

# Transfer Function Map

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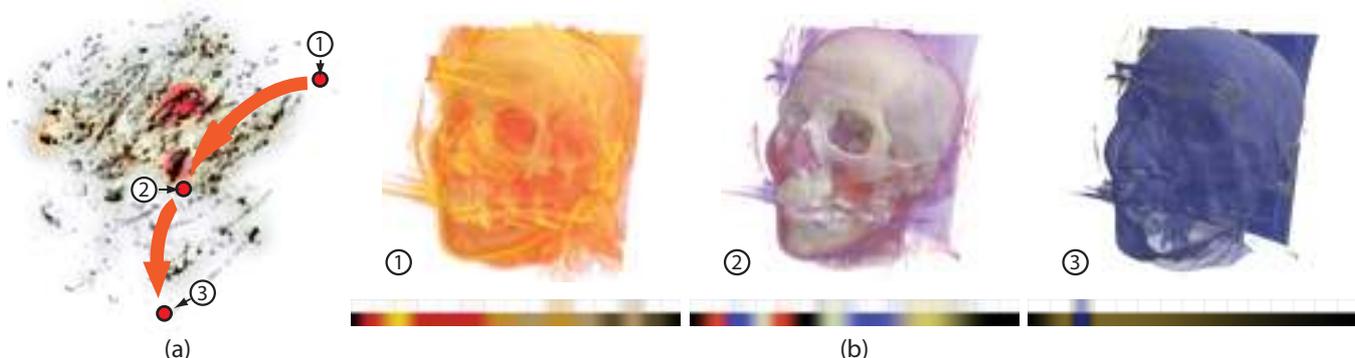


Figure 1: A collection of 16,598 transfer functions on CT head data collected from 20 users during the design process are integrated in one transfer function map in (a). Three key points on the map are selected in (a), and the corresponding volume rendered results and transfer functions are shown in (b).

## ABSTRACT

Transfer function design in volume visualization has been a challenging problem due to the huge design space. In this work, we present a system which is capable of integrating the transfer function design results from a group of users. For a specified volume dataset, intermediate and final transfer function designs for many users with different backgrounds are collected. A 2D representation of the transfer function feature space, called transfer function map, is then constructed for each volume data set by MDS projection of the collected transfer function samples. With the proposed transfer function map, interactions, including flexible navigation in the transfer function feature space and transfer function design recommendation, have been developed.

**Keywords:** Volume Visualization, Collaborative Visualization, Transfer Function Design.

## 1 INTRODUCTION

Nowadays, volume visualization is a powerful tool for scientific research and engineering applications, medical diagnosis, etc. As the rendering techniques and the graphics hardware matures, the community focuses more on how to convey the important features of the volume data, in order to create informative visualization results. However, it is still challenging for users to explore the data and produce insightful images with existing methods, which often require manual parameter adjustments with trial-and-error processes.

The key in volume rendering to map raw volume data to visual properties is the transfer function, which maps scalar values to visual properties in the rendering model, such as colors and opacities. Transfer functions essentially provide a classification of the volume data. It is a non-trivial problem to automatically generate good transfer functions that can reveal features and provoke insights in the volume data. A common practice to specify a trans-

fer function is to manually create a curve as the color and opacity lookup table. However, such straightforward classification often fails to distinguish certain features whose numerical distributions overlap in the 1D feature space. Efforts have been made to exploit derivative properties such as gradient magnitudes [11] and curvatures [9], to help on the classification quality, but it often requires additional knowledge and effort from the user, even with the latest techniques. Another perspective to transfer function design is implicate, or goal-oriented, which directly focuses on the rendered image. For example, users can also directly change the appearance of features in rendered images with sketching tools in WYSIWYG volume visualization [7].

Furthermore, users often observe that it is usually very difficult to present all essential structures and features in the volume data with only one single transfer functions. The self-occlusion, viewpoint, and the classification quality of transfer functions make it impossible to achieve such goal when practical data sets become enormous and complicated. In early work, researchers tried to generate numbers of randomly generated transfer functions and placed the rendered results in 2D screen for users to navigate and pick out [13]. However, it is difficult to involve domain knowledge with such system.

