Visualization of Three-Dimensional Ultra-High Resolution OCT in Virtual Reality

Jürgen P. SCHULZE [a,1], Claudia SCHULZE-DÖBOLD [b],
Ali ERGINAY [b], Ramin TADAYONI [b]
[a] *Calit2, University of California San Diego, La Jolla, CA, USA*
[b] *Ophthalmology Department, Lariboisière Hospital, APHP, Paris, France*

Abstract. Three-dimensional reconstruction of optical coherence tomography (OCT) images is a modern technique that helps interpret the images and understand the underlying disease. However, the 3D reconstruction displayed on commercial devices is of limited quality: images are shown on 2D screens and it is difficult or impossible to adjust the view point and capture the data set from a meaningful perspective. We did a preliminary study to evaluate the applicability of a novel, 3D TV-based virtual reality system with interactive volume rendering software to clinical diagnostics and present a workflow, which can incorporate virtual reality technology at various levels of immersion into the daily medical practice, from interactive VR systems to printed media.

Keywords. OCT, virtual reality, direct volume rendering, real-time rendering

1. Introduction

Optical coherence tomography (OCT) was introduced in 1991 and permits in-vivo non-invasive imaging of ocular structures [1]. At the present time, retinal structures can be shown with an axial resolution of 3-7µm by ultra-high resolution OCT [2,3]. Three-dimensional (3D) OCT permits to acquire an image of all retinal layers of a predefined volume [4]. Most of the current OCT devices have software for reconstructing and visualizing a 3D image from the OCT slides. However, they do not offer state-of-the-art visualization techniques. The 3D OCT reconstructions are viewed on conventional 2D screens without the possibility to view stereographic 3D. Furthermore, the view is typically limited to opaque axis-parallel slices without the ability to map opacity to the data values and see through unimportant parts. The applied image processing often reduces the visual quality below that of the original slices. With the built-in software, it is often difficult or impossible to adjust the view point.

In the past, few approaches have been taken to solve these problems by using advanced visualization techniques. Aaker et al. [5,6] used a 4-walled CAVE, which displays a 3D reconstruction of an OCT data set after segmenting it into semantically different components. This segmentation does not happen automatically or in real-time, and has to happen as a pre-processing step before the data can be viewed in the virtual reality (VR) environment. It also aims at a different visual representation than the one we are pursuing with our direct volume rendering approach, which does not require any pre-processing.

[1] Corresponding author e-mail: jschulze@ucsd.edu

Glittenberg et al. [7] ray-trace 3D OCT image stacks to create images with correct shadow representation. However, compared to our approach, theirs takes multiple seconds to render an image and is thus not useful for head-tracked VR, where update rates of 10 frames per second (fps) and more are required. Furthermore, interactive changes of the transfer function are tedious with such long rendering times.

2. Methods & Materials

In our study, we used the images of a tightly spaced (11-30 µm, ART ≥ 20) macular cube of three different retinal pathologies, acquired with the Heidelberg Spectralis OCT. For the 3D reconstruction, we used our own direct volume rendering (DVR) software Virvo [8]. Virvo renders a set of screen-parallel textured polygons to approximate a ray-casting rendering approach with alpha blending. It is very fast and produces high-quality images at interactive frame rates of 10+ fps. This software is available either as a standalone application for desktop PCs (DeskVox), or as a module for the VR framework COVISE (CaveVox), which runs on PC cluster-based VR systems. No segmentation or pre-classification is required. The data from an OCT can be viewed within minutes of scanning the patient's eye, after exporting the scanned image stack to a set of slice images.

2.1. Desktop PC

The slice images from the OCT device can be directly read into the DeskVox software with a built-in import function, and can later be saved to a single volume file (XVF file) for later use in DeskVox or CaveVox. DeskVox runs on Microsoft Windows®, Apple Mac OS® and Linux and is thus accessible to most clinicians. By using a graphical transfer function editor, the user can adjust the color and opacity settings until the image shows the features of interest for the clinician. The transfer function can then be stored with the images in the XVF file. In addition to the transfer function editor, the user can enable a region-of-interest box to constrain the displayed data area, or an arbitrarily oriented clipping plane to cut into the data set along a plane.

2.2. NexCAVE

In our laboratory at Calit2, the VR system CaveVox runs in our NexCAVE, which is a novel, 3D TV-based VR system, consisting of ten 46" diagonal passive stereo displays in a 3x3 array, with an additional display below the middle column (see Figure 1). To see 3D images, the user wears lightweight polarized 3D glasses. The NexCAVE is brighter and has an order of magnitude higher contrast than high-end projector-based VR environments [9], which makes it particularly attractive for medical use. It uses an optical tracking system to track the user's head and a wireless wand for 3D interactions.

OCT data is loaded into the CaveVox system by means of an XVF file. This file can either be created with DeskVox, or our command line conversion tool Vconv. Changes of color, opacity, brightness and contrast can be made in real-time directly from within the VR system by using a built-in graphical transfer function editor. Regions of interest and clipping planes are available just as in DeskVox, with the added convenience of positioning them with the 3D wand.

Figure 1. User in the NexCAVE with CaveVox, showing data set, menus and transfer function editor.

