Chapter

Optical Coherence Tomography in Strabismus: Innovations and Clinical Applications

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Abstract

Strabismus, a visual disorder involving eye misalignment, presents significant diagnostic and treatment challenges. Optical coherence tomography (OCT) has transformed the management of strabismus by providing high-resolution imaging of ocular tissues, which aids in accurate diagnosis and management. Continuous advancements in OCT technology, including anterior segment OCT (AS-OCT) and OCT-angiography (OCT-A), enhance preoperative planning, postoperative monitoring, and evaluation of associated conditions such as thyroid ophthalmopathy and amblyopia. This chapter aims to provide a comprehensive overview of OCT's role in strabismus management, highlight technological advancements, and discuss the integration of OCT tools in clinical practice. It will explore current research trends and future directions in the application of OCT for strabismus and amblyopia.

Keywords: anterior segment OCT, clinical applications, ocular imaging, OCT-angiography, optical coherence tomography, strabismus, amblyopia

1. Introduction

1.1 Overview of strabismus

1.1.1 Definition and types

Strabismus, commonly known as "crossed eyes" or "squint," is a condition where the eyes do not properly align with each other when looking at an object. Strabismus, or misalignment of the eyes, can be classified based on several key factors. Heterophoria is a latent misalignment, while heterotropia is a visible, consistent deviation. Ocular alignment refers to proper positioning of the eyes, with deviations such as esotropia (inward), exotropia (outward), hypertropia (upward), and hypotropia (downward). Comitant strabismus involves a constant angle of deviation in all gaze directions, whereas incomitant strabismus varies depending on gaze direction, often due to muscle weakness or paralysis. Strabismus can be constant or intermittent, depending on whether the deviation is always present or occurs only under specific conditions. Vergence classifications describe the difference in alignment at near or far distances, with conditions such as

convergence excess or divergence insufficiency. Fixation habits also play a role, distinguishing between nonalternating (one eye always fixates) and alternating strabismus (both eyes alternate). The onset of strabismus can be congenital (present at birth) or acquired later in life, influenced by trauma, nerve issues, or other conditions. Paralytic strabismus occurs when there is nerve damage affecting the extraocular muscles, leading to a loss or reduction in muscle function. Restrictive (mechanical) strabismus results from structural abnormalities, such as muscle fibrosis or scarring, that physically restrict normal eye movement. Orbital strabismus arises from anatomical abnormalities in the orbit or surrounding facial structures, such as craniofacial dysostosis or hydrocephalus, which cause the eyes to misalign due to altered bone or tissue structures [1].

1.1.2 Epidemiology and prevalence

Strabismus affects around 3–4% of the population, making it one of the most common visual disorders in both children and adults [2]. It can occur at any age, though it often manifests in early childhood. In congenital cases, the incidence is reported to be higher, with esotropia being more common than exotropia in these early cases. However, in some populations, exotropia may be more prevalent, particularly in Asia and other regions.

In terms of gender distribution, no significant gender predilection exists for strabismus as a whole [3]. However, some studies have shown that specific types of strabismus, such as intermittent exotropia, may occur slightly more frequently in females in certain demographics [4].

1.1.3 Clinical significance and impact on patients

Strabismus is not merely a cosmetic concern; it can significantly affect visual function and quality of life. Amblyopia, commonly known as "lazy eye," is a frequent complication, occurring when the brain suppresses the image from the misaligned eye, leading to reduced vision in that eye. Strabismus can also impair binocular vision, affecting depth perception and leading to issues with coordination and spatial awareness.

The psychosocial impact of strabismus on patients, especially children, can be profound [5]. Children with noticeable eye misalignment may face social stigma, bullying, and self-esteem issues. In adults, strabismus can impact professional and social interactions, leading to difficulties in maintaining eye contact or performing tasks requiring precise vision, such as driving or reading. Early detection and intervention are critical in preventing long-term complications, especially in children, where therapies such as patching or strabismus surgery can significantly improve outcomes.

1.1.4 Extraocular muscles: Location and functions

Strabismus is closely linked to the function and coordination of the extraocular muscles that are responsible for controlling eye movements. There are six extraocular muscles in each eye that work in unison to move the eye in different directions. These muscles are innervated by three cranial nerves: the oculomotor nerve (cranial nerve III), the trochlear nerve (cranial nerve IV), and the abducens nerve (cranial nerve VI).

1. The medial rectus is located on the inner (nasal) side of the eye. Its primary function is to move the eye inward toward the nose (adduction). It is innervated

by the oculomotor nerve (cranial nerve III), and its insertion point is approximately 5.5 mm from the limbus.

2. The lateral rectus, positioned on the outer (temporal) side of the eye, moves the eye outward, away from the nose (abduction). It is innervated by the abducens nerve (cranial nerve VI) and inserts approximately 6.9 mm from the limbus.

3. The superior rectus is located on the top of the eye. It primarily elevates the eye (moves it upward), with the additional roles in slight inward rotation (intorsion) and inward turning (adduction). This muscle is innervated by the oculomotor nerve (cranial nerve III), and it inserts approximately 7.7 mm from the limbus.

4. The inferior rectus is situated on the bottom of the eye. It primarily depresses the eye (moves it downward), while also contributing to slight outward rotation (extorsion) and inward turning (adduction). It is also innervated by the oculomotor nerve (cranial nerve III), and its insertion point is approximately 6.5 mm from the limbus.

5. The superior oblique originates at the back of the eye socket, loops through the trochlea (a pulley-like structure), and attaches to the top of the eyeball. Its primary function is to move the eye downward and outward (depression and abduction), with an additional role in inward rotation (intorsion). It is innervated by the trochlear nerve (cranial nerve IV). The superior oblique does not insert directly near the limbus but functions through the trochlea system.

