Advantages of Using a Ray-traced, Three-dimensional Rendering System for Spectral Domain Cirrus HD-OCT to Visualize Subtle Structures of the Vitreoretinal Interface

Carl Glittenberg, MD; Ilse Krebs, MD; Christiane Falkner-Radler, MD; Florian Zeiler, MD; Paulina Haas, MD; Stefan Hagen, MD; Susanne Binder, MD

BACKGROUND AND OBJECTIVE: To create a ray-traced, three-dimensional display system for Cirrus high-definition optical coherence tomography (Carl Zeiss Meditec, Inc., Dublin, CA) that improves the visualization of subtle structures of the vitreoretinal interface.

PATIENTS AND METHODS: High-definition optical coherence tomography (HD-OCT) data for epiretinal membranes (17 eyes), macular holes (11 eyes), and posterior vitreal detachments (17 eyes) were collected. A display system that visualizes the acquired data using ray-tracing algorithms was designed and compared with the Cirrus HD-OCT 2.0 advanced visualization software system. The area around the vitreoretinal interface was visualized using a 100-µm-thick internal limiting membrane (ILM) fitted slab as well as ILM and retinal pigment epithelium surface reconstructions.

RESULTS: Subtle structures could be visualized more distinctly using the ray-traced, three-dimensional rendering software.

CONCLUSION: A ray-traced visualization system improves the visualization of subtle structures in and around the vitreoretinal interface.


INTRODUCTION

There have been remarkable advances in the field of spectral domain optical coherence tomography (SD-OCT).\(^1\)\(^-\)\(^{17}\) Compared with standard resolution OCT systems, SD-OCT has enabled an approximate 15- to 50-fold increase in data acquisition speed, accompanied by a resolution increase of up to 3 µm attributable to broadband low-coherence light sources.\(^1\)\(^-\)\(^{17}\)

Koizumu et al.\(^{14}\) showed the advantages of using SD-OCT imaging with three-dimensional (3D) reconstruction to comprehensively analyze vitreoretinal pathologies such as vitreoretinal traction and idiopathic epiretinal membranes. They showed that 3D reconstruction can be used to gain a better understanding of the 3D morphology of pathologies in and around the vitreoretinal interface as well as the underlying pathologic mechanisms leading...
to these diseases. Their 3D reconstructions, however, did not use ray-traced shading to visualize the data. We postulate that a ray-traced, 3D reconstruction system would visualize subtle structures of the vitreoretinal interface even more distinctly and could lead to an even better understanding of these pathologies.

Ray-tracing algorithms calculate and visualize shadows being cast and or received by every structure in the specimen. These shadows increase the clarity and sharpness of very subtle structures, such as epiretinal traction lines and traction lines in and around the posterior hyaloid. Most 3D reconstruction systems for segmentational data such as OCT, computed tomography, and magnetic resonance imaging are based on ray-casting algorithms rather than on ray-tracing algorithms. To understand why a ray-tracing system would be able to visualize subtle structures more distinctly, an explanation of the differences between these two rendering systems is important.

Ray-casting algorithms send virtual rays from the camera into the dataset that is to be rendered and analyze the dataset to determine which part of it intersects these rays first. Depending on the properties of the data at that point of intersection, the pixel in the final rendered image corresponding to that point is assigned a color and brightness value. The shading of the 3D data reconstruction is determined by the angle of its surfaces to the virtual light source. Surfaces that face the light source directly will be rendered brightly. Surfaces that face the light source at an angle will be rendered less brightly. The higher the angle from the light source, the less brightly the surface will be rendered. This type of system does not take into account whether another object or another part of the same object is in front of the light source; ie, the 3D data reconstructions do not cast any shadows.

