

Visual Analysis of Optical Coherence Tomography Data in Ophthalmology

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Abstract

Optical coherence tomography (OCT) enables noninvasive high-resolution 3D imaging of the human retina and thus, plays a fundamental role in detecting a wide range of ocular diseases. Despite OCT's diagnostic value, managing and analyzing resulting data is challenging. We apply two visual analytics strategies for supporting retinal assessment in practice. First, we provide an interface for unifying and structuring data from different sources into a common basis. Fusing that basis with medical records and augmenting it with analytically derived information facilitates thorough investigations. Second, we present a tailored visual analysis tool for presenting, selecting, and emphasizing different aspects of the attributed data. This enables free exploration, reducing the data to relevant subsets, and focusing on details. By applying both strategies, we effectively enhance the management and the analysis of OCT data for assisting medical diagnoses.

Categories and Subject Descriptors (according to ACM CCS): Human-centered computing – Visualization – Visualization application domains – Visual analytics

1. Motivation

In the context of ophthalmology, optical coherence tomography (OCT) is a widely applied method to support the medical diagnosis of various ocular diseases. Based on 3D imaging of the human retina, many medical conditions can be detected. The diagnostic procedures involve searching for subtle retinal changes, analyzing multiple OCT datasets, and correlating findings with other clinical information. Yet, already exploring a single volumetric OCT dataset can be difficult, let alone comparing details in multiple of them. This becomes even more complex if different data formats have to be dealt with, e.g., in case of datasets from different OCT devices. Hence, managing and analyzing OCT data and relating them to other information are challenging and time-consuming tasks.

We present a visual analytics (VA) approach to address the peculiarities of OCT data: (i) data originating from different acquisition modalities and (ii) volumetric data of high spatial resolution combined with extracted information. Our contributions are:

Unified Data Management: We convert and structure OCT data from different sources into a common basis, allowing unified data access and management. We fuse that basis with other medical records and augment it with analytically derived information.

Visual-Interactive Analysis: We propose a novel visual design for presenting and emphasizing different aspects of the data. Coordinated interaction facilitates exploration, selecting relevant subsets, and inspecting details on demand.

2. Background

The structure of the multi-layered retina in the posterior segment of the eye cannot be examined with conventional ophthalmic methods. With OCT-based retinal imaging it is possible to display different layers of the retina and provide unmatched detail and contrast images. This improves the diagnosis of pathologies [YHI14], e.g., diabetic retinopathy, age-related macular degeneration, and glaucoma-induced retinal changes. The OCT procedure is noninvasive and completely safe without light hazard.

OCT devices are commonly based on spectral domain optical coherence technology. A laser beam scans the retina using dedicated scanning patterns in combination with active eye tracking. In this process, multiple 2D image slices are acquired and subsequently combined into 3D tomograms. For example, datasets from the Spectralis OCT (Heidelberg Engineering) can have a maximal resolution of 7 μm axial, 14 μm lateral, and 1.8 mm scan depth (1536 \times 1536 \times 512 pixels). Complementary segmentation algorithms are applied on these volumetric datasets to extract up to 11 retinal layers [EWF*14]. Altogether, typical OCT datasets contain one 3D tomogram composed of multiple 2D image slices, several extracted layers, and one fundus image of the interior surface of the eye around the OCT acquisition area.

Given this amount of data, it is challenging to identify subtle and localized changes of various abnormal conditions of the retina. Conventional analysis procedures target predefined retinal abnor-

mal conditions based on excessive global data reduction with regard to both, space and information [KRK13]. As a result, entire OCT datasets are represented by few aggregated values. But, the outcome does not disclose subtle local variations. Identifying such characteristics can be simplified and they can be effectively processed using our new VA approach.

Commercial Tools: In practice, managing, analyzing, and presenting OCT data is done via commercial software tools distributed by OCT device manufactures. Modern 3D retinal imaging has led to advances regarding the display and analysis functionality [WSF*05, MPY*16]. Yet, commercial software typically matches the respective device's capabilities and hence, software features often differ between tools.