In this paper, we propose a novel way which incorporates the transfer function design knowledge of a group of users. Intermediate transfer functions that users designed with given tools are transferred to a server. The new feature space *transfer function map* is then constructed using Multi-Dimensional Scaling (MDS). The transfer function map provides a brand new perspective of the volume data, whose features are identified by humans. The density field of the MDS layout provides clues for good transfer function, in the form of clusters. Meaningful features in volume data are searched by users of different backgrounds.

The transfer function map brings multiple benefits. Transfer functions, which were “voted” many times by users, can often be suggested by the local maximum in the density map. Such points also indicate the meaningful features in the volume data. Our system can demonstrate the transition between different features, while the transitions are based upon the local properties of the transfer function map. Users can also quickly identify how previous users explored the data sets, and compare the behavior of users of different backgrounds. Furthermore, a recommendation mechanism is

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provided for users for new transfer function design. At every step during the design of a new transfer function, the system gives several recommendation based on the local properties of the transfer function map.

The contributions of this paper are two-fold. First, we propose a transfer function map, which is a novel 2D feature space based on the operation history of many users. Second, multiple applications are derived from the transfer function map, including the navigation of the feature space and the visual recommendation.

## 2 RELATED WORK

One central topic for volume visualization is transfer function design, which specifies colors and opacities for voxel samples, to obtain informative visualization results. However, it is a non-trivial task to design satisfactory transfer functions, especially for non-expert users. Transfer function design can be categorized as either data-centric or image-based [14].

Data-centric transfer function design focuses on the numerical properties and their derivatives. The most straightforward way is to design 1D transfer functions [1], which map each scalar value to a color and an opacity value. The classification results can be improved by using derivative properties of the scalar data. For example, the gradient magnitudes of the scalar values can enhance the boundary regions in volume data [11]. Higher-order gradient magnitude are further taken into consideration in later works [10]. Kindlmann et al. [9] proposed a method to employ the curvature into multi-dimensional transfer function design. Later, the relative size [2] of features and the occlusion spectrum [3] are proposed to improve the classification capability of transfer functions. In addition to the direct usage of the scalar value and their derivatives, contour topology can also guide transfer function design [6, 17].

Image-based transfer functions are goal-oriented. For example, users can pick up good volume rendered images at each iteration, to achieve satisfying visualization results [8]. Design Galleries [13] organizes and presents image results in 2D space by multi-dimensional scaling techniques, thus helping users to compare and select. Fang et al. [5] defined transfer function design as a sequence of 3D image processing procedures. Image graphs [12] were proposed to provide a representation for the exploration process of volume data.

Although various methods were proposed to aid the transfer function design, it is still non-intuitive work for users, especially non-experts. Sketch-based user interface on direct volume rendered images are proposed for transfer function design. Features which are assigned by strokes on different volume rendered images can be fused into new results [16]. In stroke-based transfer function design [15], the layers which are defined with strokes, can further form informative results by combining them. Guo et al. [7] further propose a WYSIWYG volume visualization system, which allows users to change appearances of features by painting on the results, while intermediate results are fed back to users in real-time.

## 3 OVERVIEW

The main goal of our system is to help users find and understand complicated features in volume data sets, by letting users navigate and explore transfer functions designed before by (many) other users. Specifically, for a given volume data and many of its transfer functions, we construct a 2D representation, called a transfer function map. In a transfer function map, the user designed transfer function are placed on an MDS map, and a corresponding density map presents the clustering properties of the transfer functions.

