Review Article - Narrative Review

Taiwan J Ophthalmol 2024;14:497-501

Access this article online

Quick Response Code:

Website: http://journals.lww.com/TJOP

DOI: 10.4103/tjo.TJO-D-24-00078

Advances in intraoperative imaging in retinal diseases: A narrative review

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Abstract:

This review explores recent technological advances in intraoperative imaging during retinal disease surgeries, focusing on their applicability in clinical practice and impact on surgical outcomes. A literature search identified studies discussing new imaging technologies, their advantages over conventional methods, relevant case studies, and literature reviews. Exclusion criteria included studies unrelated to retinal diseases, imaging technologies not suitable for intraoperative use, outdated articles, and nonscientific reports. Significant advancements, particularly with optical coherence tomography (OCT), have transformed retinal surgery by providing high-resolution images and real-time feedback, enhancing surgical precision and patient safety. However, the high costs of these technologies remain a barrier to widespread adoption, despite their potential to set new standards in ophthalmic surgery.

Keywords:

Intraoperative imaging, retinal surgery, optical coherence tomography (OCT), advanced retinal imaging, real-time imaging, intraoperative OCT, high-resolution imaging, retinal surgery technology, imaging technologies in surgery

Introduction

The latest advances in intraoperative imaging for the treatment of retinal diseases include a wide variety of innovative technologies, such as intraoperative optical coherence tomography (OCT), three-dimensional (3D) visualization system, and virtual reality system.[1,2] These advances make it possible to obtain real-time, high-speed, and high-resolution images of the retina, allowing surgeons to effectively monitor surgical procedures and evaluate treatment responses intraoperatively.[3]

In this narrative review, we evaluate the evolution, incorporation, and current evidence on advances in the applicability of OCT in posterior segment ophthalmic surgery and its impact on diagnosis and treatment in real time.

Methods

The studies included were those discussing new intraoperative imaging technologies and their applications in retinal surgery, those comparing new technologies with conventional ones, relevant case studies, and literature reviews. Studies outside the scope of retinal diseases, imaging technologies not applicable intraoperatively, old articles that do not reflect recent advances, and nonscientific articles were excluded.

The following databases were used for the search strategy: PubMed, Embase, Scopus, Web of Science, and ResearchGate, with the keywords: "Intraoperative Retinal Optical Coherence Tomography," "Intraoperative imaging," "retinal diseases," "retinal surgery technology," "advances in retinal imaging," "intraoperative OCT," and "real-time retinal imaging" and manual search with the references of the selected articles

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Submission: 05-07-2024
Accepted: 14-10-2024
Published: 20-12-2024

How to cite this article: Rocha J, Fuganti RM, Casella AM. Advances in intraoperative imaging in retinal diseases: A narrative review. Taiwan J Ophthalmol 2024;14:497-501.

to identify additional relevant literature in English from April to May 2024.

Advances in Intraoperative Imaging

Since 1991, intraoperative OCT (iOCT) has evolved into a crucial tool in ophthalmic surgery, enabling surgeons to visualize retinal structures during procedures. This noninvasive technology, using low-coherence interferometry, generates high-resolution tomographic images, offering cross-sectional views of biological tissues that closely mimic histological sections. With iOCT integrated into surgical microscopes, real-time diagnostic imaging during surgery became possible, leading to improved clinical outcomes and fewer surgical complications.[4]

The technologies described [Table 1] highlight recent advances in the field, offering surgical precision and optimization of intraoperative decision-making by allowing real-time detection of subtle changes in retinal structures. These systems have significantly enhanced visualization during complex procedures, particularly for conditions such as epiretinal membranes and proliferative vitreoretinopathy (PVR), enabling the detection of complex retinal changes that were previously difficult to observe. This enhanced visualization during surgery reduces unnecessary maneuvers and minimizes potential retinal damage.[5]

Although iOCT has transformed surgical practices, a limited availability may deter wider adoption. This highlights the need to increase access for the benefits of iOCT to be fully realized in clinical practice situations. Recent advances, including portable OCT and iOCT, are continuously improving the visualization and management of retinal diseases.

Innovations in Optical Coherence Tomography and Intraoperative Optical Coherence Tomography

Binder *et al*. initially adapted OCT and microscopy for use in the posterior segment and cataract surgery.[6] Dayani *et al*. employed a portable device during planned interruptions of surgical procedures in macular surgery,[7] demonstrating its utility in real-time observation of surgery changes in retinal contour and macular hole configuration. Institutions like Duke have further developed prototypes to observe surgery-induced changes in real-time, providing the effectiveness of this integration.[8]

Bioptigen was one of the pioneers in the introduction of portable intraoperative OCT systems, which are flexible

Table 1: Comparison of the main intraoperative optical coherence tomography machines currently available on the market, highlighting their technical characteristics, advantages, and limitations