For managing OCT data, users have to rely on device-specific file formats and databases. This prohibits the exchange of OCT data and complicates comparing datasets from diverse manufactures. Recently, a common data format and an interface to convert data from different sources have been introduced [RRKH16].

For analyzing OCT data, users take measurements based on OCT tomograms directly or based on prior extracted retinal layers. Yet, supporting algorithms and associated parameters are proprietary and thus, deviations between measurements may occur [RRKH16]. This makes comparisons of analysis results from different tools error-prone. Moreover, available analysis methods tend to oversimplify the data. Typically, the tomogram is subdivided into coarse sectors and for each sector aggregated measurements are retrieved. While this reduces the amount of information that has to be examined, it also renders the analysis results spatially unspecific.

For displaying OCT data, three types of presentations are common. First, the acquired 2D image slices are shown individually. This allows to view details but flipping through the images is time-consuming. This can be problematic, especially in case of datasets with hundreds of images. Second, a fundus image is shown together with superimposed retinal layers. This helps to link the layers to the fundus but the layers can only be examined one at a time. Hence, relating multiple layers remains difficult. Third, the OCT tomogram is shown in 3D. This provides an overview of the data but adjusting the visual representation, e.g., via navigation, is often limited. Also, combined 3D visualizations of the tomogram and the layers are typically not available and thus, spatial relationships might go unnoticed. Other drawbacks include inappropriate color-coding hard-wired into the tools, lacking consideration of data quality, and limited support for additional information.

Related Work: Besides commercial software, few approaches for visually analyzing OCT data exist. The open-source software ImageJ can be used to analyze OCT images [SRHE15]. Instead of extracted retinal layers, reflectivity profiles allow to characterize retinal conditions [GBM*14]. 3D visualization based on ray-tracing and artificial shadows shows subtle structures more distinctly but images can take multiple seconds to render [GKFR*09]. Likewise, virtual reality can be employed to enhance spatial perception and facilitate an immersive data access [AGM*11, SSET13]. However, selecting and comparing parts of multiple datasets or relating them to other information is often not considered. Real-time 3D rendering has also been studied to enable online display of OCT

tomograms during acquisition and to preselect relevant subsets for reduced storage costs [PKH09, SSST11]. Yet, in-depth analysis of details still has to be done in a post-acquisition stage.

In summary, existing works offer different approaches for managing, analyzing, and presenting OCT data. Yet, each solution covers only a certain aspect. Our goal is to develop an integrated approach that (i) incorporates previous efforts regarding a common data basis, (ii) extends that basis with supplementary information, (iii) visualizes and emphasizes different aspects of the attributed data, and (iv) allows selecting relevant subsets. With the resulting flexibility, we are able to address the peculiarities of OCT data and support the retinal assessment. To this end, we collaborate with domain experts, including ophthalmic research scientists and ophthalmologists who deal with the treatment of retinal diseases. Following a participatory design, we jointly identify challenges, devise suitable visualizations, and gather informal feedback to ensure maximal practical relevance of the resulting designs.

3. Unify, Structure & Fuse Data

No matter if clinical or research use is intended, it is often beneficial or at times even needed to take data from different OCT devices into consideration. The most problematic part with this is the fact, that manufacturers only provide software for the data of their own OCT scanners. Consequently, there is no approved way of viewing, analyzing, or comparing data from different manufactures. Furthermore, there are only limited possibilities to implement own prototypes to perform such tasks, since software libraries are provided with exclusive licenses and incomplete data specifications.

To develop VA solutions for OCT data, it is essential to find a remedy for that issue. On this account, we adapt and extend the work by Rosenthal et al. [RRKH16]. Recently, they introduced a common library (UOCTE) that is capable of parsing data from the majority of current devices, e.g., Nidek, EyeTec, Topcon, and Heidelberg Engineering. In addition, they developed an associated viewer with functionality comparable to commercial tools, including layer extraction [KRR14], and display of OCT data and metadata.