6. The inferior oblique originates from the front part of the orbital floor and runs beneath the eye, attaching to the bottom of the eyeball. It primarily elevates the eye and moves it outward (elevation and abduction), while also causing outward rotation (extorsion). The muscle is innervated by the oculomotor nerve (cranial nerve III) and, like the superior oblique, does not have a direct insertion near the limbus.

1.1.5 Coordination of eye movements and strabismus

For normal binocular vision, the extraocular muscles must work in a highly coordinated fashion to align both eyes on the same target. The movements of both eyes must be synchronized, allowing them to track objects, focus, and move in parallel across different directions of gaze. This coordination is controlled by the brainstem and cerebellum that process information from the visual system and the vestibular system (balance and spatial orientation). When the extraocular muscles do not work together properly or if there is an issue with the cranial nerves supplying these muscles, strabismus occurs. Understanding the function and anatomy of these muscles is essential in diagnosing and managing different forms of strabismus.

1.2 Optical coherence tomography (OCT)

1.2.1 History and development of OCT

Optical coherence tomography (OCT) is a non-invasive imaging technique that provides high-resolution cross-sectional images of biological tissues. It was first introduced in the early 1990s by a group of researchers led by Dr. David Huang and

Dr. James Fujimoto at the Massachusetts Institute of Technology (MIT) [6]. Initially developed for use in ophthalmology, OCT has since expanded into other medical fields, including cardiology, dermatology, and oncology.

The early versions of OCT, such as time-domain OCT (TD-OCT), provided foundational advancements by allowing the visualization of retinal layers in unprecedented detail. However, its relatively slow acquisition speed and limited resolution prompted the development of newer technologies. In the early 2000s, the introduction of spectral-domain OCT (SD-OCT) revolutionized the field. By utilizing Fourier transformation of interference patterns, SD-OCT significantly improved image resolution and acquisition speed. More recently, the development of swept-source OCT (SS-OCT) has further enhanced depth penetration and speed, allowing for more detailed imaging of deeper structures, such as the choroid and the optic nerve head.

1.2.2 Basic principles and technology

OCT is based on the principle of low-coherence interferometry. It works similar to ultrasound, but instead of sound waves, OCT uses light waves (typically near-infrared light) to generate images. The system directs a beam of light onto the tissue, and the light that reflects back from different layers of the tissue is captured. By measuring the time delay and intensity of the reflected light, OCT creates a detailed, cross-sectional image of the tissue.

The light used in OCT has a short coherence length, which allows it to achieve high axial resolution, typically on the order of microns (micrometers). The resolution depends on the wavelength and bandwidth of the light source, and OCT can differentiate between various layers of the retina, from the inner-limiting membrane to the retinal pigment epithelium (RPE). The depth and resolution make it particularly suitable for diagnosing and managing retinal diseases.

Modern OCT devices employ spectral-domain or swept-source technologies to capture images rapidly and with high resolution. SD-OCT uses a broadband light source and a spectrometer to detect light reflected at different depths simultaneously, while SS-OCT employs a tunable laser and a photodetector to scan the tissue, providing enhanced penetration and faster imaging [7].

1.2.3 Advantages of OCT in ophthalmology

OCT has revolutionized ophthalmology, particularly in the diagnosis and management of retinal and optic nerve diseases. Its advantages include the following:

1. Non-invasive and fast: OCT provides high-resolution images without the need for any contact with the eye or use of contrast agents. Imaging can be completed within seconds, making it highly convenient for both patients and clinicians.

2. High-resolution imaging: The ability to visualize retinal layers in great detail allows clinicians to detect and monitor subtle structural changes, which is especially valuable for early diagnosis and treatment of diseases such as macular degeneration, diabetic retinopathy, and glaucoma.

3. Quantitative analysis: OCT not only provides images but also offers precise quantitative measurements, such as retinal thickness, nerve fiber layer thickness, and

the size of macular lesions. These measurements help track disease progression and response to treatments.

4. Real-time monitoring: OCT allows for real-time imaging, enabling immediate assessment of therapeutic interventions, such as in cases of retinal laser therapy or intravitreal injections.

5. Wide range of applications: While initially developed for retinal imaging, OCT has applications in anterior segment imaging, corneal disease assessment, glaucoma management, and strabismus and even in surgical planning. Its versatility makes it a valuable tool in comprehensive ophthalmic care.

6. Guidance in clinical decision making: OCT has become indispensable in clinical practice for its ability to guide treatment decisions. For example, it is essential in determining the need for anti-VEGF (vascular endothelial growth factor) therapy in patients with neovascular age-related macular degeneration (AMD) or diabetic macular edema (DME).

2. Clinical applications of OCT in strabismus

2.1 Assessment of extraocular muscles, retinal, and optic nerve changes

OCT has become an indispensable tool in the evaluation of various ocular structures and conditions. In the context of strabismus, OCT plays a crucial role in assessing the health and integrity of extraocular muscles, the macula, and the retinal nerve fiber layer (RNFL), offering valuable insights into both functional and structural changes in the eye.

2.1.1 Extraocular muscles

While OCT is primarily used for imaging the retina and anterior segment, it has also been applied to assess extraocular muscles, especially in cases of strabismus (**Figure 1**). Imaging the extraocular muscles can provide valuable information about their structure, size, and possible atrophy or hypertrophy, which is crucial in the diagnosis and management of strabismus. In patients with strabismus, abnormalities in extraocular muscles may contribute to or result from the misalignment. For instance, in thyroid eye disease, extraocular muscle enlargement is common and may exacerbate or even cause strabismus due to muscle fibrosis or restrictions. In these cases, OCT can offer adjunctive imaging when combined with MRI or CT to provide a detailed assessment of muscle changes. Although OCT's ability to directly visualize the extraocular muscles is limited, its value lies in its ability to complement other imaging modalities for a comprehensive evaluation of strabismus cases involving muscle pathology.

