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Clinical Utility of Intraoperative Optical Coherence Tomography

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Abstract

Purpose of review—To explore the clinical utility of intraoperative optical coherence tomography (iOCT) for the management of vitreoretinal conditions.

Recent findings—The role of iOCT in guiding surgical decision-making and surgical manipulations during vitreoretinal procedures has been evaluated by multiple studies. This imaging modality is emerging as a valuable asset during procedures for vitreoretinal interface disorders, retinal detachments, submacular surgeries and therapeutics, and in pediatric conditions such as retinopathy of prematurity. iOCT allows the surgeon to assess completion of surgical goals and to directly monitor the architectural impact of instrument-tissue interactions that may correlate with eventual prognosis. The technology has gone through numerous iterations with the eventual goal being the development of a user-friendly, efficient, and integrated system that provides surgeons with “real-time” feedback during ophthalmic surgeries to allow for a comprehensive image-assisted vitreoretinal surgery platform.

Summary—The role of iOCT in ophthalmic surgery has been evolving with the help of ongoing research to define its utility in the operating room and to develop integrative technologies. Advancements in OCT-friendly surgical instrumentation, and in integrative capabilities of this technology may help achieve more widespread adoption of this technology in the vitreoretinal surgical theater. Although the evidence appears clear that this technology impacts surgical decision-making, additional research is needed. However, further research is needed to determine the influence of this technology on overall patient outcomes.

Keywords

OCT; intraoperative OCT; iOCT; retina; surgery; vitreoretinal surgery

Introduction

Introduced in 1991, OCT has gained wide popularity as an ophthalmic diagnostic tool. This imaging modality has not only revolutionized our understanding of ophthalmic disease processes but also provided perspective on treatment and prognosis for many of these

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conditions[1–3] In the era of intravitreal pharmacotherapy, OCT has become the mainstay for guiding therapeutic decision-making. [4–6]

While OCT has been seamlessly integrated into our management of retinal conditions in the clinical setting, its adoption in the operating theater has yet to take full force. Some of the barriers to adoption in the operating room have included lack of high-speed imaging, OCT-compatible surgical instrumentation, software analysis systems, optimal integration, and efficient surgeon-feedback systems. Strides are being made in addressing these barriers, a transition that continues to evolve.

OCT in the operating room

One of the first challenges to the introduction of OCT technology in the surgical suite was the need for portability and the flexibility to image patients in different positions. Therefore a major breakthrough was development of a compact, lightweight handheld OCT machine that could be used in the operating room. [7–10] This freed the technology from a table-top engine and computer system, allowing greater flexibility in imaging patients in supine position. The handheld Bioptigen SDOIS/Envisu portable system (Bioptigen, Research Triangle Park, NC) and the stand-mounted Optovue IVue (Optovue, Fremont, CA) system are the two most commonly used portable systems that have been described for intraoperative use. [8,9,11–18]

Although the handheld systems provided flexibility in the operating room, it lacked stability and precision, being subject to motion artifacts, surgeon learning curves, and limited reproducibility of scan locations.[11–14,18,19] Microscope-mounted systems have been developed which allows the surgeon to control lateral and vertical deviations of the system using the joystick and focus controls of the microscope foot-pedal through tethering the handheld system to the microscope head. In addition to enhancing stability, these microscope-mounted systems allow for enhanced image reproducibility. [11,18]

Beyond improving the portability and reproducibility of OCT, intraoperative adoption has required modifications which allow for more seamless transitions for imaging as well as the potential of true “real-time” imaging. Real-time imaging provides feedback to guide surgical maneuvers via visualization of tissue-instrument interactions. [20–22] To address some of these demands, multiple research groups developed microscope integrated systems through developing an add-on OCT engine that utilized a portion of the common optical pathway of the surgical microscope. [23–27] This was a significant leap for transition of OCT into the surgical setting, allowing true “real-time” intraoperative OCT with visualization of surgical motion.[21,22,28,29]. Iterations of this technology have resulted in an improved interface with the surgeon via enhanced targeting and tracking of the OCT scan beam, tunable focus, and heads-up display of the OCT data stream. [20,22,23,30] Optimization of the surgeon’s heads up display is underway since effectiveness and adoption of this technology will rely on being able to provide critical information while maximizing surgeon comfort. [31] Following the research prototypes, multiple commercial systems and prototypes have been developed. For example, the Rescan 700 is built on the Lumera 700 microscope platform allowing the form factor of the microscope head to remain undisturbed. [25,32,33] Yet

another system that is commercially available and that has been studied in the operating room setting is the Haag-Streit system, which is powered by an OPMedT (OPMedT, Lubeck Germany) OCT engine and utilizes a microscope side-port for integration.[34] Finally, the next-generation iOCT prototype, Bioptigen/Leica EnFocus system, has an increased range that allows for enhanced visualization of pathology.[35]