Based on the UOCTE library, we map the data from different devices into one common domain. The result is independent from constrained manufacturer-provided functionality and it opens up new possibilities for data unification. To structure the data, we utilize a common data modeling language (UOCTML), which accompanies the library. UOCTML consists of an easily amendable XML file and a set of binary files for fundus, tomogram, and layers. This way, we are able to fuse the data with analytically derived information and other medical records. Particularly, the layers are enriched with derived attributes, including thickness, curvature, homogeneity, and deviations of such attributes from reference data. This is to inject into the data meaningful information that can help to characterize the condition of the retina. For each attribute, we compute a ranking of the layers based on the distribution of attribute values and their spatial locations. This helps users to focus on layers with abnormal characteristics.

On top of the common data basis, we develop a visual analysis tool with augmented visualization techniques for the attributed OCT data, which will be specified in the next section.

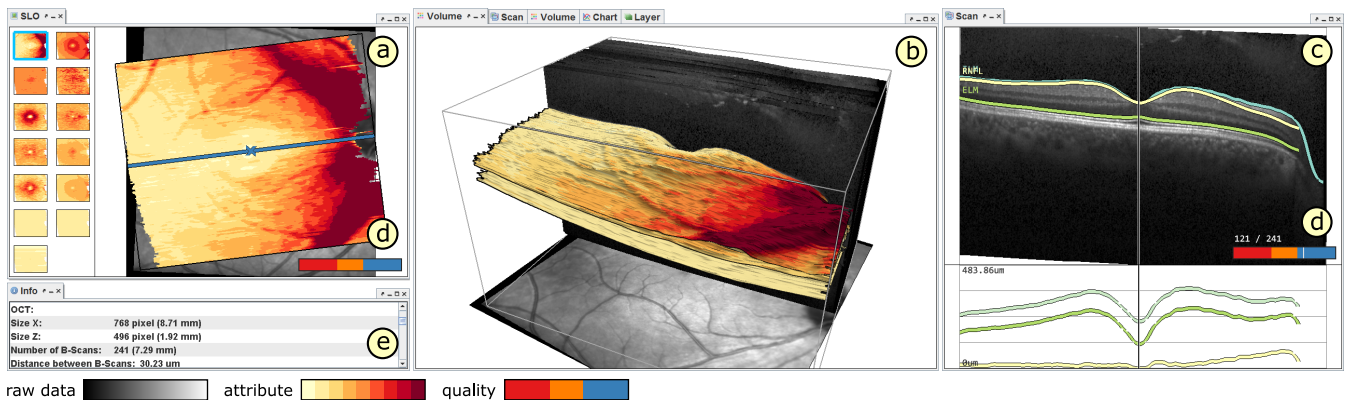


Figure 1: Overview of our prototypical visual analysis tool. The user interface allows to add and arrange multiple linked views for visualizing different aspects of OCT data. Depicted are (a) a top-down view of the fundus overlaid with a derived attribute map, (b) a 3D view showing a volume visualization together with retinal layers as surfaces, (c) a cross-sectional view with extracted layers and a detail chart, and (e) a view for supplementary information. The signal strength of slice images is color-coded and shown together with associated legends (d).

4. Visualize, Select & Emphasize Data

We aim at supporting users in visually analyzing OCT data and related information. For this purpose, we design a flexible visualization tool based on multiple coordinated views. Our tool supports: (i) visualizing the data, (ii) emphasizing details, and (iii) selecting subsets. Figure 1 shows an overview of the user interface.

Visualizing Data: Our solution shows raw data together with extracted layers, considers derived information, takes the quality of the data into account, and facilitates the exploration of relationships. To show different aspects of attributed data, we support four types of views: (i) a 2D top-down view, (ii) a 3D view, (iii) a 2D cross-sectional view, and (iv) a view for related information.