2.1.2 Macular evaluation

Macular assessment with OCT is critical in patients with strabismus, especially in those with long-standing or untreated strabismus. The macula is responsible for central vision, and any abnormalities or misalignments in the eye can lead to macular

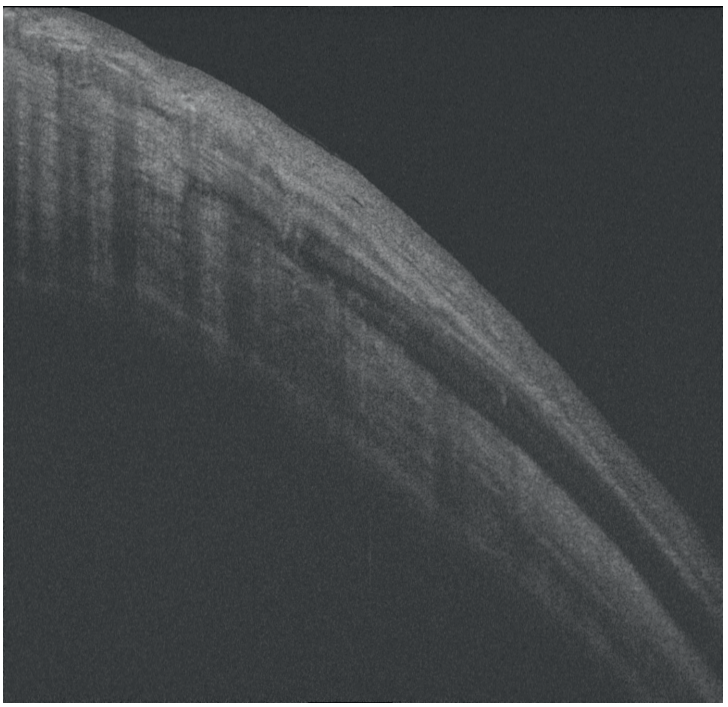


Figure 1.
Anterior segment optical coherence tomography (AS-OCT) image showing the cross-sectional view of the extraocular muscle insertion site. The image illustrates the muscle-tendon interface in the scleral region, highlighting the thickness, structural integrity, and anterior insertion point of the muscle.

changes over time. In patients with strabismic amblyopia, OCT can reveal subtle macular abnormalities, such as thinning or thickening of the retinal layers, which may not be detectable through clinical examination alone. Additionally, the presence of macular pathology, such as macular edema or macular holes, may affect the treatment plan for patients with strabismus, particularly in surgical planning. Preoperative OCT evaluation of the macula ensures that any underlying retinal pathology is addressed, optimizing the outcomes of strabismus surgery (**Figure 2**).

Optical coherence tomography angiography (OCTA) is a non-invasive imaging technique that allows detailed visualization of retinal and choroidal blood flow. It captures high-resolution images of the microvasculature, making it invaluable in diagnosing and monitoring various eye conditions. Preoperative and postoperative changes in the vascular network can also be evaluated by using OCT angiography (**Figure 3**).

Amblyopia, particularly in children, can lead to changes in the macular structure. OCTA has proven valuable in examining the microvascular changes associated with amblyopia, often present in patients with strabismus. In a study involving amblyopic children, OCTA revealed a larger foveal avascular zone (FAZ) in amblyopic eyes compared to non-amblyopic eyes. This was associated with reduced vessel density, suggesting that amblyopia may involve not just functional impairment but also structural changes in the retinal vasculature [8]. In another study involving 32 children with anisometropic myopic amblyopia, OCTA was used to assess changes in vessel density (VD) before and after treatment. Results showed significant improvements in visual acuity and VD, suggesting that OCTA is not only useful in evaluating treatment efficacy but also in tracking progress during amblyopia management and follow-up care [9].

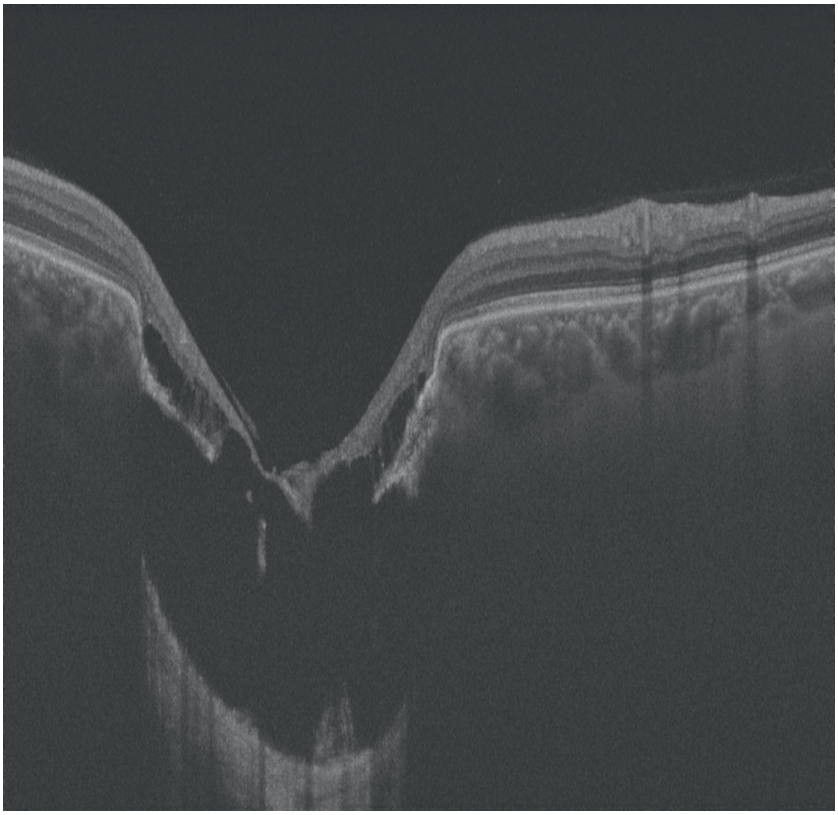


Figure 2.
Preoperative optical coherence tomography (OCT) image of the right eye showing macular scar. The scan highlights the scarring in the macular region, which is associated with reduced visual acuity in the affected eye. The patient is scheduled for surgery due to esotropia related to the visual impairment on the scarred side. The OCT image provides detailed information about the extent and location of the scar tissue.