Clinical Utility

There are many studies that have been undertaken to delineate the role of iOCT in ophthalmic surgery, anterior and posterior segment alike. [7–9,11–14,18,19,24,25,28,32,36–48] The 2-year results from the PIONEER study established the feasibility of iOCT using a microscope-mounted portable OCT system during ophthalmic surgery. [11] It also elucidated how information gathered from iOCT can help guide surgical decision-making. Subsequently, the DISCOVER study examined microscope-integrated OCT systems in ophthalmic surgery. [32] Other studies have also implicated the potential role of iOCT in surgical decision-making, such as reducing need for staining or identifying residual membranes. [9,18,24] This review will focus specifically on the role of iOCT in vitreoretinal surgery.

Vitreoretinal interface disorders

Because the vitreous is clear, vitreoretinal interface disorders including macular hole (MH), epiretinal membrane (ERM), and vitreomacular traction (VMT) can be particularly challenging to fully assess in both the clinic and the operating room. The advent of OCT in 1997 revolutionized our anatomic understanding and diagnosis of these conditions in the clinical setting.[3]

In the operating room, iOCT has the potential for significant utility in the management of these conditions (Figures 1 and 2). Membrane peeling in some form is the unifying theme of surgical management for these vitreoretinal interface disorders. These surgeries have variable outcomes with implications for the delicate retinal architecture and anatomy.[49,50] For example, some of the challenges during an internal limiting membrane (ILM) peel include the creation of a flap while avoiding inadvertent trauma to the retina, identification of the edge where ILM should be initiated, and most importantly determination of where the ILM has been already peeled.[51] Similarly, epiretinal membrane (ERM) visualization can be difficult, particularly when there is no fibrosis or pigment, thereby leading to insufficient removal of the membrane.[51]

The ability to enhance visualization of these transparent tissues with iOCT may provide significant insights to surgeons during these procedures. [7,9,13,14,18,28,52,53] As such, iOCT can guide surgical decision-making during a membrane peeling case, including the identification of membrane that needs further peeling. Alternatively, it can signal the end of a case by confirming attainment of surgical goals.[9,11,32] Specifically, studies have shown that in 13–22% of cases, intraoperative OCT identified residual membranes that required membrane peeling that would otherwise not have been identified. [11,32,37] On the other hand, in 15–40% of cases the iOCT illustrated the surgical goal had been accomplished and there was no membrane left to peel although the surgeon believed otherwise. [11,32] This

clearly demonstrates the utility of iOCT in surgical decision making during membrane peeling.

One essential component of membrane-peeling surgery that may dictate functional outcomes are the micro- and macro- level changes to the retina that can result from the surgery. At the micro level of retinal architecture, some of the commonly reported changes following membrane peeling include expansion of the distance between the ellipsoid zone and the retinal pigment epithelium and alterations of the inner retinal surface.[11,18,52,53] The overall visual implications of the microarchitectural changes remain unclear. However, one study demonstrated that these intraoperative outer retinal alterations are directly correlated with rate of anatomic normalization following MH repair.[Ref 33]. Beyond microarchitectural changes, one of the possible macroarchitectural changes to the retina during this surgery includes full-thickness retinal elevation. iOCT has demonstrated that these alterations are often directly associated with tissue-instrument interaction and may be influenced by the specific instrument utilized. [52] Utilizing iOCT, ILM peeling has been documented to result in variable changes in MH geometry (base area, height, and volume) and to the outer retinal architecture as well.[9,14,15,18]. These changes can be quite subtle and are not identifiable with traditional enface surgical microscope visualization. However, iOCT can delineate these changes. In fact, intraoperative changes in MH geometry and outer retinal architecture as identified on iOCT have been shown to correlate with anatomic surgical success defined as macular hole closure. [14,54]

Yet another vitreoretinal interface disorder that has been shown to benefit from image guidance of iOCT is vitreomacular traction syndrome (VMT).[9,11,13,32] The crux of successful VMT surgery is elevation of the hyaloid which often overlies retinal cysts resulting from traction. iOCT can help identify unroofed cysts following hyaloid elevation or can even identify subclinical full-thickness macular holes resulting from this maneuver. These findings subsequently guide surgical decision making in selection of a gas tamponade or ILM peeling in these cases.[11,13,32]

