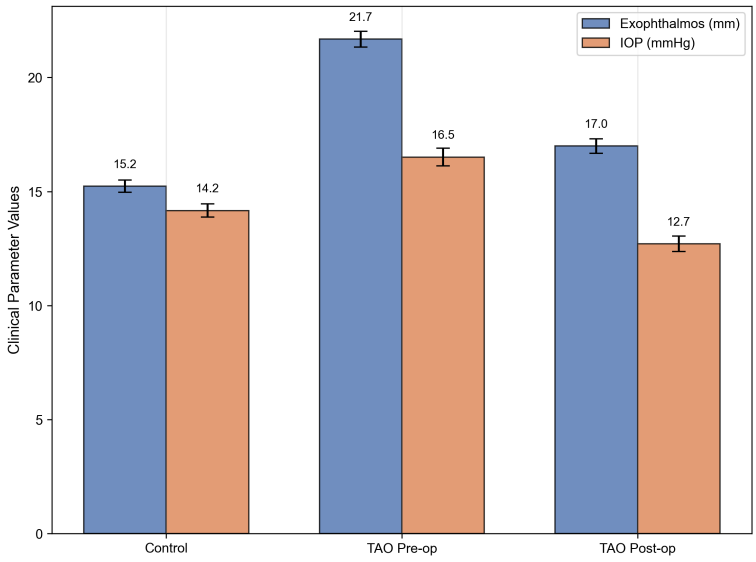

Figure 4. Clinical outcomes comparison after orbital decompression. Data are mean ± SD. For exophthalmos and IOP, all pairwise comparisons were statistically significant: TAO Preoperative vs. Control ($P < 0.001$, independent t-test), TAO Postoperative vs. PreoperativePreoperative ($P < 0.001$, paired t-test), and TAO Postoperative vs. Control ($P < 0.001$ for exophthalmos, $P = 0.002$ for IOP, independent t-tests). Abbreviation: IOP, intraocular pressure.

higher vessel densities on OCTA. Concurrently, the reduced blood flow area (BFA) indicates sluggish perfusion. Similar paradoxical hypervascularity has been reported in other orbital compressive conditions.

Three months after ETOD, the significant reduction in SVD and DVD, accompanied by an increase in BFA, strongly supports the notion that surgical decompression relieves venous compression, thereby normalizing the previously congested microvasculature. By expanding orbital volume and reducing intraorbital pressure, ETOD restores physiologic venous drainage, reduces capillary engorgement, and improves overall perfusion efficiency. The lack of significant change in SmiVD suggests that small-caliber vessels may be less susceptible to compressive congestion or require longer follow-up to exhibit measurable remodeling [27].

In contrast to our findings, Rafizadeh et al. [15] recently reported a postoperative increase in superficial vascular density using AS-OCTA. This discrepancy may stem from differences in follow-up timing (3 months vs. 6 weeks), disease activity stage, or the extent of orbital fat resection. Our findings align more closely with studies demonstrating venous congestion as a hallmark of untreated TAO and highlight the importance of distinguishing true ischemia from venous engorgement when interpreting OCTA metrics. Similarly, Masoumi et al. [3] reported decreased anterior segment vessel density in TAO patients, which may reflect differences in disease activity or OCTA scanning protocols. The innovation of this study lies in its first systematic evaluation of the comprehensive improvement in postoperative superficial, deep, and microvascular density as well as blood flow area, and in revealing their correlation with clinical indicators (proptosis, intraocular pressure), thereby providing a more complete perspective for understanding the hemodynamic effects of orbital decompression surgery. These findings suggest that the restoration of anterior segment microcirculation may involve multiple levels and mechanisms, and that improvements in deep and small vessels may require longer follow-up periods or more thorough orbital pressure relief to fully manifest.