2.1.3 Retinal nerve fiber layer analysis

OCT's ability to assess the RNFL is another valuable application in patients with strabismus. The RNFL consists of ganglion cell axons that form the optic nerve, and any damage to this layer can lead to visual impairment. OCT provides a non-invasive way to measure the thickness of the RNFL, allowing for the detection of early glaucomatous changes or optic neuropathies, In patients with strabismus, especially those with associated conditions such as optic nerve hypoplasia. RNFL analysis can help monitor the health of the optic nerve. RNFL thinning may indicate optic nerve atrophy or damage, which can affect both the treatment plan and prognosis. Additionally, in cases of congenital strabismus or amblyopia, OCT-based RNFL analysis provides insight into any subclinical optic nerve changes that could contribute to the visual dysfunction. Overall, RNFL analysis through OCT offers a detailed evaluation of optic nerve health, complementing the clinical assessment of visual function and aiding in the management of complex strabismus cases where optic nerve involvement is suspected. Patients with high myopia often present with tilted optic discs, which can complicate the diagnosis and management of associated strabismus. A study using spectral-domain OCT (SD-OCT) developed a new method for quantifying the tilt

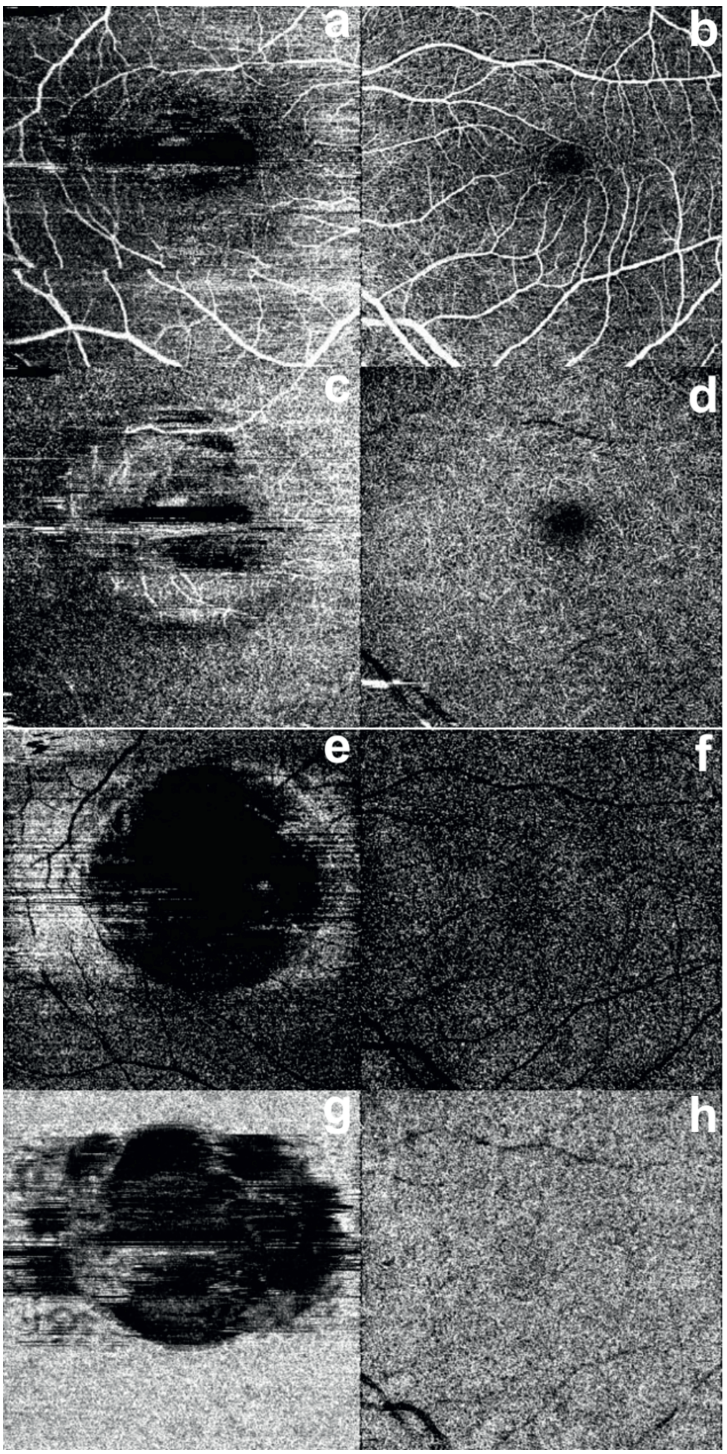


Figure 3.
OCT angiography (OCTA) images of the same patient's right and left eyes, respectively, displaying the superficial plexus (a, b), deep plexus (c, d), outer retina (e, f), and choriocapillaris (g, h). Preoperative and postoperative changes in the vascular network can also be evaluated by using OCT angiography (OCTA). In the right eye, however, shadowing caused by scar tissue is observed across all layers, making the evaluation insufficient.

angle of the optic disc. This method revealed that patients with high myopia and a greater optic disc tilt angle also had significant thinning of the RNFL, a finding that could predispose them to glaucoma [10].

