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The Integrative Surgical Theater: Combining Intraoperative OCT and 3D Digital Visualization for Vitreoretinal Surgery in the DISCOVER Study

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Abstract

Purpose—To evaluate the feasibility of integrating intraoperative optical coherence tomography (OCT) with a digital visualization platform for vitreoretinal surgery.

Methods—The DISCOVER study is a prospective study examining microscope-integrated intraoperative OCT across multiple prototypes and platforms. For this assessment, a microscope-integrated OCT platform was combined with a 3-dimensional (3-D) surgical visualization system to allow for digital display of the OCT data stream on the large immersive display. Intraoperative OCT scans were obtained at various surgical milestones were directly overlaid to the surgical view in a 55-inch passive 3-D 4K high definition display. Surgeon feedback was obtained related to system performance and integration into the surgical procedures through a prespecified surgeon questionnaire.

Results—Seven eyes of seven subjects were identified. Clinical diagnosis included epiretinal membrane (n = 3), macular hole (2), symptomatic vitreous opacity (1) and proliferative vitreoretinopathy (1). OCT images were successfully obtained and displayed on the 4K screen in all cases. Intraoperative OCT images facilitated identification of subtle retinal alterations. Surgeons reported the 4K screen appeared to provide improved visualization of the OCT data stream compared to the semi-transparent ocular view. Surgeons were able to examine the OCT data on the 4K screen without reverting to the external display system of the microscope. The system provided a uniform surgical visualization experience for both the surgeon and the assistant. In addition, the digital platform allowed all surgical personnel to simultaneously view both the OCT and the surgical field. All eyes underwent uneventful vitrectomy without reverting to the conventional microscope. No intraoperative adverse events occurred.

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Conclusion—Integration of OCT into the digital visualization system may enable unique opportunities for surgeon feedback of intraoperative diagnostics. The overlay of the OCT data onto the 4K monitor appeared to provide excellent visualization of OCT details. Further research is needed to compare the conventional microscope-based approach to the digital 3-D screen approach in regards to intraoperative OCT.

Keywords

Vitreoretinal surgery; intraoperative optical coherence tomography; iOCT; intraoperative OCT; DAVS; image-guided surgery; 3-D surgery; heads-up surgery

Introduction

The recent advances in intraoperative optical coherence tomography (OCT) technology has opened up vast possibilities in the approach to various vitreoretinal diseases during vitreoretinal surgery.[1–13] Intraoperative identification of pathological conditions and vitreoretinal structure alterations have lead surgeons to better understand the anatomy, and real-time feedback has been demonstrated to impact surgical decision making.[1–13] In addition, lab-based studies have demonstrated enhanced technical performance for surgical trainees with intraoperative OCT feedback. Recent utilization of intraoperative OCT for posterior segment surgery includes guidance for placement of retinal prosthesis electrode array and during subretinal gene therapy delivery.[14, 15] As the implementation of intraoperative OCT is rapidly expanding, seamless and detailed visualization of the intraoperative OCT data stream is becoming increasingly important.

Recent advances in digital assisted vitrectomy allow surgeons to operate while viewing the surgical field on a large, 3-D 4K high definition (HD) monitor with the use of passive polarized 3-D glasses for stereopsis.[16, 17] Digital assisted vitrectomy has several potential advantages over conventional microscopes.[16–19] The high resolution digital camera offers excellent contrast and sharpness with high dynamic range capabilities. The high sensitivity of the imaging processor and digital filter with gain adjustment may enable reductions in endoillumination intensity during macular surgery. The ergonomic environment potentially reduces fatigue and cervical/lumbar stress for surgeons. The single surgical view shared with all surgical team members may facilitate communication and enhance learning/teaching experience. Finally, the tremendous flexibility of a digital display system provides a unique opportunity for a comprehensive integrative theater to seamlessly integrate intraoperative diagnostics with an immersive visualization platform.

To date, combined applications of these two promising technologies have not been evaluated. The purpose of this study was to describe and evaluate the feasibility and potential utility of integrating intraoperative OCT into a 3-D digital visualization system.

Materials and Methods

The DISCOVER (*D*etermination of feasibility of *I*ntraoperative *S*pectral domain microscope *C*ombined/integrated *O*CT *V*isualization during *E*n face *R*etinal and ophthalmic surgery) study is designed to prospectively examine the feasibility and utility of microscope-integrated intraoperative OCT systems during ophthalmic surgery.[1, 2] The overall methods of the procedures have been previously described.[1, 2] The study was approved by the IRB at Cleveland Clinic and adhered to the tenets of the Declaration of Helsinki. All participants were enrolled with informed written consent. Among participants enrolled in the DISCOVER study,[1, 2] all subjects who underwent surgical intervention utilizing a microscope-integrated intraoperative OCT system (Rescan 700, Zeiss, Oberkochen, Germany) coupled to a 3-D heads-up display system (Ngenuity, Alcon, Fort Worth, TX) from March to April 2017 were identified and included in this analysis. All patients underwent standard small-gauge three port pars plana vitrectomy. All operations were performed using the Constellation vitrectomy system (Alcon, Fort Worth, TX). The DISCOVER study protocol includes a surgeon questionnaire that is completed following every surgical case. These questions include information related to OCT feasibility and utility. Specifically, surgical feedback is requested related to preferred format for optimal OCT viewing, the overall value of the OCT during the procedure, and whether the OCT information specifically changed the surgical procedure.