The *2D top-down view* visualizes the OCT acquisition area on top of a fundus image (Fig. 1a). Each image slice is represented as a line. All extracted retinal layers are shown as thumbnails on the side, ordered according to the computed rankings. Optionally, the thumbnails can be enlarged and superimposed over the fundus image. Derived layer attributes are color-coded using suitable and adjustable palettes [HB03]. This design extends existing displays, in that it provides an overview of attributes for all layers without having to flip through them manually.

The *3D view* shows the OCT data via direct volume rendering together with extracted layers as surfaces (Fig. 1b). Blending both 3D presentations helps to relate the tomogram to the layers. On demand, the layer surfaces are color-coded based on derived attributes. This illustrates interrelations between attribute values and the layer shapes. For spatial reference, a fundus image is mapped onto a plane which can be vertically moved through the display.

The *2D cross-sectional view* depicts the acquired 2D image slices individually (Fig. 1c). The extracted layers are displayed as superimposed lines along the horizontal image axis. This allows to identify the exact layer profiles and to visually check for segmentation errors. A detail chart shows plots of derived attributes of a single layer or of multiple layers. The chart is positioned below the

slice images and aligned horizontally to maintain the spatial context. Layers and plots are associated with unique colors.

Data quality is an important characteristic of OCT data. Therefore, in the first three views, missing values are either mapped to a special highlighting color to bring them to the users attention or to a background color to focus on certain parts of the data instead. Moreover, quality measures, e.g., the signal strength for 2D image slices, and associated legends are displayed in each view (Fig. 1d).

The *information view* displays general properties of the dataset, logs about selected values, or other patient-related records (Fig. 1e). Depending on the type of information, different basic visualizations are available, e.g., tabular presentations or document viewers. This allows users to directly check the additional information together with the different perspectives of the OCT data shown in the other views, and without having to rely on external software tools.

Emphasizing Data: We support users in comprehending the data by emphasizing details and relationships. Particularly, we provide methods for both spatial and data-oriented accentuation.

Spatial emphasis conveys the spatial properties of the visualized data. This is crucial in the 3D view. We consider two illumination methods: a local technique based on a directional lighting model and a global approach based on ambient aperture lighting [OS07]. Directional lighting illustrates the general shape of the volumetric data and enhances the perception of small-scale spatial structures. Ambient aperture lighting highlights details and relationships between neighboring parts on the layer surfaces. Stylization further emphasizes certain spatial properties. On the one hand, enhancing edges makes it easier to distinguish spatial features of the tomogram and the layers. On the other hand, customized toon-shading generates a continuous abstraction of the layers that also reinforces the perception of depth [BTM06]. Optionally, stereoscopic rendering can be activated to further facilitate 3D spatial perception.

Data-oriented emphasis highlights values of interest and steers the user's attention. For this purpose, we utilize three visual variables: color, transparency, and blur [HPK⁺16]. In the 2D and 3D

views, visual prominence is controlled via an interactive transfer function editor. The editor modifies the visual encoding to either strengthen or attenuate the influence of values in the rendered images. For instance, invalid values may be filtered out by lowering their opacity. Other value ranges can be assigned to special color palettes to compare them in the different views. The views are linked with the editor and automatically update according to user input. Figure 2 shows an example of modified colors for identifying abnormal attribute values. To further steer the user's attention, data-oriented emphasis is generated via customized depth-of-field rendering [KMH01]. Regions with values of interest are depicted sharply, whereas their surroundings are blurred in the visualization. This helps to focus on details and to maintain the context at once.

Spatial emphasis and data-oriented emphasis can also be combined. In the 3D view, different characteristics of the tomogram are accentuated via various composition modes. For example, by applying maximum intensity projection, enhanced edges, and adapted color-coding, regions with high values can be identified.

Selecting Data: We support users in exploring large OCT datasets via selections of relevant subsets. Subsets are interactively defined both spatially and data-driven.