2.2 Preoperative assessment

2.2.1 Identifying structural abnormalities including challenging cases like trauma and thyroid ophthalmopathy

OCT is an invaluable tool in the preoperative assessment of patients undergoing strabismus surgery, particularly in complex cases where structural abnormalities may affect surgical outcomes. By providing detailed cross-sectional images of ocular tissues, OCT helps identify hidden or subtle anatomical issues that may not be apparent during a routine clinical examination (**Figure 4**). In patients requiring reoperations for strabismus, particularly those with previous surgeries where muscle position data is no longer available, anterior segment OCT (AS-OCT) provides a highly effective way to localize extraocular muscles. A study involving 35 horizontal rectus muscles showed that AS-OCT was accurate in determining the distance between the muscle insertion and the limbus, matching intraoperative caliper measurements with a high level of agreement [11].

1. Trauma: In cases of ocular trauma, OCT is critical for evaluating both anterior and posterior segment structures before surgery. Traumatic injuries can affect multiple layers of the eye, including the cornea, lens, retina, and optic nerve. OCT can detect retinal tears, macular edema, or subclinical retinal detachment, ensuring that these issues are addressed before surgical correction of strabismus. Trauma-related changes, such as scarring or fibrosis of the extraocular muscles, may also complicate the surgical approach, making detailed imaging essential

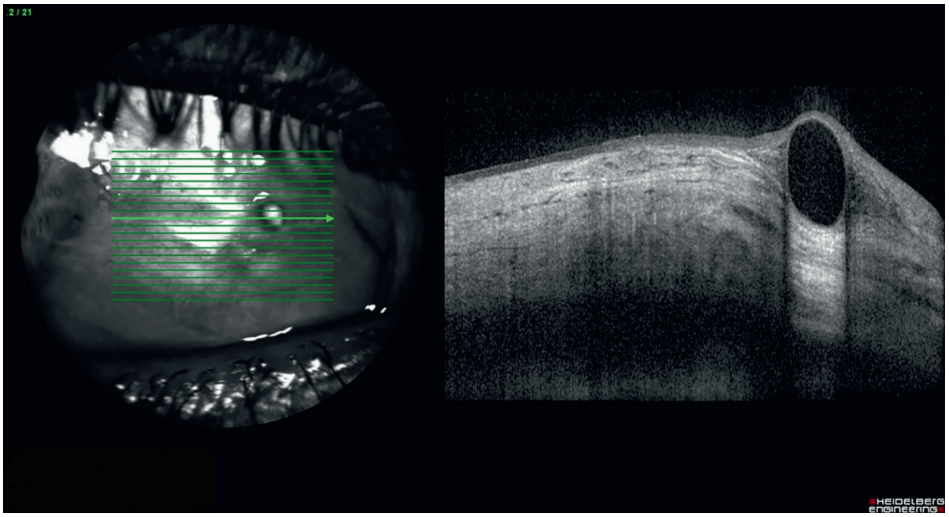


Figure 4.
Preoperative anterior segment OCT (AS-OCT) image of a patient with a history of strabismus surgery performed years ago, for which detailed surgical information is unavailable. The image reveals an inclusion cyst consistent with the possible site of the previous surgical intervention located at the region corresponding to the medial rectus muscle.

for planning. A study highlights the utility of anterior segment optical coherence tomography (AS-OCT) in managing cases of strabismus, particularly in reoperations, muscle hypoplasia, and detecting lost or slipped muscles. AS-OCT is also valuable in ocular trauma, identifying foreign bodies in extraocular muscles and differentiating their material composition. Although limited to visualizing anterior muscle segments, AS-OCT is useful in confirming muscle injury and preventing the need for MRI in some cases [12].

2. Thyroid ophthalmopathy (Graves' orbitopathy): Patients with thyroid ophthalmopathy often present with restrictive strabismus due to enlargement and fibrosis of the extraocular muscles. Preoperative OCT can assist in evaluating the integrity of the optic nerve and macula, which may be compressed by swollen orbital tissues. This is particularly important in preventing optic neuropathy, a potential complication of thyroid eye disease. Identifying early signs of optic nerve compression or macular changes *via* OCT allows for timely intervention and adjustment of surgical plans to minimize postoperative complications. Moreover, OCT can provide complementary imaging to orbital imaging techniques such as MRI and CT, especially for evaluating extraocular muscle involvement and ruling out optic nerve involvement, particularly in severe cases of thyroid ophthalmopathy. The integration of OCT findings with other imaging modalities ensures a holistic preoperative evaluation of these complex cases. In a study involving retinal perfusion variations in thyroid-associated ophthalmopathy (TAO) patients, OCT and OCTA were used to evaluate key parameters, including the FAZ and macular perfusion density (mPD). The study found that active TAO patients exhibited the lowest mPD and significant differences in retinal perfusion across stages. These findings highlight the potential of OCT and OCTA in noninvasively detecting peripapillary and macular changes, making them valuable tools for monitoring TAO progression and assessing disease severity [13].

In a study investigating extraocular rectus muscle tendons in patients with Graves' ophthalmopathy using OCT, researchers measured the medial and lateral rectus tendon thicknesses in healthy controls and patients with both inactive and active Graves' ophthalmopathy. Results showed that patients with Graves' ophthalmopathy had thicker rectus tendons compared to controls, and active disease was associated with thicker tendons than inactive disease. OCT was found to be an effective tool for assessing tendon thickness, correlating with clinical activity scores of the disease [14]. In a study evaluating the impact of conjunctiva and Tenon's capsule thickness (CTT) on strabismus surgery outcomes, researchers used swept-source anterior segment optical coherence tomography (AS-OCT) to measure the preoperative and postoperative CTT. The results revealed increased CTT on the resection side and decreased CTT on the recession side 1 year after surgery. The study also found that the corrective effect of surgery was closely correlated with preoperative CTT on the recession side, suggesting that CTT could serve as a valuable prognostic factor in strabismus surgery outcomes [15].