Digital 3-D Visualization System and Intraoperative OCT Set-up

The digital 3-D visualization system consisted of several critical hardware components: digital video camera, high-speed computer, display monitor, and passive 3-D glasses. The microscope surgeon's oculars were removed and then replaced with a dual digital video high-dynamic range camera component fitted with the Zeiss microscope interface footplate (Figure 1A). The aperture (i.e., iris diaphragm) was manipulated with a slider control switch at the base of the camera. The size of the aperture contributes to the overall depth of field and the amount of light that the camera receives. As the aperture is made smaller, the depth of field increases and the light transmitted is reduced. With a larger aperture, more light is transmitted and the depth of field is reduced. The overall depth of field is determined by multiple factors including the aperture size and the surgeon's accommodative ability. For this study, the slider aperture slider control was initially set to approximately 35–40% open (i.e., less than halfway across the slide) at the beginning of surgery. Generally, the aperture did not require additional adjustment through the case, but could be changed if needed for alterations in surgical visualization. An OLED 55-inch 3-D 4K ultra HD monitor which utilizes passive row interlaced 3-D display technology with a resolution of 3840 × 2160 pixels (8.3 million pixels) was placed to the right of the patient near the foot end of the bed (the distance between the surgeon and the monitor was approximately 1.5 m). The vertical height of the monitor was set at the surgeon's eye level for a comfortable ergonomic working position (Figure 1B–C). White balance was adjusted prior to the first case of each surgical session. The color profile utilized was dependent on surgeon preference and location of surgical manipulations (e.g., external, wide-angle retina, macular peeling). The brightness and contrast of the data injection of the OCT signal was also adjusted within the Rescan system setup to maximize viewing on the OLED screen. These levels varied from case-to-case; however, the initial brightness setting was reduced to around 30 and the contrast level was increased to approximately 45–50. The current system resolution allowed for 1920×1080 pixels per eye, capable of displaying 2160 horizontal lines.[16] The surgeon, assistant and other surgical personnel wore passive 3-D polarized glasses during surgery.

The surgical video was recorded in multiple formats: 3-D and 2-D stream live video of surgical field with or without intraoperative OCT.

Intraoperative OCT Platform

The DISCOVER study includes two microscope-integrated OCT systems, the Rescan 700 and the EnFocus (Bioptigen Inc., Research Triangle Park, NC). Given the capability for injection of the OCT datastream utilizing the heads-up display system, the Rescan 700 platform was selected for initial evaluation. The Rescan 700 is a real-time microscope-integrated intraoperative spectral domain OCT system that equipped with an 840 nm wavelength light source with a scanning speed of 27,000 A-scans per second. The axial image resolution in tissue is 5.5 μm and the A-scan range is 2 mm in tissue and scan length is adjustable from 3 to 16 mm. Scan rotation is adjustable 360 degrees. The system includes Z-tracking, focus control for image stabilization and quality control. As noted above, the ocular injection for the intraoperative OCT brightness and contrast parameters were adjusted prior to starting the case.[1, 2, 13]

System Integration

The real-time intraoperative OCT imaging and HD video were combined on the 55-inch 3-D 4K HD monitor (Figure 1D, Supplemental Video 1). With passive 3-D polarized glasses, two-dimensional intraoperative OCT B-scans overlay was visible for only one eye. Based on the DISCOVER study protocol, intraoperative OCT imaging was obtained at various surgical milestones, according to surgeons' preference. All surgeries were performed by a trained vitreoretinal surgeon (JPE) with assistance from a vitreoretinal surgery fellow. The intraoperative OCT system was operated by an imaging research technician. A noncontact wide-angle viewing system (Resight, Zeiss) or direct contact lens was utilized for surgical and intraoperative OCT visualization.

Results

Seven eyes of 7 patients were enrolled with a variety of retinal diseases including epiretinal membranes (n = 3), full thickness macular holes (2), symptomatic vitreous opacity (1) and traumatic retinal detachment with severe proliferative vitreoretinopathy (PVR, 1). All study participants underwent small-gauge vitrectomy procedures. These procedures included vitrectomy with or without membrane peeling as well as complex retinal detachment repair with membrane peeling and retinectomy. All procedures were completed using the 3-D digital system without reverting to the conventional optical microscope. Detailed intraoperative OCT images observed on the large 4K HD monitor enabled identification of subtle alterations in retinal microstructure. Excellent contrast and image visualization was reported by the surgeons while utilizing the 4K screen for OCT review. In 100% of cases, successful intraoperative OCT image acquisition was performed.

Intraoperative OCT was successfully utilized during surgery to confirm normal foveal anatomy (Figure 2, Supplemental Video 2), to identify residual epiretinal membranes, and to evaluate macular hole anatomy (Figure 3, Supplemental Video 3). The intraoperative OCT data stream was successfully visualized using both lenses in the noncontact wide-angle viewing system (Resight, Zeiss) and the high magnification contact lens. One advantage of the contact lens for OCT visualization was the smaller relative size of the surgical view. This allowed the OCT B-scans to be viewed over a surrounding black background, which provided enhanced visualization of subtle retinal structures (Figure 4, Supplemental Video 4).

The system was also successfully utilized for more complex surgical pathology. In one traumatic retinal detachment case with severe PVR, intraoperative OCT was successfully used to evaluate the retinal surface for membrane location. Following membrane removal, an inferior 180 degree peripheral retinectomy was performed with subsequent subretinal membrane removal. Perfluorocarbon liquid were then infused to stabilize and flatten the retina. Intraoperative OCT demonstrated reattachment of posterior retina with residual subclinical subretinal fluid. In addition, the OCT identified subtle residual focal membranes and diffuse retinal thickening (Figure 5).

Utilizing the digital system, surgeons were able to review the OCT data on the 4K display without looking away from the surgical field. The OCT datastream details was more easily visualized on the 4K screen with the increased contrast setting for the 3-D monitor compared to the microscope ocular heads-up display. This was true for both widefield imaging and high-magnification macular work. The smaller field of view and “working window” that was noted with a high-magnification contact lens also created a dramatic view of the OCT due to its overlay on the surrounding black background of the screen. The quality of the OCT data was comparable to review on the microscope monitor and significantly improved compared to the data injection display into the microscope ocular.