Table 4. Subgroup analysis of treatment response

Analysis	Subgroup	n	Outcome measure	Mean ± SD or r (95% CI)	*P*-value
By preoperative exophthalmos	High (≥ 21.4 mm)	23	SVD reduction (percentage points)	7.99 ± 1.31	0.001
	Low (< 21.4 mm)	22	SVD reduction (percentage points)	6.63 ± 1.30	
	Difference	45	Mean difference	1.36 (0.57 to 2.14)	
By preoperative perfusion	Low (< 49.40%)	22	Exophthalmos reduction (mm)	4.49 ± 0.85	0.093
	High (≥ 49.40%)	23	Exophthalmos reduction (mm)	4.89 ± 0.70	
	Difference	45	Mean difference	-0.40 (-0.87 to 0.07)	
By age	Younger (< 41 years)	21	SVD reduction (percentage points)	7.61 ± 1.33	0.211
	Older (≥ 41 years)	24	SVD reduction (percentage points)	7.07 ± 1.54	
	Difference	45	Mean difference	0.54 (-0.33 to 1.42)	
Correlation analysis	Exophthalmos reduction vs. SVD reduction	45	Pearson's r	0.346 (0.058 to 0.580)	0.020
	Postoperative IOP vs. postoperative SmiVD	45	Pearson's r	0.024 (-0.271 to 0.315)	0.875

Continuous variables are presented as mean ± standard deviation. Between-group comparisons were performed using independent t-tests. Correlations were assessed using Pearson correlation coefficients with 95% confidence intervals. Abbreviation: SVD, superficial vascular density; SmiVD, small vessel density; IOP, intraocular pressure.

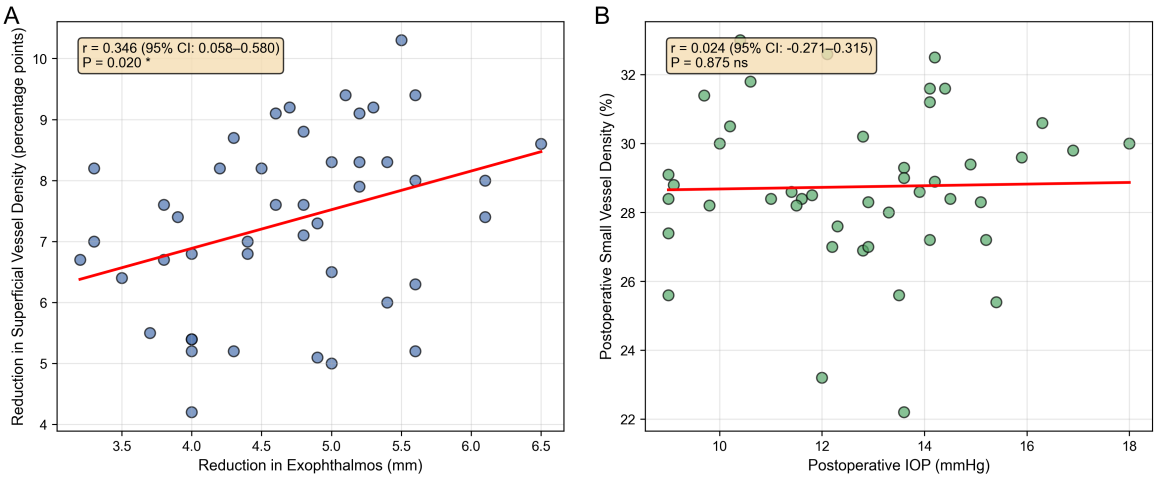

Figure 5. Correlation analysis of key postoperative indicators. A. Scatter plot showing the correlation between the degree of exophthalmos reduction and the reduction in superficial vascular density (SVD) after ETOD surgery. A significant positive correlation was observed (r = 0.346, P = 0.020). B. Scatter plot showing the correlation between postoperative intraocular pressure (IOP) and postoperative small vessel density (SmiVD). No significant correlation was observed (r = 0.024, P = 0.875). Abbreviation: SVD, superficial vascular density; IOP, intraocular pressure; SmiVD, small vessel density.

However, despite the notable postoperative improvement in blood flow indices, they did not fully return to the levels seen in the healthy control group. This suggests that the damage to microvasculature in TAO may not be entirely reversible. Chronic high intraorbital pressure and inflammation can lead to structural changes in vessel walls, such as basement membrane thickening, pericyte loss, and fibrosis [28], which may limit complete recovery of blood flow. Additionally, a follow-up period of three months might have been insufficient to observe the ultimate plateau phase of microcirculatory recovery. Future studies should extend the follow-up duration to clarify the dynamic process and final outcome of microcirculatory improvement.