Ray-tracing algorithms are significantly more complex. When the rays sent out from the virtual camera intersect the 3D data reconstruction, three secondary rays are generated. These secondary rays are responsible for calculating the effects of transparency/refraction, reflection, and shadow properties on the rendering of the 3D data reconstruction. For example, when rays hit the 3D data reconstruction, they send out secondary rays to any given light source in the scene. These secondary rays analyze whether another part of the 3D data reconstruction is blocking the light from that source. The algorithms then create an appropriate shadow on the 3D data reconstruction. The strength and shape of the shadow are adjusted according to the translucency/opacity of the different parts of the data reconstruction. These shadows significantly add to the realism and clarity of the rendering. The secondary rays that are created when a primary ray intersects an opaque or transparent part of an object continue the course of the primary ray (unless altered by a refraction setting) until it intersects the next part of the 3D data reconstruction, at which time three new tertiary rays are created.

The capability to visualize ray-traced shadows on 3D reconstructions of OCT datasets significantly increases the clarity of the visualization and the amount of information contained in such reconstructions. The primary drawback with ray tracing and the reason it is rarely used in this context are that the number of rays that need to be calculated is exponentially higher than in ray casting, making rendering speed much slower.

The Cirrus HD-OCT 2.0 (Carl Zeiss Meditec, Inc., Dublin, CA) advanced visualization system software was the onboard visualization software on Cirrus high-definition optical coherence tomography, which we used for the acquisition of data in this study. Although it creates informative surface reconstructions of the internal limiting membrane (ILM) and the retinal pigment epithelium (RPE) as well as useful ILM-to-RPE retinal thickness maps (ILM-RPE RTM), this software version does not contain a comprehensive 3D data reconstruction system. The best way to visualize the vitreoretinal interface using this software version was to use the ILM fitted slab (a summation en-face view whose depth is controlled by the user). However, this view did not give a comprehensive overview of the entire 3D structure of pathologies.

It was the purpose of this study to determine whether it was possible to create an external 3D reconstruction and rendering system for the Cirrus HD-OCT using ray-tracing algorithms, which could distinctly visualize subtle structures of the vitreoretinal interface.

**PATIENTS AND METHODS**

HD-OCT data of patients with vitreoretinal pathologies were collected using an SD-OCT system...
(Carl Zeiss Meditec Cirrus high-definition optical coherence tomography) with an axial resolution of 5 µm, a transverse resolution of 20 µm, a scan speed of 27,000 A-scans per second, an A-scan depth of 2.0 mm, a field of view of 20° × 20°, and an 840 nm superluminescent diode laser. Each eye was scanned using the 512 × 128 macular cube setting, which results in 128 B-mode scans with a pixel resolution of 512 × 1,024 pixels. Line scanning laser ophthalmoscope (LSLO) fundus images were acquired from each patient, using the Cirrus HD OCT’s integrated LSLO.

Three-dimensional surface reconstructions of the ILM, the RPE, the ILM-RPE thickness, as well as ILM fitted slab images (with a slab thickness of 100 µm), were created of each dataset using the onboard software (Carl Zeiss Meditec Cirrus HD-OCT 2.0 advanced visualization system). The 100-µm setting was chosen because it provides the optimum balance between clarity of visualization and amount of information contained in the slab (the slab includes structures of the vitreous, epiretina, and retina).

The single B-mode scans were exported manually as 24-bit bitmaps and converted to the Joint Photographic Experts Group Format (JPEG), which were subsequently imported into the rendering and ray-tracing program Cinema 4D XL 10.5 Studio Bundle (Maxon Computer Inc., Friedrichsdorf, Germany). Additionally, ILM-to-RPE height maps as well as LSLO fundus images were exported from the Cirrus HD-OCT and imported into Cinema 4D. Cinema 4D was chosen because of the quality of its ray-tracing algorithms, its user-friendliness, and its high rendering speed.