Educationally, surgeons reported improvements in the operative teaching environment, particularly given that both the surgeon and assistant were able to simultaneously visualize the identical surgical field and the OCT. In the conventional microscope set-up, only the surgeon is able to view the OCT data through the oculars. In addition, other members of the surgical team (e.g., medical students, residents) were able to view the intraoperative OCT data and the surgical field simultaneously, enhancing their surgical educational experience.

No significant subjective increase in operative time was noted. A small increase in time was spent adjusting fine focus at the beginning of the case to maximize depth of focus during the case. Generally, surgeons felt the ergonomics and comfort of the surgical environment was good, and there were less challenges with the potential accommodative disconnect between the assistant and surgeon during the cases. There were not intraoperative adverse events and there were no adverse events attributed to the visualization system. The median intraoperative OCT scanning time was 2.2 minutes (range: 1.6–4.2 minutes).

Discussion

Until recently, surgical visualization innovation has been relatively static with conventional microscopy still the dominant approach to vitreoretinal surgery. However, the digital revolution and significant advances in ophthalmic diagnostics has placed surgical visualization at a potential inflection point. Integration of real-time intraoperative diagnostics and 3-D digital systems provide unique opportunities for a comprehensive integrative digital surgical theater. In this study, the feasibility and potential utility of the integration of these two cutting-edge technologies for multiple vitreoretinal surgical procedures was explored. In all surgical cases, intraoperative OCT images were successfully obtained and the surgical procedures was completed in their entirety with 3-D digital visualization.

The concept of a 3-D digital approach to ophthalmic surgery was originally reported in the mid-1990s for better ergonomics during surgery.[20] The system was first introduced in anterior segment surgery with integration of diagnostic overlays, followed by clinical use in vitreoretinal surgery.[19, 21–23] Recent advances in CPU/GPU speed, high-resolution camera technology, and the OLED 4K HD display monitor has provided a major iterative change in the potential role of 3-D digital technology in vitreoretinal surgery. The digital approach provides unique advantages to the traditional microscope head. With standard surgical microscopes, beam splitters, inverters, and laser filters are all required for safe and effective microscope operation. However, digital solutions obviate the need for these additional components, reducing the potential form factor of the microscope head and potentially enhancing the quality of surgical view. The current system is equipped with an adjustable iris aperture which balances between depth of field and image brightness.[16] Utilizing a larger iris aperture and digital processing may also enable operating at reduced levels of illumination. Adam et al reported that vitrectomy was comfortably performed at endoillumination level of 10% of maximum output (i.e., about a quarter of the standard setting) with a similar heads-up display system.[18] One important drawback of a digital approach to surgery is the potential latency and delay of the surgical view. In the 3-D system used in this study, there is a 0.09 second latency that may result in a slight delay in perception between surgeon hand movements and the image motion on the screen. There were no reported concerns with latency for any surgical cases in this study. The latency of the Ngenuity system is dependent on the capability of monitor display and image rendering software. The latency was unaffected by whether the microscope integrated OCT scanner was turned on or off. In this study, the Ngenuity system had a latency of 0.09 seconds Generally, this minimal delay is well-tolerated particularly for vitreoretinal surgery with the relatively slower instrument motion.[16] With the newest system upgrades, the latency will be shortened to 0.07 second with the upgraded monitor which were not available for this study; however, it may be reasonable to assume that shorter latency will reduce the discomfort during rapid surgical maneuvers.

Although the Rescan 700 utilizes heads-up display capabilities, studies have suggested that many surgeons may prefer to utilize the external microscope display screen to review the OCT information.[1] The limited size and resolution of intraoperative OCT images seen through the eyepiece limits clinical utility and surgeon ability to discriminate subtle anatomic features. In addition, the semi-transparent nature of the heads-up display image also further limits identification of key tissue characteristics. The requirement for surgeons to utilize the external monitor minimizes the capacity for true “real-time” intraoperative OCT with the system. Transitioning to a 3-D digital system with intraoperative OCT integration provides a unique opportunity for real-time image-guided surgery. In the current system, the detailed intraoperative OCT B-scans overlaid on the surgical field provided an efficient approach to multi-modal surgical visualization.

The overall median intraoperative scanning time in this study of 2.2 minutes was more than 50% shorter than that of 4.9 minutes in the PIONEER study.[5] Direct comparison of this data must be interpreted with the understanding that the OCT systems employed in both studies were different (e.g., microscope mounted intraoperative OCT was utilized in the PIONEER study). However, the shorter scanning time in this study suggests the current system may have significantly higher efficiency. Further research is needed to directly compare microscope-integrated OCT scanning times with and without utilization of the digital platform. In addition, more data is needed to evaluate overall surgical times between the different systems. These additional comparative research studies are currently underway.

Future research will also be helpful for larger scale quantitative comparisons between conventional microscope-integrated OCT systems and the 3D digital systems. However, in this preliminary report, surgeons found that the 3D display was often sufficient for OCT review without having to look away to the monitor. This is in contrast to previous studies where in 30% or more of cases the surgeons needed to review the OCT on a monitor while looking away from the surgical oculars,[1, 2] In addition, when a macular contact lens was utilized, the increased "black space" on the monitor provided an outstanding canvas for the OCT signal that was comparable to the level of detail noted on the microscope monitor. In fact, the significantly increased size of the OCT on the 4K display may provide some benefits over the monitor review.

Educationally, the digital system provides the unique advantage of allowing everyone in the room to have the identical surgical view as the surgeon. Subjectively, this enhanced the surgeon/assistant interaction throughout the case. In addition, this allowed all participants on the surgical team (e.g., medical students, residents, nurses) to view the OCT data overlay with the 3D surgical view. Previous research has demonstrated that utilizing intraoperative OCT feedback enhances learning surgeons ability to more accurately and a precisely perform ophthalmic surgical tasks (i.e., corneal suturing).[24] More research is needed to better understand the potential educational enhancements realized through combining these modalities.