The pipeline of the system is shown in Figure 2. The transfer functions for several data sets, designed by a variety of users, are transferred to a central storage server. The final and intermediate transfer functions are being collected, while users use the tool we have provided. The MDS layouts can be generated based on the

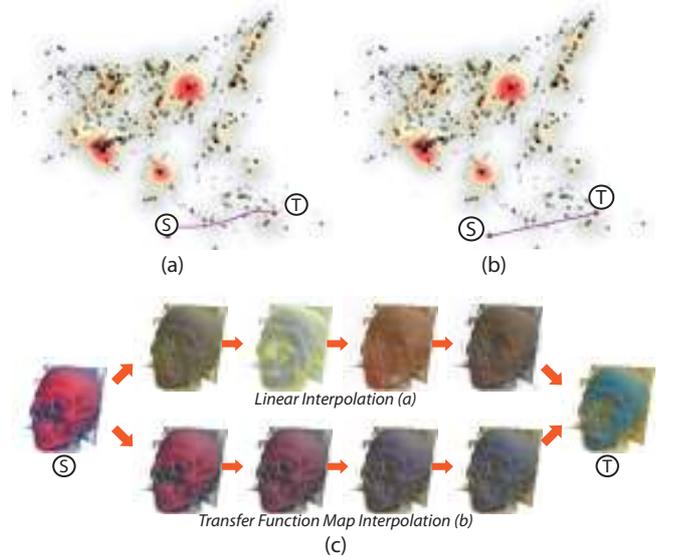


Figure 3: Transfer function map navigation with two interpolation schemes: (a) linear interpolation; (b) transfer function map interpolation. The position of the intermediate transfer functions are shown as trajectories in (a) and (b).

dissimilarities between the stored transfer functions that are being collected. Density maps are further calculated according to the local density of the MDS layouts, resulting in a transfer function map. The system further provides a flexible navigation and exploration to users of the map. Finally, a visual recommendation function can help the users to further design new transfer functions.

## 4 TRANSFER FUNCTION MAP

The main goal of our system is to help users find and understand complicated features in volume data sets, by letting users navigate and explore TFs designed before by (many) other users. In a TF map, the user designed TFs are placed as nodes on an MDS map, and a corresponding density map presents the clustering properties of the TFs.

MDS techniques are used to present the differences between collected TF nodes in the 2D map. The distance metric is defined as weight sum of the lookup tables distance  $d_L$ , a volume rendered image distance  $d_I$ , and the visibility histogram distance  $d_V$  [4]:

$$d^2(T_1, T_2) = \beta_L d_L^2(T_1, T_2) + \beta_I d_I^2(T_1, T_2) + \beta_V d_V^2(T_1, T_2), \quad (1)$$

where  $\beta_L$ ,  $\beta_I$  and  $\beta_V$  are the weights for the distances  $d_L$ ,  $d_I$ , and  $d_V$ , respectively. The weights can be adjusted for interactive navigation. Since  $d_I$  and  $d_V$  are view-dependent, we compute images and visibility histograms from multiple viewpoints to obtain average values.

Density maps are generated and visualized based on the distribution of TFs in the 2D space. Kernel Density Estimation (KDE) is utilized to generate a smooth and continuous density map.

## 5 APPLICATIONS

In our system, users can mark TFs in the TF map, and observe how the TFs interpolate from one to another in an animation of the volume rendered images. The intermediate TFs are obtained by weighted averaging neighborhood TF nodes in the map. It virtually create a continuous 2D map, and we can obtain a TF  $\hat{T}(x)$  at any position inside the plane. Animated results can be shown by setting key frames on the TF map (Figure 1).

In order to find the neighboring transfer function nodes in a transfer function map, we first triangulate the map by the positions of the

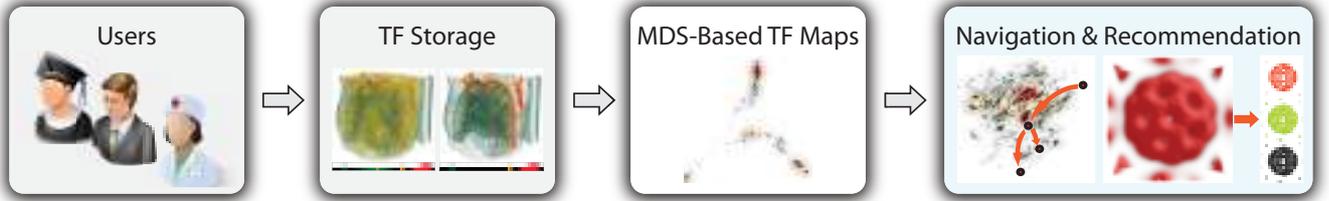


Figure 2: The pipeline of the system. First, transfer functions are collected from users, then transfer function maps are generated using MDS layouts and density maps. The map navigation and recommendation system are provided to users for further exploration of the volume data.