A series of subroutines were programmed that allow Cinema 4D to visualize 3D HD-OCT data. One of these subroutines imports the 128 B-Mode scan JPEG images and the LSLO fundus images and creates a ray-traced 3D data reconstruction of each dataset that floats above the corresponding LSLO fundus image (Figs. 1-7). Another subroutine creates 3D ray-traced ILM-to-RPE thickness maps, which also float above the corresponding LSLO fundus image. Both subroutines used ray-traced shading, which let the reconstructions throw shadows on themselves. Several additional subroutines were also created to manipulate the 3D-reconstructions in virtual space, perform 3D measurements, and morph preoperative to postoperative reconstructions. To discover whether ray tracing offers an advantage over ray casting, a parallel set of subroutines was created that do not use ray-traced shading.

The 3D visualizations (with ray tracing turned on and off, respectively) created with our subroutines were then compared with the visualizations created by the Cirrus HD-OCT onboard software to determine whether the ray-traced system really can provide additional information about the vitreoretinal interface.

RESULTS

HD-OCT data from 45 patients with epiretinal membranes (17 eyes), macular holes (11 eyes), and posterior vitreal detachments (PVD) (17 eyes) were collected. It was possible to create an effective ray-traced rendering and visualization system for the Cirrus HD-OCT using the subroutines programmed in Cinema 4D. Depending on the complexity of the data and the resolution and quality settings of the final images, the rendering time per image ranged from several seconds to several minutes (if print quality was desired).

In all datasets, the use of ray-traced rendering improved the clarity of subtle structures of the vitreoretinal interface compared with the onboard software visualization system of the Cirrus HD-OCT as well as to the nonray-traced 3D visualization system created for the study. The following examples show how the ray-traced rendering system increases the amount of information that can be gained from a dataset.

In Figures 1 through 6, the top row shows a spectral domain B-mode scan and an LSLO fundus image with an overlay of an RTM. The second row from the top shows the 3D surface reconstructions (ILM, RPE, and ILM-RPE) as well as a 100-µm ILM thickness slab created by the onboard software of the Cirrus HD-OCT. The third row from the top shows images from the 3D rendering system we created for the study with ray-traced shading turned off. The bottom row shows the same images from the 3D rendering system we created for the study with ray-traced shading turned on.

Healthy Patient With Slight PVD

Figure 1 shows images from a healthy patient with slight PVD. In the 3D surface reconstruction of
the ILM as well as in the ILM fitted slab (second row from top), structures of the vitreous are not visible at all. In the 3D reconstruction without ray-traced shading (third row from top), structures of the vitreous are visible, but the insufficient contrast makes it difficult to differentiate them from structures under or behind them. The 3D reconstruction system with the ray tracing turned on (bottom row) distinctly visualizes the shape of the papilla, the macula, and the retinal vessels. It also clearly visualizes vitreal floaters as well as the point where the PVD may be adherent to the papillary rim. This may also be part of Cloquet’s channel (white arrow).

Figure 1. The 3D reconstruction system with the ray tracing turned on (bottom row) distinctly visualizes the shape of the papilla, macula, and retinal vessels in a healthy patient with slight PVD. It also clearly visualizes vitreal floaters as well as the point where the PVD may be adherent to the papillary rim. This may also be part of Cloquet’s channel (white arrow).

Figure 2. Images for PVD and VMT. The placoid bands of hyperreflectivity (large white arrow) that extend from the back of the PVD into the area of retinal adhesion are visualized more distinctly using the 3D reconstruction system with the ray tracing turned on (bottom row), where it is clear that these bands surround the entire area of retinal attachment. The traction forces within the vitreous itself are also visualized more clearly using ray-traced shading (small white arrow) showing that the traction lines all point directly to the area of the retinal adhesion directly over the CNV (asterisk). The image in the center of the bottom four images shows a fluorescence angiography of this patient.

Patient with PVD and Vitreomacular Traction (VMT)

Figure 2 shows images from a patient with PVD and VMT over a beginning choroidal neovascularization (CNV). The diagnosis was verified with fundus examination, ultrasound studies, and fluorescein angiography. As described previously in other patients by Koizumi et al., the patient has a convex PVD with placoid bands of hyperreflectivity that extend from the back of the PVD into the area of retinal adhesion. Epiretinal membrane (ERM) formation can be seen in the area beneath the PVD. In the 3D surface reconstruction of the ILM as well as in the
ILM fitted slab (second row from top), the PVD itself cannot be visualized at all. The area of retinal adhesion, however, can be visualized very well, as can the ERM formation under the PVD. In particular, the ILM fitted slab visualizes the ERM formation around the area of retinal attachment very well.