Although this integrative approach provides significant opportunities for image-guided surgery, there are still significant needs for maximizing the image-guided surgery platform. One of the remaining issues related to intraoperative OCT technology would be targeting the intraoperative OCT field-of-view to the area of interest.[3, 11, 25] Novel approaches to tracking both tissues and instruments may improve imaging efficiency and enhance visualization of the impact of surgical maneuvers.[26, 27] Additional enhancements to intraoperative OCT may also include 3-D volumetric real-time OCT scanning through the use of high-speed OCT engines.[28] Although this approach provides a unique opportunity for OCT-based visualization of the 3-D impact of surgical maneuvers, traditional cross-sectional views may provide greater details for evaluating subtle changes in the outer retina. Additional research is needed to understand the various benefits of both 2-D and 3-D intraoperative OCT approaches. Nevertheless, the 3-D 4K screen is novel modality that provides a unique opportunity for multi-dimensional viewing of the OCT datastream.

Additional improvements in components of the system, including intraoperative OCT analysis software platforms, are needed to truly provide the comprehensive digital surgical theater. Additional digital display options may also be explored, such as augmented reality goggles or digital microscope oculars. Ultimately, a complete digital microscope may also be considered as a viable alternative. Additional intraoperative diagnostics, such as OCT angiography, may further enrich the surgical feedback platforms during vitreoretinal surgery.

Limitation of this study include small sample size and non-comparative nature of this study. Specific limitations of the current integrative systems include the additional set-up time required as well as the increased footprint of the systems required in the operating room. In addition, the digital camera still requires an existing microscope to provide the optics for posterior segment visualization. Minimizing the size requirement of the microscope portion of the visualization system would further enable use in smaller operating rooms.

This study demonstrated the feasibility and potential utility of integrating intraoperative OCT into a digital surgical visualization system for vitreoretinal surgery. Based on our literature review, we were unable to identify any previous reports of utilizing intraoperative OCT with a 3-D digital surgical system. Integration of detailed intraoperative OCT images into the flexible high-resolution viewing format appeared to provide more comfortable visual integration of the two data streams based on surgeon feedback compared to semi-transparent overlay in the microscope oculars. Additional research is needed to evaluate overall impact on surgical safety and efficacy. In addition, future work is needed in enabling technologies for intraoperative OCT integration, such as tracking and software analysis systems. Finally, understanding both the impact on clinical outcomes and the comparative assessment of digitally-enabled platforms to conventional systems is going to be critical to better evaluate the overall value of the technology. Many of these studies are already ongoing and we look forward to those results in the future.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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References

1. Ehlers JP, et al. Determination of feasibility and utility of microscope-integrated optical coherence tomography during ophthalmic surgery: the DISCOVER Study RESCAN Results. JAMA Ophthalmol. 2015; 133:1124–1132. [PubMed: 26226623]
2. Ehlers JP, Kaiser PK, Srivastava SK. Intraoperative optical coherence tomography using the RESCAN 700: preliminary results from the DISCOVER study. Br J Ophthalmol. 2014; 98:1329–1332. [PubMed: 24782469]

3. Ehlers JP, Tao YK, Srivastava SK. The value of intraoperative optical coherence tomography imaging in vitreoretinal surgery. Curr Opin Ophthalmol. 2014; 25:221–227. [PubMed: 24614147]
4. Ray R, et al. Intraoperative microscope-mounted spectral domain optical coherence tomography for evaluation of retinal anatomy during macular surgery. Ophthalmology. 2011; 118:2212–2217. [PubMed: 21906815]
5. Ehlers JP, et al. The Prospective Intraoperative and Perioperative Ophthalmic ImagiNg with Optical CoherEncE TomogRaphy (PIONEER) Study: 2-year results. Am J Ophthalmol. 2014; 158:999–1007. [PubMed: 25077834]
6. Ehlers JP, et al. Membrane Peeling-Induced Retinal Alterations on Intraoperative OCT in Vitreomacular Interface Disorders From the PIONEER Study. Invest Ophthalmol Vis Sci. 2015; 56:7324–7330. [PubMed: 26559478]
7. Scott AW, et al. Imaging the infant retina with a hand-held spectral-domain optical coherence tomography device. Am J Ophthalmol. 2009; 147:364–373. e362. [PubMed: 18848317]
8. Pichi F, et al. Intraoperative SD-OCT in macular surgery. Ophthalmic Surg Lasers Imaging. 2012; 43:S54–60. [PubMed: 23357325]
9. Binder S, et al. Feasibility of intrasurgical spectral-domain optical coherence tomography. Retina. 2011; 31:1332–1336. [PubMed: 21273942]
10. Toygar O, Riemann CD. Intraoperative optical coherence tomography in macula involving rhegmatogenous retinal detachment repair with pars plana vitrectomy and perfluoron. Eye (Lond). 2016; 30:23–30. [PubMed: 26656086]
11. Ehlers JP. Intraoperative optical coherence tomography: past, present, and future. Eye (Lond). 2016; 30:193–201. [PubMed: 26681147]
12. Hahn P, et al. The use of optical coherence tomography in intraoperative ophthalmic imaging. Ophthalmic Surg Lasers Imaging. 2011; 42(Suppl):S85–94. [PubMed: 21790116]
13. Pfau M, et al. Clinical Experience With the First Commercially Available Intraoperative Optical Coherence Tomography System. Ophthalmic Surg Lasers Imaging Retina. 2015; 46:1001–1008. [PubMed: 26599241]
14. Rachitskaya AV, et al. Intraoperative OCT Imaging of the Argus II Retinal Prosthesis System. Ophthalmic Surg Lasers Imaging Retina. 2016; 47:999–1003. [PubMed: 27842194]
15. Gregori NZ, Lam BL, Davis JL. Intraoperative Use of Microscope-Integrated Optical Coherence Tomography for Subretinal Gene Therapy Delivery. Retina. 2017
16. Yonekawa Y. Seeing the world through 3-D glasses. Retina Today. 2016:28–31. 34.
17. Read SP, Fortun JA. Visualization of the retina and vitreous during vitreoretinal surgery: new technologies. Curr Opin Ophthalmol. 2017; 28:238–241. [PubMed: 28306625]
18. Adam MK, et al. Minimal Endoillumination Levels and Display Luminous Emittance during Three-Dimensional Heads-up Vitreoretinal Surgery. Retina. 2016
19. Eckardt C, Paulo EB. Heads-up surgery for vitreoretinal procedures: an experimental and clinical study. Retina. 2016; 36:137–147. [PubMed: 26200516]
20. Franken RJ, et al. Microsurgery without a microscope: laboratory evaluation of a three-dimensional on-screen microsurgery system. Microsurgery. 1995; 16:746–751. [PubMed: 9148102]
21. Weinstock RJ, Donnenfeld ED. 3D Visualization In Ophthalmology. Cataract Refract Surg Today. 2008:62–65.
22. Weinstock RJ. Operate with your head up. Cataract Refract Surg Today. 2011; 8:66–74.
23. Montes de Oca I, et al. Accuracy of toric intraocular lens axis alignment using a 3-dimensional computer-guided visualization system. J Cataract Refract Surg. 2016; 42:550–555. [PubMed: 27113877]
24. Todorich B, et al. Impact of Microscope-Integrated OCT on Ophthalmology Resident Performance of Anterior Segment Surgical Maneuvers in Model Eyes. Invest Ophthalmol Vis Sci. 2016; 57:OCT146–153. [PubMed: 27409466]
25. Tao YK, Srivastava SK, Ehlers JP. Microscope-integrated intraoperative OCT with electrically tunable focus and heads-up display for imaging of ophthalmic surgical maneuvers. Biomed Opt Express. 2014; 5:1877–1885. [PubMed: 24940546]