Device	Type	Features	Advantages	Limitations
RESCAN 700 (Carl Zeiss)	iOCT	Real-time imaging and 3D and 4D volumetric imaging	High precision and improves surgical decision-making and feedback	High cost and limited accessibility
Bioptigen	Portable iOCT	Flexible and easy to integrate in surgeries	Reduces postoperative complications and aids in precise execution	Lower image quality compared to nonportable OCT
NGENUITY (Alcon)	3D imaging system	High-resolution heads-up 3D microscopy	Improved visualization, ergonomic, and no conversion to traditional microscopes	Requires specialized equipment and learning curve for surgeons
ARTEVO 850 (Carl Zeiss)	3D imaging system	Real-time, high-resolution digital microscope for retina surgeries	Enhances precision and accuracy in surgery	Expensive and requires advanced technological infrastructure
Beyeonics One	Reality augmentation system	Headset-controlled, 3D-augmented reality, high magnification, and hand-free control	Advanced real-time visualization and tool manipulation and reduces reliance on traditional microscopes	Limited real-world application data and requires investment in augmented reality technology
Handheld OCT	Portable OCT device	Portability for telemedicine and remote locations	Useful in pediatric, remote, and underserved regions, and easy maneuverability	Lower image quality and difficulty centering scans
SeeLuma	Digital binocular with heads-up display	Integrated with the OCULUS BIOM 5c, automated surgical parameter adjustments	Allows uninterrupted surgery and enhances ease and speed during procedures	High cost and limited widespread use
Cole Eye iOCT System	iOCT	Integrated into surgical microscopes and provides real-time imaging of retinal structures during surgery	Significant impact on decision-making and helps identify subtle retinal details in complex cases	Expensive and limited to advanced surgical centers
Leica EnFocus	iOCT	Microscope-integrated, offers high-resolution tomographic images during surgery	Improves visualization of fine retinal details and increases safety during complex surgeries	High cost, primarily available in specialized centers

OCT=Optical coherence tomography, iOCT=Intraoperative OCT, 3D=Three-dimensional, 4D=Four-dimensional and easy to integrate into the surgical environment. These systems offer unprecedented flexibility for ophthalmologists, greater safety during surgery, and reducing the risk of postoperative complications. The images generated aid in surgical decision-making and precise execution of techniques.[9]

Commercial Systems and Advanced Technologies

The development of commercial systems such as the Zeiss RESCAN 700, combined with advances in real-time 3D and four-dimensional (4D) imaging technologies driven by graphics processing units, has significantly improved feedback during surgery. Innovations such as heads-up display technology and the demonstration of 4D volumetric OCT data offer new perspectives on surgical feedback, highlighting the importance of OCT in the accuracy and safety of contemporary ophthalmic procedures.[8]

Applications of Intraoperative Optical Coherence Tomography

iOCT captures cross-sectional images of the retina layers in real-time, enabling more precise decisions during retina surgery through better visualization of anatomical structures and provides additional information of microarchitecture changes after instrument–tissue interaction[2] iOCT was first adopted by surgeons to view anterior segment structures during anterior segment procedures such as deep anterior lamellar keratoplasty.[10]

In 2014, the Prospective Intraoperative and Perioperative Ophthalmic Imaging with Optical Coherence Tomography study investigated the feasibility, safety, and utility of iOCT in both anterior and posterior segment surgical procedures. This was the first prospective, single-center, consecutive case series study that reported the use of portable iOCT in surgeries involving 275 cases of anterior segment procedures, such as cataract and corneal surgeries, and 256 cases of posterior segment procedures, including vitrectomies for membrane peels in 146 cases. The primary goal was to evaluate how iOCT can inform surgical decision-making and improve the understanding of tissue configurations during surgeries. iOCT was successfully used in 98% of the procedures, and surgeons reported being influenced by iOCT in 43% of vitreoretinal procedures involving membrane peeling surgeries. In 13% of membrane peeling cases where surgeons believed all membranes had been peeled, iOCT revealed residual membrane, influencing the decision to continue peeling.[11]

The DISCOVER study evaluates the feasibility and utility of microscope-integrated iOCT during ophthalmic surgery over 3 years using Zeiss Rescan 700, Leica Enfocus, and Cole Eye iOCT system. This prospective, single-center, multisurgeon case series assesses the impact of iOCT on surgical decision-making and outcomes. Eight hundred and fifty-seven eyes (244 anterior segment and 593 posterior segment) has undergone incisional ophthalmic surgery with iOCT. This study has shown that iOCT influenced surgeon decisions in 29.2% of cases, including the identification of residual membranes, subretinal fluid, and occult retinal breaks.[12]

Parolini *et al*. have shown a real-life setting of iOCT which involves 256 eyes that underwent elective surgery. The results demonstrate high feasibility and utility in wide range of vitreoretinal pathologies. iOCT impacts the surgical outcome in epiretinal membrane and internal limiting membrane (ILM) peeling, reducing the risk of iatrogenic damage. It also demonstrated improvement in the management of complex macula holes, facilitated the precise placement of autologous retina transplants and ILM, and guided the placement of macular bucklers in high myopic eyes. Integrating iOCT into surgical microscopes allows real-time images, enhancing visualization during surgery.[13]