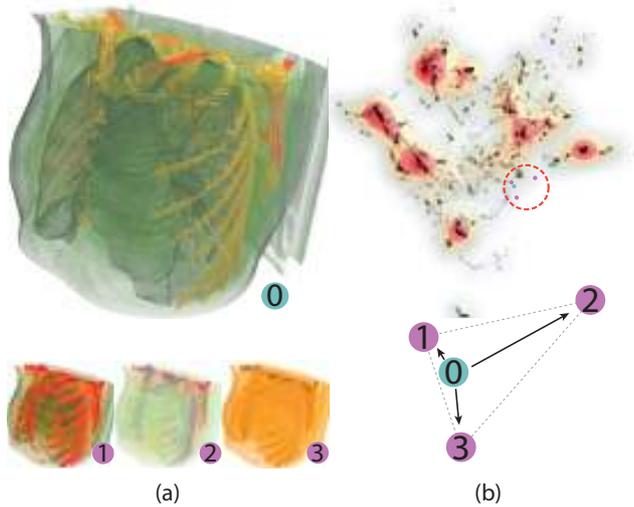


Figure 4: Visual recommendation for user operation: (a) the current status 0 of the user operation and the recommended rendering results 1, 2, and 3; (b) the corresponding transfer function map and the local triangle mesh.

nodes, and then the interpolated transfer function can be figured out by piece-wise linear interpolation with the barycentric coordinates. Specifically, for any 2D position  $x$  in the transfer function map, the interpolated transfer function is defined as

$$\hat{T}(x) = \lambda_1 T_1 \oplus \lambda_2 T_2 \oplus \lambda_3 T_3, \quad (2)$$

where  $\lambda_i \geq 0, i = 1, 2, 3$  ( $\lambda_1 + \lambda_2 + \lambda_3 = 1$ ) are the barycentric coordinates of the triangle that contains  $x$ , and  $T_i, i = 1, 2, 3$  are the transfer functions on the vertex of the triangle. The operator  $\oplus$  is defined as the blending of two transfer functions by adding the opacity values and color values in CIE  $L^*a^*b^*$  color space. Thus, a continuous 2D transfer function map can be constructed.

A second application for the TF map is the visual recommendation. When a user changes the current TF, the system automatically allocates nearby TF nodes in the map as recommended ones. The position of the TFs that is active is positioned in the MDS layout when the user updates the TF. There are multiple benefits with a visual recommendation mechanism. First, users can navigate around the TF map, to see and learn how other users designed TFs. Second, meaningful features of the volume data are available in the TF map, which is instructive for other users. Third, the newly designed TFs by the user can be added into the map, which will also guide other users.

## 6 RESULTS AND DISCUSSION

We set up experiments to collect user transfer functions on several data sets, and discovered features in the transfer function map.