26. Ehlers JP, et al. Visualization of real-time intraoperative maneuvers with a microscope-mounted spectral domain optical coherence tomography system. Retina. 2013; 33:232–236. [PubMed: 23190928]
27. El-Haddad MT, Tao YK. Automated stereo vision instrument tracking for intraoperative OCT guided anterior segment ophthalmic surgical maneuvers. Biomed Opt Express. 2015; 6:3014–3031. [PubMed: 26309764]
28. Carrasco-Zevallos OM, et al. Live volumetric (4D) visualization and guidance of in vivo human ophthalmic surgery with intraoperative optical coherence tomography. Sci Rep. 2016; 6:31689. [PubMed: 27538478]

Summary Statement

Significant advances over the last few years have enabled the use of OCT during surgery and enhanced the potential of digital vitreoretinal surgery. In this report, those technologies are combined into a seamless integrative surgical theater, enabling the surgeons to view both the OCT and the surgical field simultaneously on a large-screen immersive display. The merging of these technologies may allow for unique opportunities in the future for surgeon feedback and display features.

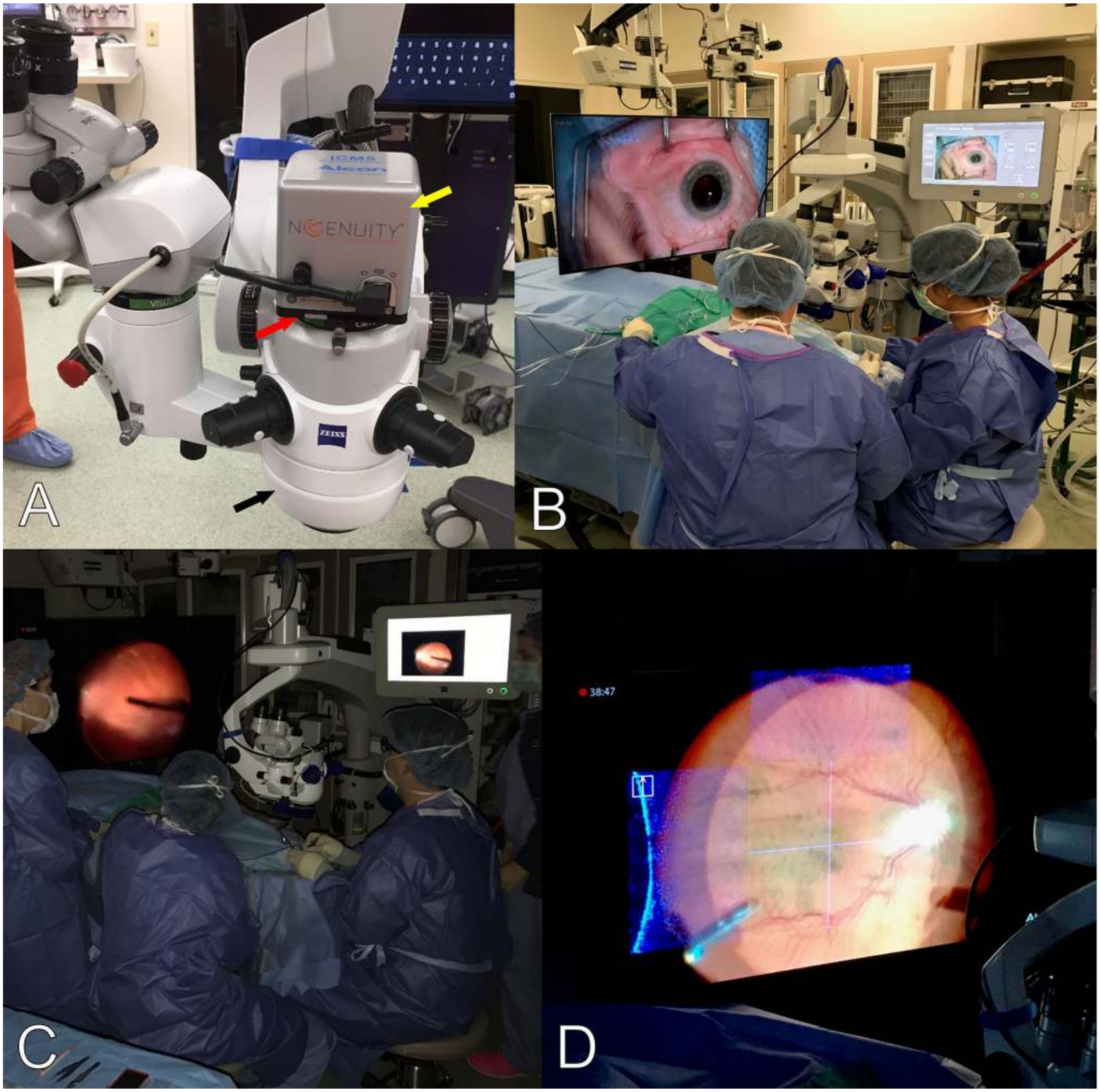

Figure 1. A microscope integrated intraoperative OCT with a 3-D digital display system