2.2.2 Surgical planning and customization

OCT has significantly enhanced the precision of surgical planning in strabismus cases by offering detailed insights into ocular structures. In complex cases, such as those involving trauma or restrictive strabismus, OCT enables surgeons to customize their approach to the unique anatomical characteristics of each patient.

1. Corneal topography and anterior segment imaging: In cases where anterior segment abnormalities are present, such as in trauma or post-surgical corneal scarring, OCT provides high-resolution images of the cornea and anterior chamber. This can be crucial in avoiding corneal complications during surgery and ensuring that any pre-existing anterior segment pathology does not interfere with the surgical correction of strabismus.

2. Posterior segment assessment: Preoperative OCT of the posterior segment allows for careful assessment of the retina and optic nerve, both of which are essential for visual function. In patients with previous retinal surgery, macular diseases, or optic neuropathy, OCT can help in predicting the visual outcomes of strabismus surgery. For example, patients with pre-existing macular pathology may have limited visual recovery postoperatively, and this information is vital for setting realistic expectations for both the surgeon and the patient. It is also useful in demonstrating pathologies associated with high myopia (**Figure 5**).

3. Customization of surgical approach: OCT also plays a role in tailoring the surgical technique based on the individual patient's anatomy. In cases of reoperation, OCT is useful for detecting scar tissue or muscle slippage, which may

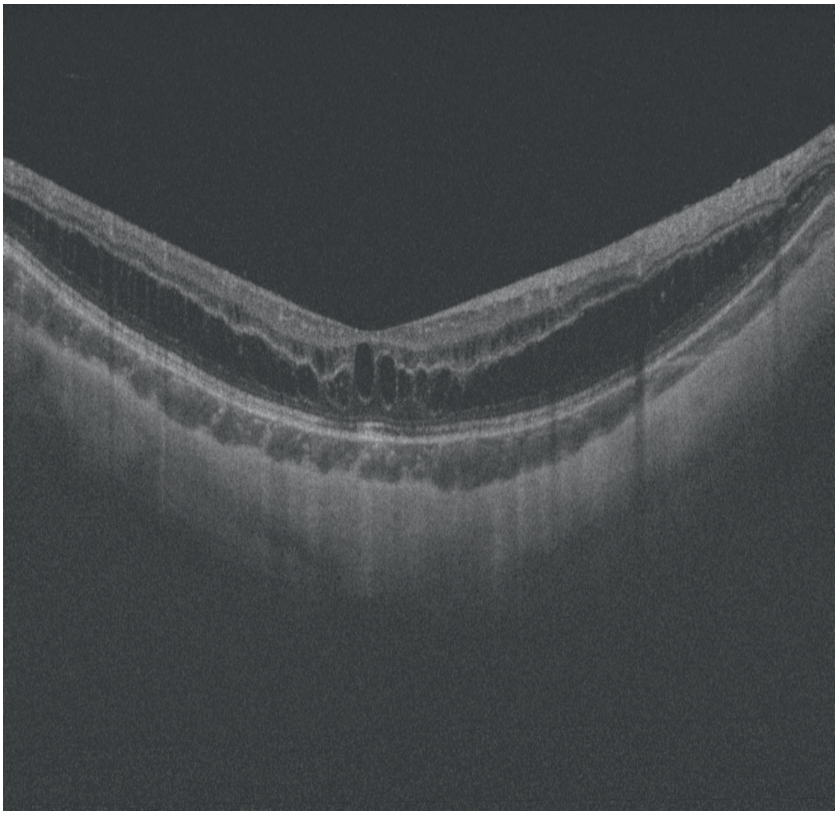


Figure 5.
Optical coherence tomography (OCT) image of the macula in a child with myopic macular retinoschisis. The scan reveals intraretinal splitting, with visible schisis cavities predominantly in the outer retinal layers.

require a more customized surgical approach. In a prospective observational study, the role of swept-source anterior segment optical coherence tomography (SS-ASOCT) in extraocular muscle imaging was evaluated in 150 subjects, covering 1104 extraocular muscles. The study included normal eyes, re-operated eyes, paralytic and non-paralytic strabismus, post-traumatic strabismus, and eyes with thyroid disease. The mean age of the subjects was 38.15 ± 16.25 years, and muscle insertion was identified in over 90% of cases. SS-ASOCT provided clinically valuable information by imaging the anterior 4–14 mm of the rectus muscles, facilitating optimal preoperative surgical planning. The tool proved especially useful in complex cases, such as traumatic muscle slippage and thyroid muscle hypertrophy, making it a reliable aid in surgical decision-making for various strabismic conditions [16].

OCT's ability to provide detailed structural images enhances preoperative planning by identifying hidden anatomical challenges and optimizing the surgical approach. This results in better patient outcomes, particularly in complex and high-risk cases where precise anatomical information is critical.

2.3 Intraoperative use: Intraoperative optical coherence tomography (iOCT)

2.3.1 Real-time imaging and guidance

The advent of intraoperative optical coherence tomography (iOCT) has marked a significant advancement in ophthalmic surgery, offering real-time, high-resolution imaging during surgical procedures. iOCT integrates OCT technology into the surgical microscope, allowing surgeons to visualize ocular structures in cross section without interrupting the surgery. This real-time imaging capability is particularly beneficial in strabismus surgery, where precise manipulation of delicate ocular tissues is crucial.