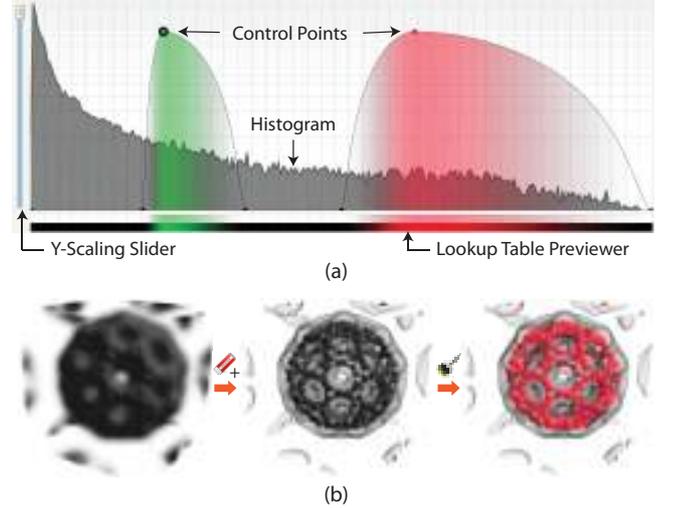


Figure 5: Two transfer function design tools provided for users. (a) The traditional control points-based 1D transfer function design interface. The black curve indicates the histogram of the feature. Users can use control points to control the define the intended opacity values and colors, and other blank areas are smoothed and interpolated according to the control points. (b) WYSIWYG volume visualization [7]. Users can use different painting tools to sketch on the image, in order to change the appearance of features, without direct accessing the transfer functions.

### 6.1 Experiment Setup

The transfer function data is collected over the internet, after users downloaded and run a binary package published online. Several items of user information are recorded, including names, gender, affiliation, background, etc. Users can choose either traditional curve-based transfer function design interface (Figure 5 (a)) or sketch-based user interface [7] (Figure 5 (b)). In the curve-based user interface, users can add control points to specify color and opacity transfer functions. Specifically, the heights of the control points define the opacity value, and the colors of the control points define the color. Cubic interpolated values are defined for both color and opacity transfer functions. On the other hand, user can use different painting tools to directly change the appearances of the volume rendered image. For example, the outer part of the bucky data is removed by the eraser tool first, and then the inner part is colorized with red color (Figure 5 (b)).

There are two types of tasks for users: a free transfer function design and a goal oriented transfer function design. In the former task, users can specify transfer functions freely. On each step, the current transfer function and the camera status are recorded.

Before the experiment, we make several hypotheses to explore the transfer function map:

- **H1:** The transfer function map generated by curve-based and WYSIWYG transfer function design tools would be different;

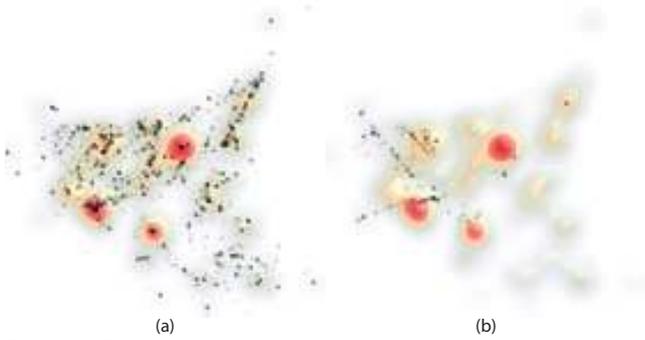


Figure 6: Transfer function map comparison between two provided design tools on CT head data: (a) traditional curve-based transfer function; (b) WYSIWYG transfer function design. The density map in both figures are identical for reference.

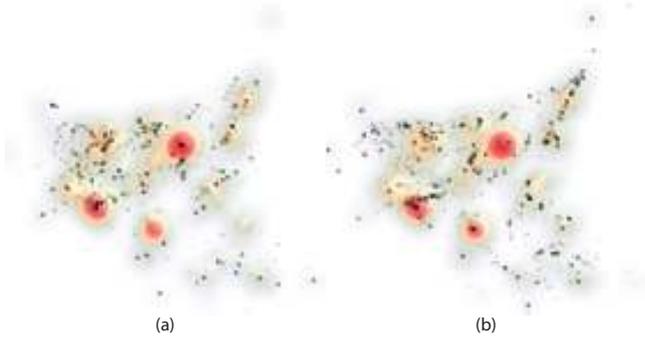


Figure 7: Comparison between expert users (a) and novice users (b).

- **H2:** Transfer functions generated by expert users and users with no experience would form different patterns in the transfer function map, and the difference would be more obvious in the goal-oriented explore mode.