(**A**) The microscope integrated intraoperative OCT platform (Rescan 700). Black arrow indicates microscope head. The microscope oculars are replaced with a dual digital video camera component of the 3-D digital visualization system (Ngenuity, yellow arrow). The aperture (iris diaphragm) can be adjusted by slider control switch (red arrow), the larger aperture (more light, shallower depth of field) is available when the slider is on the right side. (**B, C**) Heads-up display positioned approximately 1.5 m from the surgeon. External monitor of the microscope's data management system is seen on the right. (**D**) View of the 3-D display monitor seen close to assistant's position. Without passive polarized 3-D glasses, fundus view is an overlapping double-image, while intraoperative OCT scans are observed as single image.

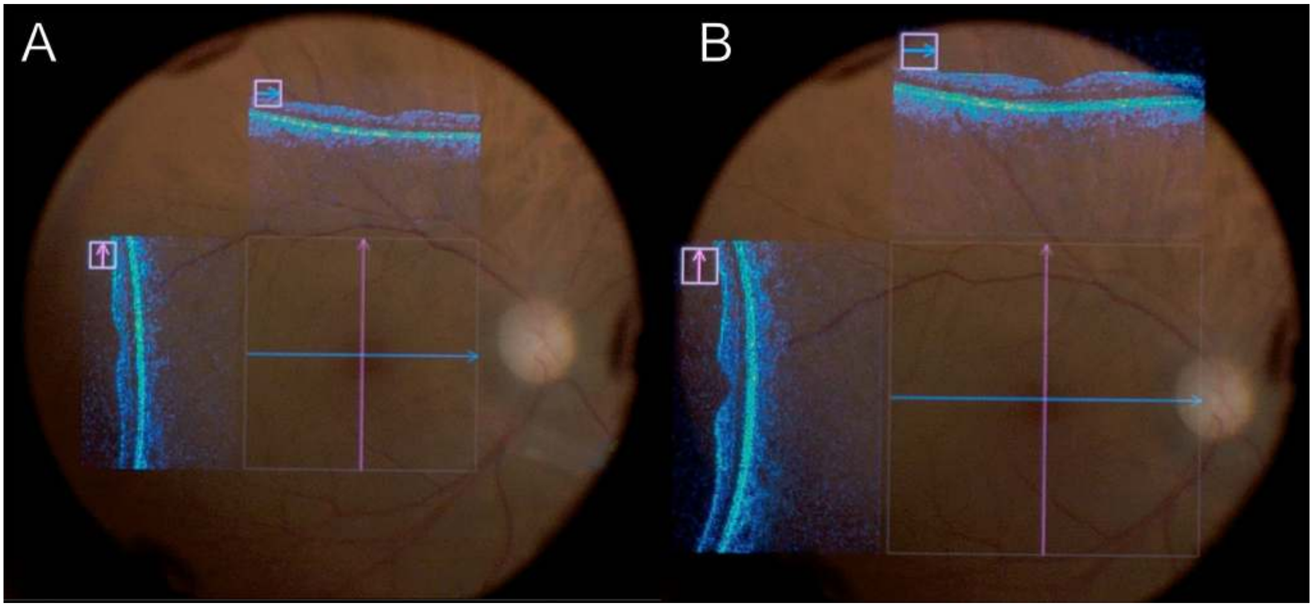

Figure 2. Surgical view with intraoperative OCT of normal fovea captured from 2-D stream video recording

Normal foveal contour is observed in both horizontal and vertical OCT scans. Two examples are shown based on the length of OCT scan, standard length (**A**), and longer OCT scan (**B**). The length of OCT-scan is adjustable from 3 to 11 mm.