In strabismus surgery, iOCT can assist in several ways:

1. Visualization of tissue planes: iOCT provides detailed images of the sclera, Tenon's capsule, conjunctiva, and extraocular muscles. Real-time imaging helps in identifying the exact location and depth of tissues, which is essential for precise dissection and minimizing tissue damage. iOCT has brought a new level of precision to strabismus surgeries, especially in cases where tissue manipulation is complex. One study demonstrated the utility of iOCT during scleral suturing in strabismus surgeries, allowing the surgeon to visualize scleral passes in real time. This reduced the risk of deep scleral penetration or muscle misplacement, which are common causes of surgical failure in strabismus correction. iOCT ensured the precise positioning of extraocular muscles, particularly in reoperations where scarring made anatomical landmarks less visible [17].

2. Assessment of extraocular muscle insertion and pathology: During surgery, iOCT can help visualize the insertion points of extraocular muscles on the sclera. This is particularly useful in reoperations or complicated cases where scar tissue or previous surgical alterations may obscure normal anatomical landmarks. iOCT aids in identifying residual muscle tissue and any anomalous insertions or pathologies.

3. Guidance in complex cases: In cases involving restrictive strabismus, such as in thyroid ophthalmopathy or scarring from trauma, iOCT assists in visualizing fibrotic tissues and adhesions. This guidance allows for careful dissection and release of restrictive tissues, reducing the risk of inadvertent damage to surrounding structures.

4. Verification of surgical manipulations: Surgeons can use iOCT to confirm the success of muscle recessions, resections, or transpositions intraoperatively. By imaging the surgical site immediately after manipulation, any adjustments can be made on the spot, enhancing the overall outcome of the surgery.

2.3.2 Enhancing surgical precision

iOCT enhances surgical precision by providing unparalleled visualization of ocular structures at a microscopic level. This precision translates into several clinical benefits:

1. Improved outcomes: Precise surgical manipulations reduce the likelihood of residual strabismus postoperatively. iOCT allows for exact measurements and positioning of extraocular muscles, which is critical for achieving optimal ocular alignment.

2. Reduced complications: By enabling surgeons to see beneath the surface tissues, iOCT helps in avoiding inadvertent damage to underlying structures such as the sclera or intraocular contents. This is especially important when operating near thin scleral areas or previous surgical sites. In complex strabismus cases, especially those involving previous surgeries where the risk of muscle slippage is high, iOCT proved essential. In one example, examining the use of OCT for imaging rectus muscle insertions in pediatric strabismus patients, OCT was employed pre-, intra-, and post-operatively. The study compared OCT measurements with intraoperative caliper measurements, demonstrating moderate-to-good correlation. OCT proved valuable in managing strabismus, particularly in cases where muscle insertions were unclear due to previous surgeries. The use of intraoperative OCT helped enhance surgical precision, providing significant implications for improving outcomes in strabismus surgery [18].

3. Customization of surgical techniques: Each patient's anatomy can present unique challenges. iOCT allows surgeons to tailor their techniques in real time based on the intraoperative findings. For example, if iOCT reveals thinner-than-expected sclera, the surgeon might modify the placement of sutures or the extent of muscle manipulation to prevent complications like scleral perforation.

4. Educational tool: iOCT serves as an excellent educational resource for training surgeons. Real-time imaging provides immediate feedback on surgical techniques and tissue responses, facilitating learning and skill development.

5. Documentation and evaluation: Intraoperative images can be saved for postoperative analysis and documentation. This can be valuable for assessing surgical techniques and outcomes, and for medico-legal purposes.

2.3.3 Integration with surgical microscopes and navigation systems

Modern surgical microscopes equipped with iOCT seamlessly integrate imaging into the surgeon's field of view. Some systems offer heads-up displays or augmented reality overlays, allowing surgeons to see OCT images without diverting their attention from the surgical field. Additionally, combining iOCT with surgical navigation systems enhances the surgeon's ability to plan and execute precise maneuvers.

2.3.4 Limitations and future directions

While iOCT offers significant advantages, there are limitations to consider:

1. Learning curve: Surgeons must become accustomed to interpreting OCT images intraoperatively and integrating this information into their surgical decision-making process.

2. Equipment costs: The implementation of iOCT requires significant investment in specialized equipment, which may not be readily available in all surgical centers.

3. Tissue penetration: OCT imaging depth is limited, which may restrict visualization in certain cases with dense fibrosis or opacification. Future advancements may address these limitations through enhanced imaging technologies, improved user interfaces, and more widespread availability of iOCT systems.

2.4 Postoperative monitoring

2.4.1 Evaluating surgical outcomes and effects on ocular structures

Postoperative monitoring with OCT plays a pivotal role in assessing the outcomes of strabismus surgery and evaluating the effects on ocular structures. Anterior segment ischemia is a rare but serious complication of strabismus surgery. In one case, OCTA was used to monitor iris vasculature post-surgery, revealing early signs of ischemia in a patient who had undergone two rectus muscle recessions. The ability of OCTA to detect these subtle changes in blood flow allowed the surgical team to intervene early, preventing further complications and preserving visual function [19]. OCT provides high-resolution images that allow clinicians to visualize changes in both the anterior and posterior segments of the eye following surgical intervention.

1. Extraocular muscle assessment: After strabismus surgery, it is essential to ensure that the extraocular muscles are correctly positioned and functioning as intended. While OCT primarily focuses on the retinal and optic nerve structures, its indirect benefits include monitoring how well the eyes are aligned postoperatively by observing the overall functional outcomes and any secondary effects on the posterior segment.