## 6.2 Visual Verification of the Hypothesis

For the hypothesis **H1**, we conducted experiments to compare the two transfer function design tools we provide for users, including traditional curve-based and WYSIWYG transfer function design. The comparison of the two transfer function maps generated with these tools are shown in Figure 6. The patterns in the transfer function maps are quite different. Transfer functions that are designed with WYSIWYG tools seem to be more concentrated in a certain region in the map. The reason for this phenomenon can be explained. First, with traditional curve-based tools, although the results is widely distributed, most of the intermediate transfer functions that are generated trial-and-error process in less significant. Second, due to the goal-oriented nature of the WYSIWYG tool, there are limited possibility for a certain operation. Thus the distribution of the WYSIWYG tool is more concentrated.

Another experiment is performed to verify hypothesis **H2**. The transfer function map generated by expert and non-expert as illustrated in Figure 7. However, there is little difference in transfer function maps generated by experts and non-experts. A possible explanation is the following. Transfer function design is a challenging task. Intensive trial-and-error processes are inevitable even for experts using traditional curve-based tools. Experts may spend less time on a task, but they still need to explore the transfer function feature space to get an overview of what they should do.

## 6.3 User Trajectories in the Transfer Function Map

We also investigate how users design transfer functions. In this experiment, a user trajectory is defined if a sequence of transfer func-

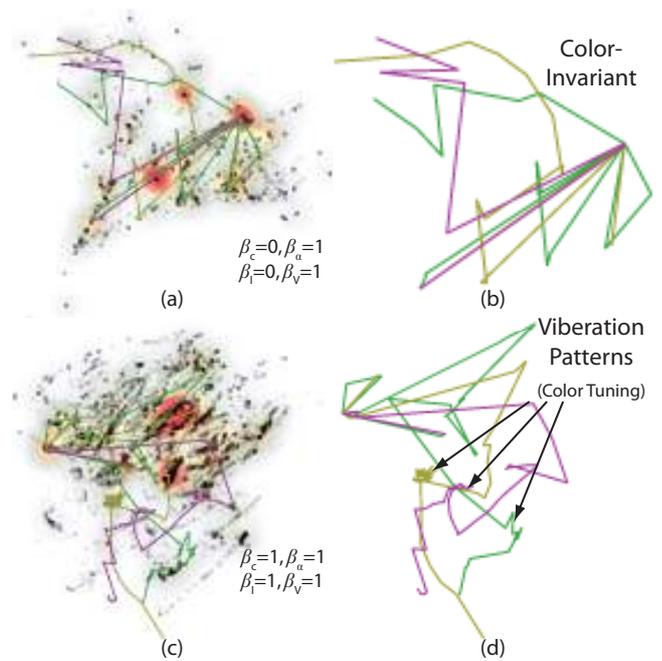


Figure 8: User trajectories in the transfer function map: (a) and (b): trajectories on a color-invariant map; (c) and (d): trajectories on a transfer function map which accounts all metrics

tions belong to the same history record of a user. In Figure 8, three user trajectories are overlaid and highlighted in the transfer function maps, which are generated with two different distance metrics defined by the weights in the figure.

In Figure 8, the purple trajectory is generated by an expert in free exploration mode. We take the final result of the design as a task, and ask an expert(yellow trajectory) and a non-expert(green trajectory) to participate in the task. We overlay and highlight the three trajectories in the transfer function map, which are generated with two different distance metrics. In Figure 8 (a), the opacity lookup table distance and visibility histogram distance are considered, which are color-invariant. We notice that in Figure 8 (d) there are some vibration patterns in the user trajectories, while they do not exist in (a). We can derive that the user is tuning color and keeping opacity values on those operations in the vibration region. Such interesting patterns can be interactively identified by tuning the distance metrics in the system.

## 7 CONCLUSIONS

In this work, we propose the TF map, which can help to coordinate the efforts of the TF design from many users. In the TF map, different TFs are placed with an MDS projection, and density maps are provided to highlight features in the map. We further provide flexible TF map navigation with animation and a visual recommendation system to investigate the features. A number of TFs are collected with a remote TF design tool, and several experiments are conducted to identify features in the TF map.