2.3. Anaglyph Images

Volume rendering software provides a great way to view 3D OCT scans interactively, but is not practical for the dissemination of results through traditional channels of paper-based media, such as patient records, publications, or scientific posters. For these cases, we use high resolution anaglyph stereo images, which can be viewed with inexpensive 3D glasses. In our current workflow, we produce these images by using an SLR camera on a special tripod mount, which allows taking two pictures from points an eye distance apart from one another. By taking these pictures in the NexCAVE, we can achieve a resolution of up to 9 times high definition (HD), if we photograph the 3x3 array of HD monitors.

We convert the two photographs to anaglyph in Photoshop, by converting them to grayscale and coloring each of them in their respective anaglyph colors (we use red and cyan), before alpha blending them together. This process can alternatively be done with one of many specialized stereo image processing programs available on the internet. The result is a color image, which can be printed on paper with any color printer and viewed with red/cyan anaglyph stereo glasses.

3. Results

Using the OCT image stack of a macular hole, captured with a field of view of 5°x15° and a slice distance of 11µm as an example, we compare the OCT device's internal visualization software (Figure 2) to DVR images in DeskVox, CaveVox, and an anaglyph image.

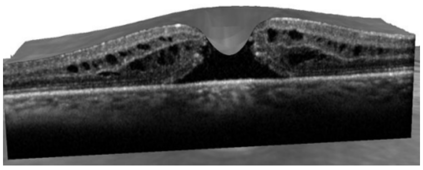

Figure 2. 3D view of the macular hole created by the built-in software of the Heidelberg Spectralis OCT.

3.1. Desktop PC

DeskVox is superior to the OCT's built-in visualization software because it allows viewing the entire data set with DVR technology, rather than just showing opaque cross-sections and surfaces. The image resolution is much better than on clinically available devices, and it enables visualization in depth and of detailed retinal structures is possible. Combined with the interactive transfer function editor and the clipping tools, DeskVox allows much more detailed analysis of the data (see Figure 3, left). However, compared to the NexCAVE version, the lack of a stereographic 3D view and head-tracking makes it harder to find good viewing angles.

3.2. NexCAVE

We found that the images in the NexCAVE (see Figure 3, right) show details more clearly and are much easier to view than the other methods thanks to head-tracked stereo, which allows rapid and intuitive changes of the viewpoint. Thanks to the integrated transfer function editor, it is easy to change the visual parameters of the image without having to go back to a desktop PC. The 3D reconstruction of retinal pathologies shows details which are hard to discern in conventional OCT images. For example, the wall of the macular hole can be seen at an exceptional level of detail when the user's viewpoint is placed in the center of the hole.

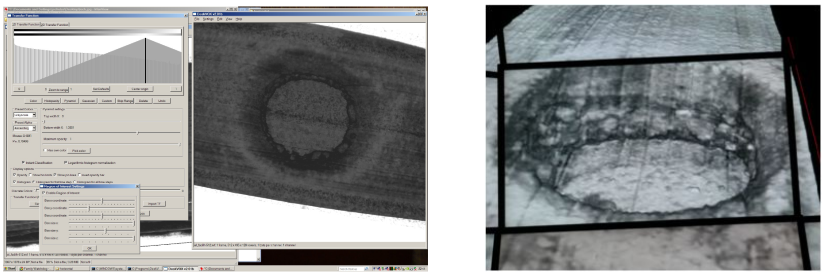

Figure 3. Macular hole in DeskVOX (left) and CaveVox in the NexCAVE (right).

3.3. Anaglyph Images

Despite our crude way in which we created our anaglyph images, which is by photographs of the images in the NexCAVE, these images turned out to be extremely useful in our own observation, as well as countless anecdotal comments by ophthalmologists at the ARVO conference in 2012, where we presented a poster with three such images, and provided anaglyph glasses to the audience [10]. We were surprised how little this decades-old technology is used in the field, yet how useful it can be. An important observation in this context is that although anaglyph has the disadvantage of virtually eliminating the original colors of an image, this is not an issue in the case of OCT images, because these are best viewed as grayscale images anyways. Figure 4 shows the macular hole as an anaglyph image.

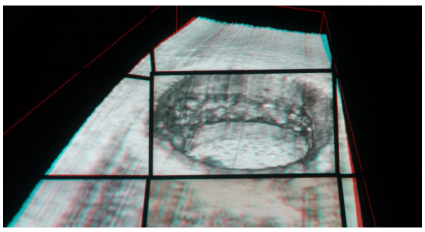

Figure 4. Macular hole in anaglyph 3D, viewable with red-cyan glasses, if image shown in color.

4. Conclusions

Extraordinarily high-quality 3D OCT image reconstruction and visualization can be achieved with modern VR systems and is of great value in clinical analysis. They allow better utilization of the technical advances of OCT devices with ultra-high resolution and 3D acquisition in a clinical environment. These VR systems can process OCT image stacks instantly into high-quality 3D pictures, which can be interactively viewed. New 3D TV-based VR systems are sufficiently compact and affordable to be installed in a medical unit. Alternative display options, such as desktop-based DVR, and anaglyph printed stereo images complement the VR system when VR is not necessary, or computers are not available for documentation and distribution of results. To our knowledge, we present the first use of interactively rendered DVR with 3D OCT image stacks, as well as the first use of anaglyph stereo for their dissemination in printed media.

In the future, we want to integrate rendering anaglyph images into our Virvo library, so that we can create high resolution anaglyph images of OCT data without having to use a camera.

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