2. Retinal and macular evaluation: OCT is crucial for detecting any changes in the retina, particularly the macula, following strabismus surgery. Strabismus can have long-term effects on retinal structures, especially in patients with amblyopia or pre-existing retinal conditions. OCT allows for the precise measurement

of macular thickness, providing insights into whether surgical realignment has contributed to improvements in visual function. In cases where strabismus surgery may inadvertently affect intraocular structures, OCT helps identify any adverse effects, such as retinal edema, subclinical retinal detachment, or macular changes. By assessing these postoperative retinal changes, clinicians can make timely interventions to prevent further complications. Postoperatively, monitoring retinal and choroidal blood flow can provide valuable insights into the healing process and long-term ocular health. In a study evaluating horizontal rectus muscle surgeries, OCTA was used to measure changes in vessel density and choroidal thickness. The results showed a significant increase in vessel density in the superficial capillary plexus (SCP) and choriocapillaris (CC) in the first week post-surgery. This indicated a transient increase in blood flow in the retina and choroid, which was normalized by 1-month post-surgery [20]. Another study compared single- and two-muscle surgeries using OCTA. Patients who underwent two-muscle surgeries exhibited more significant changes in retinal vessel density than those who had only one muscle operated on. This was particularly evident in the parafoveal region, where vessel density increased in the early postoperative period. These findings suggest that more extensive strabismus surgeries may lead to greater hemodynamic changes in the retina, requiring closer monitoring with OCTA [21].

3. Optic nerve evaluation: Although rare, strabismus surgery could have indirect effects on the optic nerve, especially in cases involving significant ocular manipulation or trauma. OCT enables the monitoring of the RNFL, helping to detect any early signs of optic nerve damage or atrophy, which may not be evident through clinical examination alone.

2.4.2 Long-term follow-up and prognosis

Long-term follow-up with OCT is essential in ensuring that the benefits of strabismus surgery are maintained over time and that any potential complications are addressed promptly. Postoperative OCT scans allow for continuous monitoring of ocular structures, offering valuable data on the stability of the surgical outcome. (1) Monitoring for recurrence or overcorrection: Strabismus surgeries may, in some cases, lead to overcorrection or recurrence of the initial misalignment. OCT can help track the functional success of the surgery and guide decisions for further corrective procedures, if needed. (2) Prognosis and visual recovery: In cases where strabismus surgery is performed on patients with associated conditions such as amblyopia, thyroid ophthalmopathy, or optic neuropathy, OCT plays a significant role in monitoring the long-term prognosis. For instance, visual improvements post-surgery may depend on the health of the retinal layers and optic nerve. OCT imaging allows for objective measurements of these structures, helping to predict long-term visual outcomes. (3) Detecting late complications: Some patients may develop late complications following strabismus surgery, including retinal detachment, macular edema, or optic nerve changes. OCT provides an ongoing monitoring tool to detect these complications early and ensure that they are managed before they result in significant vision loss. By integrating OCT into long-term postoperative care, clinicians can ensure comprehensive monitoring of both the functional and anatomical outcomes of strabismus surgery, enhancing overall patient prognosis.

3. Summary of key points

OCT and OCTA have revolutionized strabismus management, providing critical insights at each stage—preoperative, intraoperative, and postoperative. AS-OCT offers precise localization of extraocular muscles, improving surgical planning and outcomes, especially in reoperations and trauma cases. Intraoperative OCT enhances surgical precision by offering real-time feedback, minimizing complications. Postoperatively, OCTA helps monitor retinal and choroidal changes, providing early detection of issues such as ischemia and abnormal healing. OCT and OCTA also contribute significantly to the management of amblyopia, revealing vascular changes such as an enlarged FAZ in amblyopic eyes, and evaluating optic disc and retina in myopic patients.

4. Future outlook

The integration of AI with OCT, advancements in OCTA technology, and the potential for long-term monitoring of retinal health are expected to further enhance the role of OCT in strabismus management. As these technologies evolve, they will likely improve the precision and outcomes of surgeries while offering better diagnostic tools for related conditions such as amblyopia and myopia.

5. Conclusions

OCT and OCTA have become essential tools in strabismus management, offering precise preoperative planning, real-time intraoperative guidance, and effective postoperative monitoring. These technologies improve surgical precision, reduce complications, and provide valuable insights into retinal and choroidal changes. OCT and OCTA also enhance the diagnosis and treatment of related conditions such as amblyopia and myopia. As these imaging technologies continue to evolve, they promise to further optimize strabismus management, ultimately improving patient outcomes and care.

Despite their significant advantages, these technologies require both user expertise and interpreter experience, which can limit their effectiveness in centers with insufficiently trained staff. Additionally, patient cooperation plays a crucial role in obtaining accurate images. This poses a particular challenge in pediatric age groups and in patients with conditions such as restricted eye movements or nystagmus, where involuntary eye movements can lead to difficulties in imaging. Furthermore, patients with poor cooperation may result in suboptimal image quality or incomplete scans. Another important limitation is the high cost of those devices, which can be prohibitive for many centers, especially in resource-limited settings. The lack of accessibility in some institutions restricts the widespread use of these technologies.

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Conflict of interest

The author declares no conflict of interest.

Nomenclature

OCT	optical coherence tomography
AS-OCT	anterior segment optical coherence tomography
iOCT	intraoperative optical coherence tomography
OCTA	optical coherence tomography angiography
RNFL	retinal nerve fiber layer
FAZ	foveal avascular zone
VEGF	vascular endothelial growth factor
SCP	superficial capillary plexus
CC	choriocapillaris
Scleral Pass	a surgical technique involving the placement of sutures through the sclera during strabismus surgery

Appendix

In this chapter, we explored the detailed role of optical coherence tomography (OCT) in the assessment, surgical planning, and postoperative monitoring of strabismus. We covered the application of different OCT techniques including anterior segment OCT (AS-OCT), intraoperative OCT (iOCT), and OCT angiography (OCTA). We also included several references demonstrating how these technologies are employed in real-life scenarios, providing valuable insights into extraocular muscle assessment, retinal and macular changes, and optic nerve evaluation and the utility of OCT in trauma-induced strabismus, thyroid ophthalmopathy, and amblyopia.

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