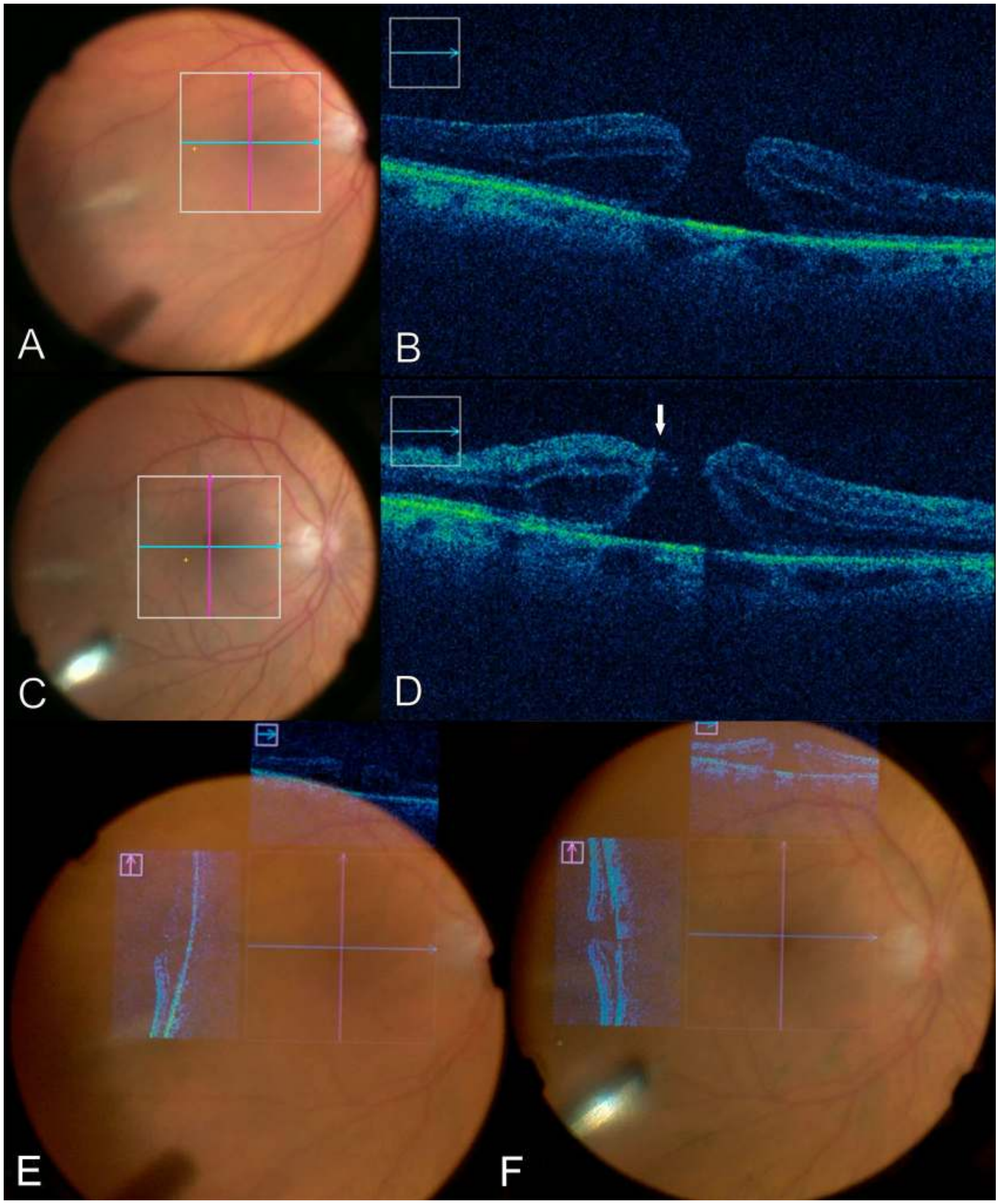

Figure 3. Surgical view with intraoperative OCT of fovea in a case with macular hole

Prior to internal limiting membrane (ILM) peeling, an intraoperative OCT scan is obtained. The surgical view (A) and OCT B-scan is provided (B). Following ILM peeling, the surgical view from the microscope data display shows the OCT aiming target (C) and the OCT B-scan demonstrates removal of the ILM with minimal material at the hole edge (white arrow, D). The digital overlay on the 3-D screen is also provided before ILM peeling (**E**) and following ILM peeling (**F**). In this case, indocyanine green staining was performed followed by ILM peeling with a membrane loop. Intraoperative OCT was utilized to confirm the completion of ILM peeling and to identify any microstructural alterations of the retina.