Interestingly, iOCT has also helped elucidate the intraoperative dynamics of the preoperative anatomic alterations that occur in vitreoretinal interface disorders. Preoperative connecting inner retinal strands have been controversial in their origin and their disposition during ILM peeling. Hypotheses of origin have included glial or inflammatory tissue within a potential space between the ILM and the posterior vitreous cortex, that might be removed through ILM peeling.[55] However, one report has elegantly shown via iOCT that these inner retinal projections or connecting strands are visible on the inner retinal surface immediately following ILM peeling and that this resolves postoperatively without any substantial changes to the nerve fiber layer.[53]

iOCT can also directly influence the surgical approach during vitreoretinal interface surgery. For example, utilization of vital dyes (such as indocyanine green (ICG), triamcinolone and other steroid suspensions) is a common part of vitreoretinal interface surgery. These dyes have been shown to have an impact on intraoperative OCT-based visualization of tissues. [56–58]. Quantitative analysis of iOCT in one study revealed a notable increase in hyperreflectivity at the ILM/ERM interface thus improving ease of recognition of the ILM

during OCT guided membrane peeling.[56] Beyond contrast-enhanced iOCT, OCT-guided membrane peeling has the potential to reduce the utilization of these stains thereby decreasing the surgical time and minimizing the potential risks to the retina associated with utilization of these dyes.[24]

Retinal Detachment

While the function of iOCT in rhegmatogenous retinal detachment (RRD) surgery may not be intuitive, emerging data has elucidated its potential role. [11,19,32] The rates of anatomic success (as defined by re-attachment of the retina) during RRD repair are very high, while vision recovery following surgery is variable. The explanation for this discrepancy likely lies in the microarchitectural changes that take place in the macula during the detachment period and potentially during surgical repair. One study reported changes in foveal architecture following perfluoro-n-octane (PFO) infusion during RRD repair including generalized blunting of IS/OS junction and loss of external limiting membrane detail with outer retinal corrugations.[19] Additionally, this study identified some patients with varying degrees of subclinical full thickness macular hole following PFO infusion that interestingly did not persist in the immediate postoperative period and a large percentage of eyes had persistent subfoveal fluid under PFO tamponade (Figure 3). In this small study, the degree of intraoperative change in the foveal architecture were positively correlated with visual outcomes postoperatively.[19] Therefore, findings on iOCT may help to prognosticate visual acuity outcomes following RRD repair and can help physicians guide patient expectations during the post-operative course. Reports from the DISCOVER study further highlights the utility of iOCT during RRD repair, particularly in surgical decision making.[32] One reported example is an eye with proliferative vitreoretinopathy with a subretinal band, iOCT revealed a subretinal band was completely flat under perfluorocarbon liquid when en face visualization gave the impression of elevation.[32] As a result, the surgeon in this case decided to abandon further membrane peeling, thereby decreasing tissue-instrument interactions and total surgical time.

Other vitreoretinal conditions

iOCT has also proven its value in elucidating the pathophysiology and in surgical intervention for optic pit related maculopathy and proliferative diabetic retinopathy (PDR). [32,38,40] In terms of optic pit pathophysiology, It has been hypothesized that anomalous connections between intraocular and extraocular spaces enable vitreous or cerebrospinal fluid into and under the retina. [59] iOCT findings have corroborated a direct connection between the vitreous and the area of the schisis in optic pit maculopathy.[40] In addition, during optic pit surgery, iOCT has been able to confirm collapse of macular schisis cavity during aspiration of fluid from the optic pit.

PDR surgery is fraught with challenges given the complex vitreoretinal relationship in this condition. Rapid, real-time feedback to the surgeon can help determine and guide surgical maneuvers during this delicate surgery. iOCT can play an instrumental role by helping identify surgical dissection planes, identification of tractional membranes and the consequent areas of retinal detachment and may facilitate identification of subclinical retinal

breaks (Figure 4).[32] In dense vitreous hemorrhage cases, iOCT frequently identifies underlying pathology, including retinal edema and epiretinal membranes.[38]

As subretinal therapeutics are evolving, image-guided delivery of these injections may become increasingly important. An example of this is subretinal tissue plasminogen activator (tPA) for treatment of submacular hemorrhage in patients with neovascular age related macular degeneration. Precise delivery of tPA between the retina and retinal pigment epithelium may be challenging intraoperatively, particularly in the presence of subretinal blood. Image guidance via iOCT may aid in localization of the cannula for delivery of tPA to the subretinal space. [12] Utilizing image-assisted delivery and image-guided confirmation, iOCT may become a critical component to targeted therapeutics, such as gene therapy and stem cell therapy, which will require precise delivery. Similar to delivery of subretinal therapeutics, removal of subretinal PFO may also benefit from iOCT guidance (Figure 5). [60]

