3D Visualization of Intracranial Aneurysms with Multidimensional Transfer Functions

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Abstract. Clear identification of vascular structures is of vital importance for the planning of surgical treatment of intracranial aneurysms. A valuable tool for performing this task is direct volume visualization of CT-angiography (CTA) data making use of transfer functions based on the measured intensity values. In this work, we introduce direct 3D visualization of intracranial aneurysms with transfer functions based on multiple features extracted from the CTA dataset. We have provided a framework for the creation of multidimensional transfer functions which has been adjusted to the needs of clinical environments. Results were evaluated with a set of 10 clinical cases from our archive and have shown a substantial improvement when compared with the standard 3D visualization approach. Clear separation of bones and vessels was achieved even for cases were the target structures were embedded in the skull base. No pre-processing of the data, such as explicit segmentation was applied. All tests were performed on standard PCs equipped with modern 3D graphics cards.

1 Problem and Background

Direct volume visualization has been successfully applied for the planning of surgical procedures for the treatment of intracranial aneurysms. Frequently, CT-angiography (CTA) data represents the basis to produce 3D renderings of vascular structures by mapping the measured data values to color and opacity values, using standard transfer functions. Due to the nature of the CTA data and the occurring partial volume effect, this approach works only well if the vessels are anatomically well separated from the skull base. Otherwise, the data values for bone structures and vessels filled with contrast agent are too similar, making a clear delineation difficult.

As a drawback, intracranial aneurysms are frequently situated close to the skull base, which makes it difficult to achieve a clear 3D representation using standard transfer functions. A solution to this problem could be subtraction-CTA, which is problematic due to the required double exposure to high radiation. Alternatively, further features inherent to the data have to be taken into account in order to support a clear delineation of the target structures.

Transfer functions based on multiple features were introduced by Levoy [1]. However, due to the complexity of the task involved in their creation, the use of this strategy was initially not very user friendly. Recently, Kniss and Kindlmann [2] proposed a user interface that allows interactive manipulation of multidimensional transfer functions for direct volume rendering. In addition to this, we introduce multidimensional transfer functions to the clinical problem of intracranial aneurysms close to the skull base. Furthermore, we propose to use this strategy for surgery planning, by providing clinically adequate tools for the manipulation of multidimensional transfer functions supported by extensive use of consumer graphics hardware.

2 Methods

The definition and adjustment of standard 1D transfer functions based on the original data values only, is a complex task requiring extensive experience with visualization tools [3]. Adding further degrees of freedom increases the complexity and effort for the user. Bearing this in mind, a tool was developed allowing the surgeon to easily create adequate transfer functions. Functionality to set color and opacity intuitively is provided so the user can paint the transfer function as a 2D plane, where the x-axis and y-axis represent the data value and gradient magnitude respectively. Information regarding the data properties is presented in such a way that relevant sections of the volume are easily identified. This information is used as background for the working area, providing precise separation of tissues in the transfer function editor, and consequently in the visualized volume.

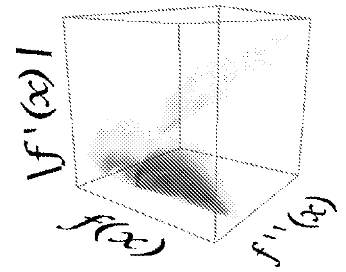


Fig. 1. 3D Histogram of CTA dataset

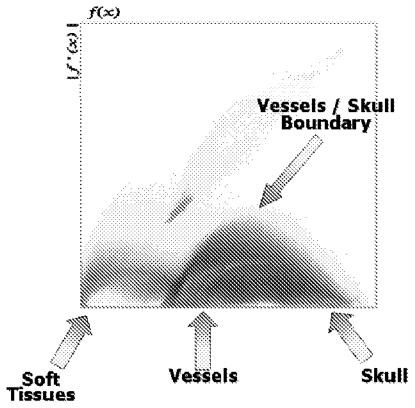


Fig. 2. 2D Scatter plot of histogram

For every voxel of the CTA dataset three different features were used. In addition to the given data value, the gradient magnitude and a boundary function based on first and second directional derivative were extracted. The gradient was computed using central differences, and the second directional derivative was obtained with the Hessian matrix approximation. The border function corresponds to the equation suggested by Kindlmann [4]. A 3D histogram is created with its three axis representing data value, first and second directional derivative (see Fig. 1). Examination of this data reveals information about the location of tissues and boundaries between them. A 2D scatter plot of the histogram is then computed in order to meaningful provide this information. Thereby, the x-y axis represent the measured data values and the gradient magnitudes respectively (see Fig. 2). Tissue boundaries come out as Gaussian curves with their zero crossings at the values corresponding to the adjacent tissues. These curves reach their maximum gradient value at the point which corresponds to the average location of the boundary center.

The mentioned scatter plot is placed as background of the working area where the surgeon can paint the 2D transfer function. Since tissues and their boundaries can be clearly identified, it is possible to apply opacities and colors to each tissue individually. Boundary emphasis can be also applied giving more weight to one of the tissues. One can for example, put emphasis to the vessel side of the skull/vessel boundary while ignoring the skull side, and in this way reduce artifacts produced due to the partial volume effect.