In the present cohort, the reduction in exophthalmos was significantly correlated with the reduction in SVD (r = 0.346, P = 0.020), suggesting that greater orbital decompression is associated with proportionally greater vascular normalization. No significant correlation was found between postoperative IOP and SmiVD (r = 0.024, P = 0.875). These findings indicate that while ETOD generally improves both clinical and hemodynamic measures, individual responses may vary and may be influenced by additional factors such as baseline orbital compliance or microvascular remodeling.

Subgroup analyses revealed that only preoperative exophthalmos significantly influenced the magnitude of SVD reduction (P = 0.001), whereas perfusion level and age did not (P = 0.093 and P = 0.211, respectively). This indicates that the benefit of ETOD in improving anterior segment microcirculation is broadly applicable and not limited by these baseline factors, further supporting the wide suitability of this surgical approach for TAO patients who meet standard surgical indications [29].

This study had several limitations. First, its retrospective design may have introduced selection bias. Second, the modest sample size may have limited the statistical power of subgroup analyses. Third, the follow-up duration was only three months, which precluded assessment of long-term trends in microcirculatory changes. Fourth, the SS-OCTA device used in this study was not specifically designed for anterior segment imaging (i.e., not a dedicated AS-OCTA system); although standardized scanning protocols were applied, measurements may not have been directly comparable to those obtained with dedicated AS-OCTA systems. Additionally, the study did not incorporate TAO activity scores (e.g., Clinical Activity Score, CAS), thus limiting our ability to analyze how inflammatory activity influences pre- and postoperative microcirculatory changes.

Although this study suggests that ETOD may improve anterior segment microcirculation by reducing intraorbital pressure, it did not directly measure the dynamic relationship between changes in intraorbital pressure and blood flow measures; therefore, the proposed mechanism remains an indirect inference. Future studies should incorporate intraoperative or postoperative intraorbital pressure monitoring techniques to directly verify a causal relationship between reduced intraorbital pressure and microcirculatory recovery, thereby providing more robust evidence for the hemodynamic effects of the procedure.

Furthermore, this study observed correlations between preoperative and postoperative SS-OCTA measures (such as superficial vascular density and small vessel density) and clinical outcomes, suggesting that these measures may serve as biomarkers for predicting surgical efficacy or patient selection. For example, whether patients with lower preoperative small vessel density experience a more significant postoperative reduction in intraocular pressure, or whether the degree of preoperative vascular density impairment can predict the extent of postoperative microcirculatory recovery, are both worthy of further validation through prospective studies. Incorporating SS-OCTA indicators into clinical decision-making pathways holds promise for achieving personalized, precision management of TAO surgery.

Future research could advance in several directions: prospective, large-scale studies with extended follow-up could delineate the complete temporal trajectory of anterior segment microcirculatory recovery after ETOD; integrating SS-OCTA parameters with TAO-specific quality-of-life questionnaires and more detailed visual function tests (e.g., contrast sensitivity, visual fields) would clarify the functional significance of microcirculatory improvement; investigating whether preoperative OCTA metrics can serve as predictive biomarkers for surgical outcomes; and employing more advanced OCTA analytical techniques - such as quantitative blood flow velocity mapping and vascular morphometric analysis - to multidimensionally elucidate the nature of microvascular pathology in TAO and its remodeling following surgical intervention.

In summary, ETOD not only effectively reduces proptosis and IOP but also significantly restores impaired anterior segment microcirculatory perfusion in TAO patients. These findings provide novel evidence for the therapeutic value of ETOD at the microcirculatory level. As an objective, noninvasive, and quantifiable imaging tool, SS-OCTA shows considerable promise in assessing TAO severity, uncovering its pathophysiologic mechanisms, and monitoring treatment response, and may become a valuable adjunctive modality in the comprehensive management of TAO in the future.

Conclusion

ETOD effectively reduced exophthalmos and lowered IOP while significantly normalizing anterior segment hemodynamics in patients with thyroid-associated ophthalmopathy. Specifically, the surgery reduced pathologically elevated superficial and deep vessel densities and

increased blood flow area. The procedure demonstrated a significant positive correlation between exophthalmos reduction and vessel density reduction. SS-OCTA provides a novel, objective, and quantitative tool for monitoring microcirculatory changes and evaluating surgical outcomes in TAO.

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Disclosure of conflict of interest

None.

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