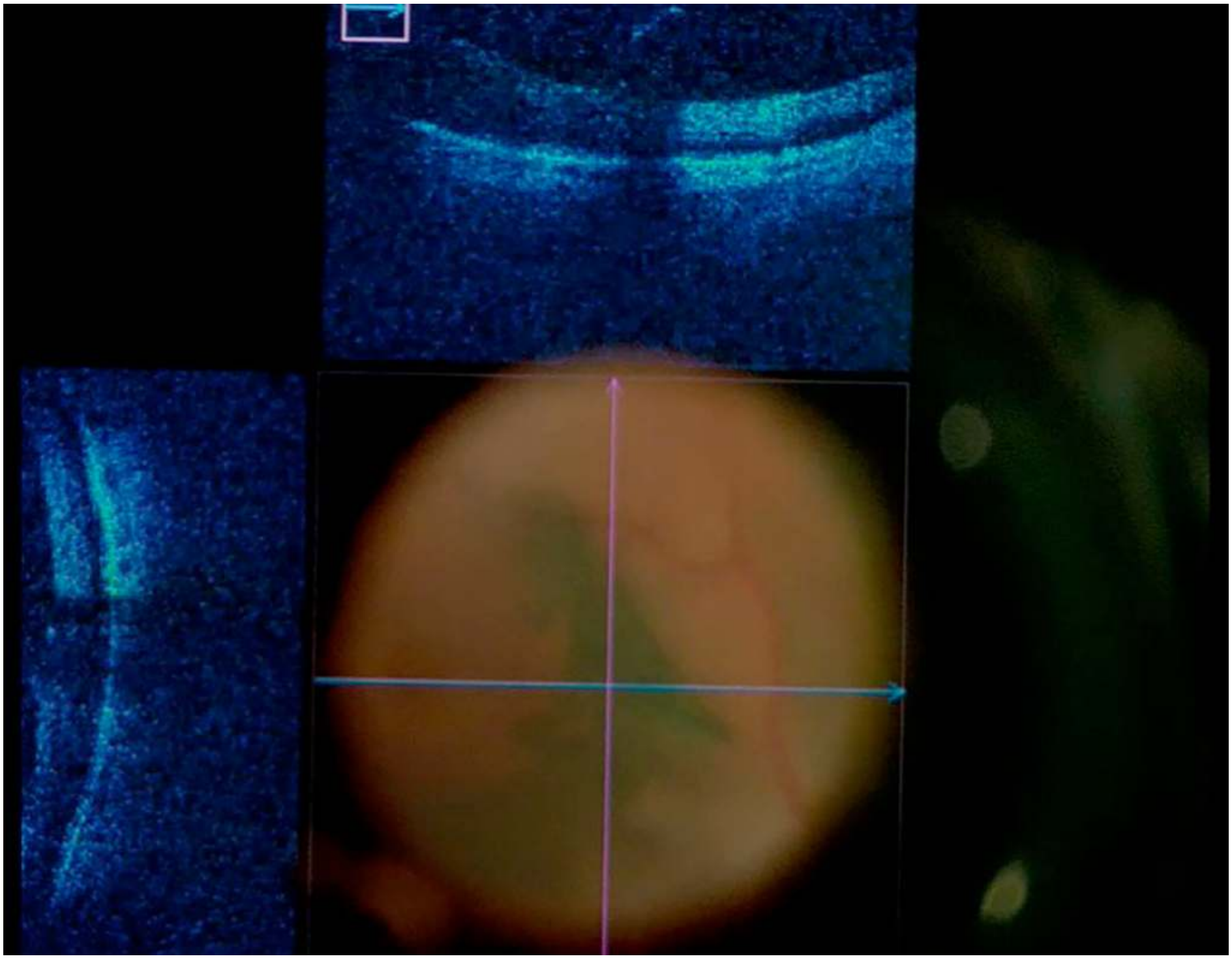

Figure 4. Intraoperative OCT and Digital Surgical Visualization Utilizing Contact Lens Visualization

The higher magnification and narrower field of view provides greater “black” space for the intraoperative OCT overlay, enhancing visualization of the OCT data. This figure demonstrates OCT visualization during membrane peeling and identification of membrane edge.

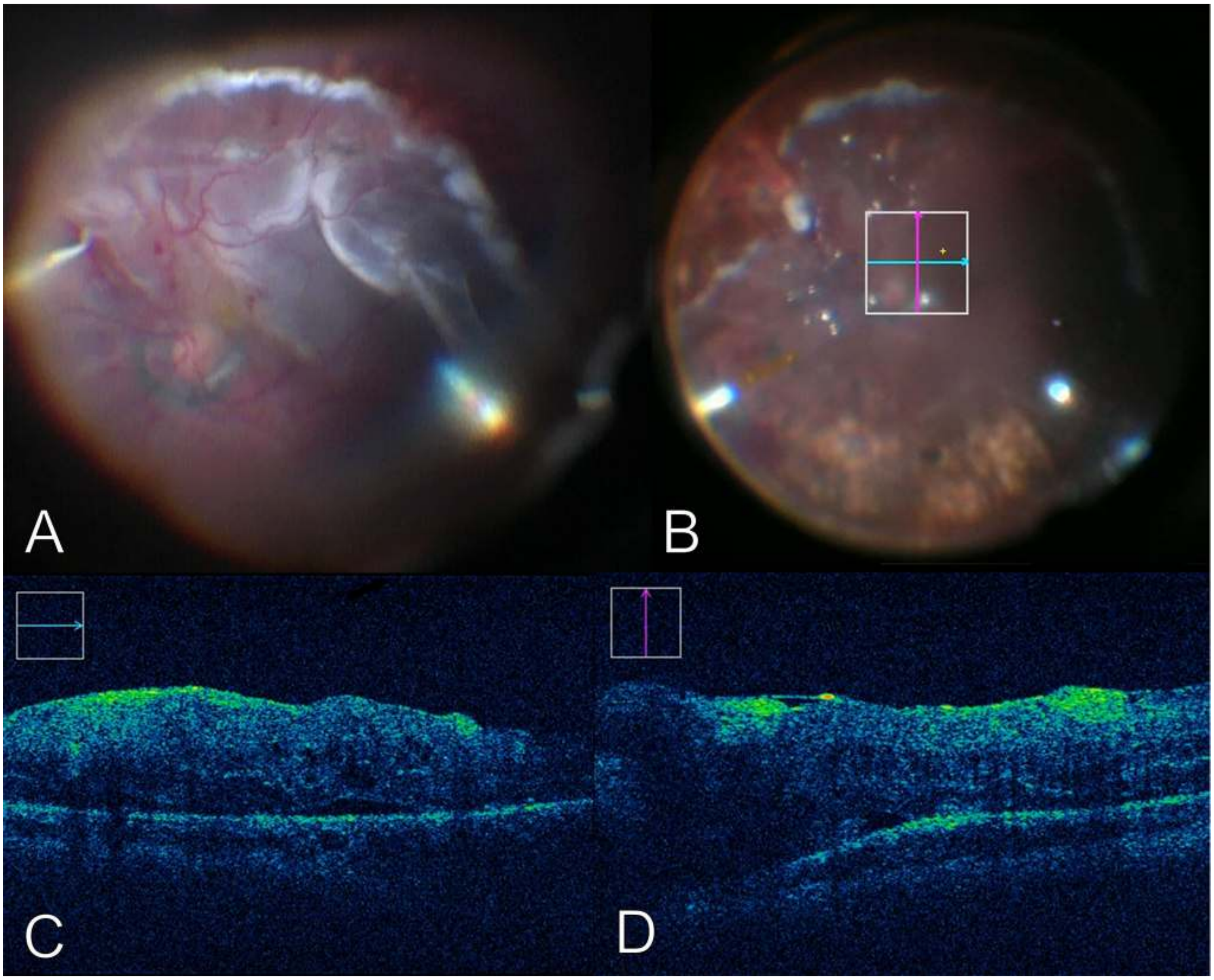

Figure 5. A successful utilization of intraoperative OCT for complex surgical pathology

(**A**) Funduscopic image of retinal detachment with severe proliferative vitreoretinopathy. Existence of subretinal membrane prevented retinal attachment. Application of peripheral circumferential diathermy is seen. (**B**) Funduscopic view following retinectomy and subretinal membrane removal. Perfluorocarbon liquid are infused to stabilize and flatten the retina. (**C, D**) Horizontal and vertical intraoperative OCT B-scans demonstrate reattachment of the posterior retina with subclinical subretinal fluid. Subtle residual focal membranes and diffuse retinal thickening are also delineated.