In the 3D reconstruction without ray-traced shading (third row from top), the PVD, VMT, and ERM are visible, but the insufficient contrast makes it difficult to differentiate the placoid bands of hyperereflectivity that extend from the back of the PVD into the area of retinal adhesion. These are visualized more distinctly using the 3D reconstruction system with the ray tracing turned on (bottom row), where it is made clear that these bands surround the entire area of retinal attachment. The traction forces within the vitreous itself are also visualized more clearly using ray-traced shading, showing that the traction lines all point directly to the area of the retinal adhesion directly over the beginning CNV. When rendered in a resolution of $640 \times 480$ pixels on a 2.13-GHz dual core desktop computer, the rendering time for the ray-traced full reconstruction was 9 seconds.

**Patient With Thick ERM**

Figure 3 shows images from a patient with an ERM, which is partially detached. The diagnosis was confirmed clinically through fundus examination and ultrasound examination. In the 3D surface reconstruction of the ILM as well as in the ILM fitted slab (second row from top), the ERM itself cannot be visualized at all; only the wrinkling of the retina is visible. In the 3D reconstruction with ray tracing turned off (third row from top), the lack of contrast makes it difficult to differentiate between the membrane and the retina below. The wrinkling of the retina cannot be seen at all. The 3D reconstructions with ray tracing turned on (bottom row) clearly show the 3D structure of the membrane as well as the wrinkling beneath it. When rendered in a resolution of $640 \times 480$ pixels on a 2.13 GHz dual core desktop computer, the rendering time for the ray-traced full reconstruction was 6 seconds.

**Patient With Idiopathic ERM**

Figures 4 and 5 show the preoperative and postoperative (pars plana vitrectomy with membrane peeling) images from a patient with idiopathic ERM. In Figure 4, the ray-traced visualizations (bottom row) show the wrinkling of the retina much more clearly than the other visualizations. They also show that the wrinkling points toward an area where there is an elevation of the ERM, which may have been caused by a focal vitreoretinal traction. This elevation cannot be seen in the other visualizations (top three rows). The ray-traced visualizations in Figure 5 (bottom row) show that although the wrinkling of the retina is completely gone after the surgery, there are three small areas where what may be some membranous structures remain. That these are in-
deed membranous structures cannot be verified at this time. Additional examinations of the patient over time will perhaps determine whether these areas actually correspond to ERM and any possible clinical significance. These three areas cannot be visualized with the other systems (second and third rows from top). They are also not visible in the B-mode scan (top left) and seem to appear only as a summation of signals from several adjacent B-mode scans when visualized with ray-traced shading. All images show a remaining foveal thickening after the surgery. When rendered in a resolution of 640 × 480 pixels on a 2.13-GHz dual core desktop computer, the rendering time for the ray-traced full reconstruction was 7 seconds for the preoperative image and 6 seconds for the postoperative image. The preoperative visual acuity of this patient was 0.64 (EDTRS at 4 m) and increased to a postoperative visual acuity of 1.0 (EDTRS at 4 m).

**Patient With Macular Hole**

Figures 6 and 7 show a patient with a macular hole. The unsatisfactory contrast in the LSLO image in Figure 6 is a result of poor media in the patient. The 3D reconstruction with ray tracing (bottom row) shows not only the hole itself more distinctly than the other visualization systems (top three rows), but also a slight perifoveal retinal wrinkling that is nearly missed by the ILM fitted slab and is not visible in the ILM surface reconstruction at all. This wrinkling is very subtle and barely visible in the B-mode scans. Only with the contrast offered...
by ray-traced shading can the wrinkling be made visible. When rendered in a resolution of 640 × 480 pixels on a 2.13-GHz dual core desktop computer, the rendering time for the ray-traced full reconstruction was 5 seconds.