In the future, several improvements can be applied on this work. Currently the experiments are limited to 1D transfer functions. Multidimensional transfer functions, which can distinguish more volume data features, may bring much more interesting features in the transfer function map. Dimension projection methods with higher precision may provide better presentation of the transfer function space.

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## REFERENCES

- [1] C. L. Bajaj, V. Pascucci, and D. Schikore. The contour spectrum. In *Proceedings of IEEE Visualization 1997*, pages 167–174, 1997.
- [2] C. Correa and K.-L. Ma. Size-based transfer functions: A new volume exploration technique. *IEEE Trans. Vis. Comput. Graph.*, 14(6):1380–1387, 2008.
- [3] C. Correa and K.-L. Ma. The occlusion spectrum for volume classification and visualization. *IEEE Trans. Vis. Comput. Graph.*, 15(6):1465–1472, 2009.
- [4] C. Correa and K.-L. Ma. Visibility histograms and visibility-driven transfer functions. *IEEE Trans. Vis. Comput. Graph.*, 17(2):192–204, 2011.
- [5] S. Fang, T. Biddlecome, and M. Tuceryan. Image-based transfer function design for data exploration in volume visualization. In *Proceedings of IEEE Visualization 1998*, pages 319–326, 1998.
- [6] I. Fujishiro, T. Azuma, and Y. Takeshimat. Automating transfer function design for comprehensible volume rendering based on 3d field topology analysis. In *Proceedings of IEEE Visualization 1999*, pages 467–470, 1999.
- [7] H. Guo, N. Mao, and X. Yuan. WYSIWYG (What You See Is What You Get) volume visualization. *IEEE Trans. Vis. Comput. Graph.*, 17(12):2106–2114, 2011.
- [8] T. He, L. Hong, A. E. Kaufman, and H. Pfister. Generation of transfer functions with stochastic search techniques. In *Proceedings of IEEE Visualization 1996*, pages 227–234, 1996.
- [9] G. L. Kindlmann, R. T. Whitaker, T. Tasdizen, and T. Möller. Curvature-based transfer functions for direct volume rendering: Methods and applications. In *Proceedings of IEEE Visualization 2003*, pages 513–520, 2003.
- [10] J. Kniss, G. L. Kindlmann, and C. D. Hansen. Multidimensional transfer functions for interactive volume rendering. *IEEE Trans. Vis. Comput. Graph.*, 8(3):270–285, 2002.
- [11] M. Levoy. Display of surfaces from volume data. *IEEE Comput. Graph. Appl.*, 8(3):29–37, 1988.
- [12] K.-L. Ma. Image graphs - a novel approach to visual data exploration. In *Proceedings of IEEE Visualization 1999*, pages 81–88, 1999.
- [13] J. Marks, B. Andalman, P. A. Beardsley, W. T. Freeman, S. Gibson, J. K. Hodgins, T. Kang, B. Mirtich, H. Pfister, W. Ruml, K. Ryall, J. Seims, and S. M. Shieber. Design galleries: a general approach to setting parameters for computer graphics and animation. In *Proceedings of ACM SIGGRAPH 1997*, pages 389–400, 1997.
- [14] H. Pfister, W. E. Lorensen, C. L. Bajaj, G. L. Kindlmann, W. J. Schroeder, L. S. Avila, K. Martin, R. Machiraju, and J. Lee. The transfer function bake-off. *IEEE Comput. Graph. Appl.*, 21(3):16–22, 2001.
- [15] T. Ropinski, J.-S. Praßni, F. Steinicke, and K. H. Hinrichs. Stroke-based transfer function design. In *Proceedings of IEEE/EG International Symposium on Volume and Point-Based Graphics*, pages 41–48, 2008.
- [16] Y. Wu and H. Qu. Interactive transfer function design based on editing direct volume rendered images. *IEEE Trans. Vis. Comput. Graph.*, 13(5):1027–1040, 2007.
- [17] J. Zhou and M. Takatsuka. Automatic transfer function generation using contour tree controlled residue flow model and color harmonics. *IEEE Trans. Vis. Comput. Graph.*, 15(6):1481–1488, 2009.