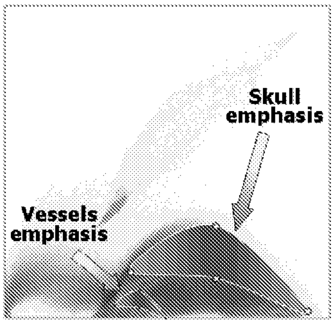


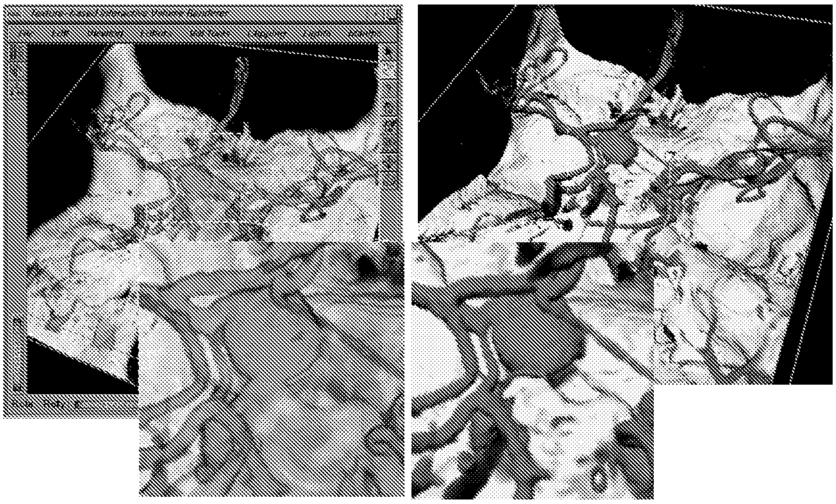
Fig. 3. 2D transfer function

A widget was designed to ease the painting of the transfer function. Its shape is based on the Gaussians that correspond to the boundary model. The curve shape was modeled using quadratic Bézier curves whose control points can be shifted over the painting area (see Fig. 3). Color and opacity can be selected and set to give more emphasis to either side of the boundary. Additionally, a pen is available in order to perform fine tuning of the transfer function if required.

The visualization is performed making use of the pixel shader unit available on PC graphics cards. The extracted data values are stored as RGBA values of a 3D texture. This texture is used as “previous texture” input for the “dependent texture” shader operation (according to the OpenGL extensions of NVidia). The transfer function is stored as a 2D texture consisting of 256 x 256 texels which is then used as “dependent texture”. As a result, the RGBA texture output contains the color and opacity values obtained from the mapping of the CTA data with the transfer function. Then, the resulting opacity is combined with the border function using the register combiners. Finally, the output values of the shader unit are then used for texturing the proxy geometry that forms the visualization as proposed by Cabral [5].

Since the data features stored as source 3D texture are computed only once at data loading time, and the transfer function is stored as a dependent texture,

Fig. 4. Comparison against standard 1D transfer functions



the process of creating the transfer function is completely interactive providing real-time feedback.

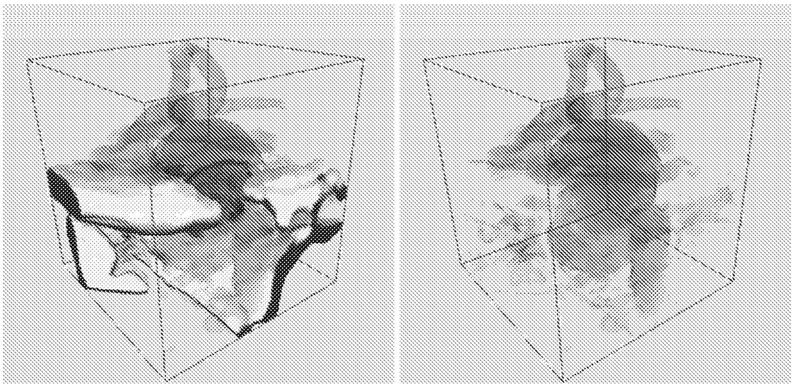
3 Results

We have validated our approach with 10 cases. The applied CTA data consisted of images with a 512 x 512 pixel matrix and 70-130 slices. The voxel size was 0.2 x 0.2 x 0.5 mm. In order to focus the visualization on the lesion, sub-volumes containing the area of interest for each dataset were created using a resolution of 256 x 256 x 64 voxels. For each case, different settings of multidimensional transfer functions were designed aiming at an optimal representation of each aneurysm including a clear separation of vascular and bone structures. Above all, no preprocessing such as explicit segmentation of the data was necessary. For an evaluation of the presented approach the obtained results were compared with 3D representations based on standard 1D transfer functions [6] and intraoperative findings. Especially in areas with intensive partial volume effect, results obtained with the suggested technique led to considerably improved visualizations in comparison to using 1D transfer functions (see Fig. 4). As a result, the neck of the aneurysm and the feeding vessel were clearly identified in difficult cases (see Fig. 5).

4 Discussion and Conclusion

The presented work demonstrates the value of direct volume rendering using multidimensional transfer functions for a considerably improved visualization of aneurysms close to the skull base in preparation of surgery.

Fig. 5. Skull removal from a CTA dataset



The approach can be applied with minor effort by the surgeon using the developed tools. Its main advantage over 1D transfer functions becomes evident when partial volume effects prevent a correct visualization of the target structures. On the other hand, all the tests were conducted on PCs equipped with consumer high-performance graphics cards. Thereby, the entire visualization process is interactive and the suggested approach is made affordable for clinical application.

Overall, the suggested strategy allows a convenient and clear separation of anatomical structures with limited differences in data values. In consequence, it makes direct volume visualization more useful for clinical application.

Note: Color plates are available at:
http://www9.informatik.uni-erlangen.de/Persons/Vega/bvm2003/

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