Spatial selections enable users to specify regions of interest. We integrate various selection methods based on points and geometric shapes. Individual points can be selected in all views to show their assigned values via tooltips. In the 3D view, tomogram and layer selections are realized via interactive clipping geometry, including planes, spheres, or layer surfaces. For example, clipping the tomogram via adjustable planes helps to relate selected parts to the layers (Fig. 2). In the 2D views, polygon selection allows users to interactively set multiple corners to define spatial regions of interest. Users can choose to apply such selections to single image slices and layers, or to groups of them. This way, inspecting the same regions in different parts of the data is possible. All spatial selections can be expanded or reduced using binary operations.

Data-driven selections permit users to specify value ranges of interest. For raw OCT data, the transfer function editor facilitates selecting one or multiple value ranges. To support such selections, a histogram is shown for reference. For derived attributes, users can choose which attributes are to be mapped onto the layer representations. This helps to focus on those data characteristics and to relate them to their spatial context. In addition, the detail chart in the 2D cross-sectional view enables selecting value ranges by brushing parts of the attribute plots.

Specified selections are automatically propagated to interlinked views. Moreover, selections may be applied in combination with the emphasizing methods to adapt the visual representations.

User Interface: We integrate our visualization, emphasis, and selection techniques in a flexible user interface. Instances of the four views can be dynamically added and freely arranged. Each instance is controlled independently via coordinated interaction techniques. We particularly support free navigation and linking and brushing.

Free navigation facilitates exploration by adjusting the visual representations. This is necessary, as showing complete OCT datasets together with other information can easily exceed the available

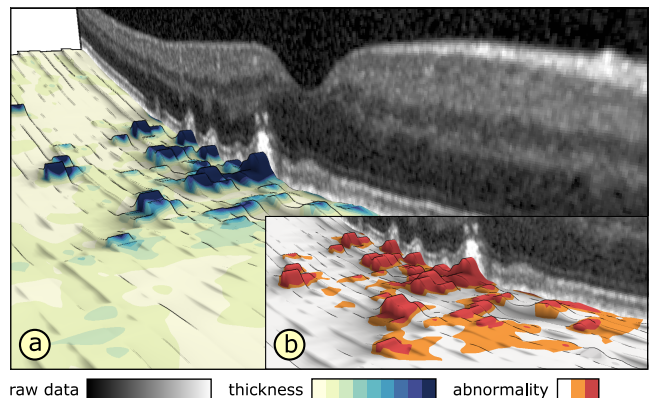


Figure 2: *Selecting and emphasizing data. The 3D view shows a selected layer, colored by its thickness (thin: green, thick: blue). Illumination and enhanced edges facilitate the spatial perception of the layer's shape (a + b). Abnormal thickness compared to reference data is emphasized via spatial and data-driven selections (b). The small scattered elevations (orange, red) indicate the presence of drusen, a sign for age-related macular degeneration.*

screen space. Navigation allows to overview the data and to inspect details at close range. In 3D views, the virtual camera is interactively controlled to take different points of view on the data. In 2D views and information views, zooming and panning permits showing different sections in greater detail. All navigation is smoothly animated to prevent sudden changes in the rendered images.

Linking and brushing is supported for selected parts. Parts of one dataset at separate locations may be compared via multiple view instances that have been adjusted to show respective close-up displays. Likewise, multiple datasets can be loaded and analyzed simultaneously using different views. Based on the common data basis this is even possible for datasets acquired via different devices. This provides a distinct advantage compared to existing software tools that are based on fixed layouts and thus, only allow to visualize one aspect of one dataset at a time.

5. Conclusions

We presented a VA approach for managing, analyzing, and presenting OCT data. A unified data basis incorporates data from various devices and derived information. A visual analysis tool supports exploration and emphasis of different data aspects, and selections of relevant subsets in interlinked views. Our VA approach constitutes a systematic enhancement of existing work and hence, can be a useful aid for retinal assessment using OCT.

We ascertained the general utility of our solutions in first tests with domain experts (one being an author of this paper). To improve our design, we plan to integrate guidance for different diagnostic tasks. In this context, specifications of dedicated workflows and further evaluations of our tool will become necessary.

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