**DISCUSSION**

The examples above clearly show that ray-traced shading in 3D reconstructions of SD-OCT data can considerably increase the clarity of visualizations of the vitreoretinal interface compared with both the onboard software of the Cirrus HD-OCT as well as our nonray-traced comparison system. Whether our system visualizes structures more clearly than nonray-traced 3D visualization systems used on other hardware platforms cannot be definitively determined without performing a direct comparison of the same patients, using different hardware platforms. It appears, however, after reviewing the literature on the subject, that the ray-traced system we created for this study visualizes PVD, ERM, and macular holes considerably more distinctly and in greater detail than other comparable systems on other hardware platforms.9,14 The obvious drawback is, of course, the long rendering time of our system.

The ability to visualize these subtle structures more distinctly will be useful for illustrative and educational purposes. This technology may also help lead to a better understanding of the 3D structure of pathologies as a whole, which could lead to a better understanding of their pathogenesis. In Figure 1, the ray-traced imaging provides an improved overview of the 3D structure of the specimen but offers no real diagnostic advantage other than a clearer visualization. This is useful for illustrative and educational purposes but has little clinical relevance. Figure 3, however, clearly shows that ray tracing improves the visualization of the location and size of the placoid bands of hyperreflectivity on the back of the posterior hyaloid, as well as the traction forces within the
PVD itself, which could lead to a better understanding of the microstructure of PVD and VMT.

Figures 2 through 4 show that ray tracing improves the visualization of epiretinal membranes, which could aid in earlier diagnosis of these membranes and may help improve treatment strategies. In Figure 2, the traction forces within the vitreous itself are also visualized more clearly using ray-traced shading, showing that the traction lines all point directly to the area of the retinal adhesion directly over the CNV. This gives credence to the postulation by Krebs et al.\(^\text{18}\) that there is a correlation between posterior vitreal adhesion and the development of exudative age-related macular degeneration. Although the ERM below the PVD is visible without the ray tracing, the ray tracing increases the visibility of the extent and location of the ERM in relation to the PVD. In Figure 4, the area where the traction lines in the ERM focus would have been completely missed using the other visualization methods. Such information could provide insight into the pathogenesis of ERMs.

Figure 5 shows that it is possible to visualize small remnants of ERMs after surgery, which may help clarify when and why ERMs reoccur. Figure 6 shows that it was possible to show a subtle perifoveal wrinkling of the retina, which would have been completely missed using other visualization methods. This could also aid in the earlier diagnosis of these membranes. The impact of this visualization method on the understanding of the vitreoretinal interface is speculative at this time and warrants additional investigation. All of the above-noted vitreoretinal pathologies need to be studied in more depth using this new technology to establish its actual benefit.

Whether ray tracing can improve the diagnostic visualization of SD-OCT data on a clinical basis is uncertain. Although each image only takes between 5 and 10 seconds to render, at this time, the rendering time of ray-traced reconstruction is too slow to be applicable on an everyday basis. For this system to be practical, it needs to be able to render the data in real time. We are designing a system that would achieve the clarity of the above examples in real time. This new system would have to be tested in a clinical setting to verify whether ray tracing is diagnostically beneficial.

Although the ray-traced system we developed shows considerably more detail than the visualizations provided by the onboard software of the Cirrus HD-OCT, the RPE and ILM surface reconstructions of the Cirrus HD-OCT, as well as its ILM-to-RPE retinal thickness maps, are informative and considerably more time efficient than our ray-traced system. Reportedly, the upcoming Cirrus HD-OCT software version will include a nonray-traced, real-time 3D reconstruction system. This would be a useful addition to the Cirrus HD-OCT to obtain an immediate overview of the 3D structure of a pathology. The ray-traced system described in this article could then be used as an external adjunct to the onboard system to investigate selected patients more closely for scientific purposes and visualize pathologies more distinctly for illustrative and educational purposes.

**REFERENCES**