Finally, an additional potential critical space for iOCT is pediatric vitreoretinal applications. As expected, imaging in the clinical setting can be challenging and sometimes not possible in the pediatric population. In such cases, perioperative imaging may be the only option. One instance where perioperative imaging while under anesthesia has proven to be very helpful is monitoring of intraocular tumors in the pediatric population [61] Not only does iOCT help with diagnosis, but it also helps with monitoring response to treatment in this population. Other reported instances where iOCT has shown to be beneficial include evaluation of retinal detachment and retinal schisis in retinopathy of prematurity, evaluation of the vitreoretinal interface in patients with congenital vitreoretinopathies, and in evaluation of chronic macular holes and scars and traumatic schisis in shaken baby syndrome. [7,8,62]

Conclusion

Just as the advent of OCT has revolutionized the diagnosis and management of retinal diseases in the clinical setting, iOCT is poised to change the approach to vitreoretinal disease in the operating room. In addition to providing real-time feedback during surgery to assist with surgical decisions, iOCT also helps shed light on the pathophysiology of various disease processes. It further helps monitor the microarchitectural changes resulting from surgical manipulations, educating the surgeon on the consequences of every surgical step, motivating efficient and safer surgical techniques.

While much progress has been made in transitioning OCT into the operating room, there still remains much room for improvement, particularly with regards to integrating the technology seamlessly into a surgeon feedback platform. The speed and quality of image acquisition need further enhancements. Additionally, improvements in software analysis for intrasurgical applications and OCT-compatible instrumentation are needed for more widespread utilization and adoption. While multiple studies have established the impact of iOCT on surgical decision-making, continued research is needed to validate its utility with regards to improved patient outcomes.

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Abbreviations

OCT	optical coherence tomography
ioCT	intraoperative OCT
SDOCT	spectral domain optical coherence tomography
MH	macular hole
ERM	epiretinal membrane
VMT	vitreomacular traction
ILM	internal limiting membrane
RRD	rhegmatogenous retinal detachment
PFO	perfluoro-n-octane
PDR	proliferative diabetic retinopathy

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Key Points

- Numerous studies have established the utility of iOCT in vitreoretinal surgical decision making by providing real-time feedback on tissue-instrument interactions and by highlighting microarchitectural changes to the retina resulting from surgical manipulations.
- iOCT has also been shown to shed light on pathophysiology of various disease processes such as optic pit maculopathy, and vitreoretinal interface disorders.
- Widespread utilization of OCT in the operating room theater requires further integration of the technology into a surgeon feedback platform, improvements in software analysis for intrasurgical applications, and development of OCT-compatible instrumentation.

Figure 1. Intraoperative OCT During Epiretinal Membrane Surgery

(A) Pre-peel intraoperative OCT demonstrating prominent epiretinal membrane (arrowhead) with some increased shadowing following administration of indocyanine green for staining.

(B) Post-peel intraoperative OCT confirming complete removal of epiretinal membrane.

Figure 2. Intraoperative OCT and Macular Hole Surgery

(A) Following internal limiting membrane peeling, intraoperative OCT confirms complete membrane removal around the macular hole.

Figure 3. Proliferative Diabetic Retinopathy and Intraoperative OCT

(A) Complex combined tractional rhegmatogenous retinal detachment involving the macula. (B) Utilizing intraoperative OCT, a subclinical retinal hole (arrowhead) is identified with associated tractional membranes. Identification of this retinal break facilitates surgical repair and removal of membranes.

Figure 4. Subretinal Perfluorocarbon Liquid, Proliferative Vitreoretinopathy and Intraoperative OCT

(A) Subfoveal perfluorocarbon liquid (arrowhead) is identified utilizing intraoperative OCT.

(B) Associated proliferative vitreoretinopathy and retinal detachment are visualized with intraoperative OCT. Preretinal membrane (arrow) identification is facilitated with intraoperative OCT and guides surgical maneuvers for membrane removal.

Figure 5. Retinal Detachment Repair and Intraoperative OCT

(A) Macula-involving rhegmatogenous retinal detachment visualized with intraoperative OCT with associated subfoveal fluid (arrowhead). (B) Following placement of perfluorocarbon liquid, significant improvement in subretinal fluid is visualized, but persistent submacular fluid remains (arrowhead).