Its primary applications include macular surgeries of the vitreoretinal interface, assessment of the ILM desquamation, differentiation of retinoschisis areas in rhegmatogenous detachments, evaluation of fibrovascular proliferation in tractional retinal detachments, and providing critical information for submuscular surgeries. Despite its benefits, the excessive cost remains a barrier to widespread use.[14]

Handheld Optical Coherence Tomography

Handheld OCT devices are proving to be valuable tools in telemedicine, since they increase portability, allowing for easy maneuverability and positioning as needed, especially useful in pediatric patients and remote or underserved areas.[15,16] The portability of these devices allows for the capture of high-quality images at the patient's care, facilitating the early detection of ocular diseases such as glaucoma and diabetic retinopathy. The images can be transmitted in real-time to ophthalmology specialists, enabling rapid diagnosis and treatment decisions without requiring patient travel. In addition, handheld OCT enables continuous monitoring of chronic eye diseases and promotes collaboration between healthcare professionals, even in regions with limited medical infrastructure. Their practicality makes these devices ideal for use in mobile clinics and by community health workers, thus expanding access to ophthalmic care.[15]

However, it still faces challenges in delivering intraretinal therapy and centering scans on the area of interest due to lower image quality.[16]

Three-dimensional Imaging

3D imaging systems, such as the NGENUITY (Alcon Laboratories, Inc.) and ARTEVO 850 system (Carl Zeiss Meditec, Oberkochen, Germany), offer high-resolution, heads-up 3D microscopy that improves visualization and eye structure resolution. These systems reduce the need for artificial lighting and enhance ergonomics,[2] improving precision, accuracy, and surgical outcomes. Research by Agranat *et al*. and Giansanti *et al*. has shown that these systems are as effective and safe as traditional surgical microscopy.[2,17-19]

In 2010, researchers reported the first vitreoretinal surgery between an optical microscope and a 3D digital screen. Agranat *et al*. described 272 cases using this system in vitreoretinal surgeries using the Alcon NGENUITY digital viewing system, concluding with no complications and no cases converted to the use of a traditional microscope, by describing how safe it was.[18] The NGENUITY uses a high–dynamic range 3D digital camera mounted on a standard surgical microscope. In the study by Giansanti *et al*., a total of 240 patients undergoing surgery with the NGENUITY system were found to have outcomes comparable to those achieved with traditional surgical microscopy in terms of efficacy, safety, and duration of surgery.[19]

The ARTEVO 850 system is another 3D imaging platform integrated with a digital microscope,[12] offering detailed and real-time imaging of vitreoretinal structures during retina surgeries, thereby enhancing precision, accuracy, and surgical outcomes.

The Beyeonics One™ ophthalmic exoscope is an imaging system that allows surgeons to view magnified, 3D images of the surgical field, accessible and controlled by an immersive surgical headset with augmented reality. The optical design provides detailed, sharp, high-magnification images of the surgical field. There are no restrictions on using microscopes and monitors. Head gestures are used to control frequent functions such as focus, zoom, panning, lighting, and overlays.[20] Schwartz *et al*. demonstrated the viability and safety of Beyeonics One by performing vitreoretinal surgery on 36 eyes of 36 individuals undergoing retinal detachment and macular surgery performed by experienced surgeons.[21]

SeeLuma™ is a digital binocular with intuitive user interfaces and a design that allows surgeons to view a heads-up display directly without having to turn their necks. It is possible to combine the OCULUS BIOM 5c with SeeLuma™, automatically adapting parameters such as zoom, focus speed, white balance, image inversion, and pedal layouts, allowing for uninterrupted surgery.[22]

The virtual reality systems are an immersive 3D imaging with a deeper perception during vitreoretinal surgeries by a more realistic view.[2]

Furthermore, the use of a 3D heads-up surgical visualization system has been proven to offer anatomical and functional results comparable to those of conventional microscope surgery in the treatment of various retinal diseases. In addition, a reduction in the amount of lighting required for intraocular surgery has been shown to reduce the risk of phototoxicity.[21]

Integration of Intraoperative Optical Coherence Tomography and Four-dimensional Imaging

The integration of iOCT with 4D imaging technologies represents a significant advancement in ophthalmic surgery. Li *et al*. explored this integration in procedures such as macular hole surgery, subretinal injections, and membrane peeling, highlighting the enhanced surgical precision and outcomes.[23] Shiraki *et al*. demonstrated the first use of iOCT to identify proliferative membranes during vitrectomy for PVR. This integration facilitates the visualization of retinal structures, surgical tools, and tool–tissue interactions with micron-level resolution, which is crucial for high-accuracy procedures.[17]

Such integration facilitates the visualization of retinal structures, surgical tools, and tool–tissue interactions with micron-level resolution, crucial for procedures such as subretinal injections that demand high accuracy and depth perception.[24]

Table 1 shows the comparison of the main iOCT machines currently available on the market, highlighting their technical characteristics, advantages, and limitations.

Conclusions

Advances in intraoperative imaging, particularly the development and integration of OCT and iOCT technologies, have significantly improved the safety, precision, and outcomes of retinal surgeries. Continued innovation and reduction in costs will likely expand the accessibility and application of these advanced imaging systems in ophthalmic surgery.

Data availability statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interests in this paper.

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