Distance-based transfer function design: Specification Methods and Applications

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Abstract

We employ distances as a second dimension for transfer function (hereafter TF) specification. Distances refer to selected reference shapes. When distance-based TFs are applied to medical volume data and anatomic structures as reference shapes, they can support diagnostic procedures and therapy planning. As an example, distance-based TFs may be used to explore the neighborhood of a tumor which is essential to assess whether a surgical removal is feasible. In this paper, we discuss methods to specify 2d distance-based TFs, the use of predefined but adjustable templates to reduce the interaction effort and an efficient implementation of these TFs.

1 Introduction

Transfer function (TF) design is an essential aspect of medical volume rendering. Transfer functions map intensity values of scalar CT or MRI data to grey values or color and opacity. One-dimensional TFs operate on the intensities of the voxels; they are used to emphasize relevant structures and to suppress or hide other structures. Without dedicated support, TF specification is tedious and the ability to emphasize structures is limited to those which can be distinguished based on their intensity values. In order to enhance the visualization, multidimensional TFs have been developed. The idea of using gradient magnitude as a second dimension for the opacity specification is due to Levoy [Lev88] and allows to emphasize material boundaries characterized by large gradient magnitudes. In this paper we discuss a special class of multidimensional TFs, where *distance* is employed as a second data dimension. With distance-based TFs, the distance to reference objects is considered in the assignment of opacity and grey values. In medical applications, reference objects are primarily surfaces of anatomical structures, such as organs which have been identified and delineated in advance. With distance-based TFs, it is possible to show voxels which have a certain distance to the curved surface of an organ. If this distance is continuously changed, the user may inspect an organ by slicing according to the organ surface which may be very effective, for example in the search for lung nodules in CT thorax data. We discuss predefined but adjustable templates for the definition of TFs on a 2d domain. With

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these templates, 2d TFs are composed of linear basis functions defined over a rectilinear grid. Based on this grid type an efficient bilinear interpolation is performed in order to generate lookup-tables for volume rendering. While we are interested in distance-based TFs, the interaction facilities presented are also applicable to the specification of TFs for other 2d TFs.

2 Related Work

Previous work focussed on goal-oriented processes of TF specification. Marks et al. [MAea97] introduced ”Design galleries” as a general approach for selecting visualization parameters in a multidimensional space. TF specification with this approach is accomplished by selecting previews (from a randomized selection) to guide the search process. This interaction style is more intuitive than fine-tuning some numerical input. Koenig [KG01] introduced the idea of composing TFs from primitive linear functions, such as a tent-function. Fang et al. [FBT98] suggested to analyze image-properties to combine TF specification with image processing operators, such as edge enhancement. The use of a *reference TF* which is adapted later to similar datasets was described by Rezk-Salama [RSHSG00]. This is one of a very few systems which can reliably produce expressive visualizations of MRI data, which is difficult to accomplish due to inhomogeneities. The concept of reference TFs has been extended and adapted for neurosurgical questions [VST$^+$03]. Multidimensional TFs have been intensively studied in a series of publications by Kindlmann and Kniss [KD98], [KKH02], [KWTM03]. Two issues are discussed in these publications in detail: the design of user interfaces for the huge parameter space of multidimensional TFs and efficient visualization by employing hardware support. In principal, multidimensional TFs allow the user to produce adequate visualizations in particular of CT data. However, much effort is required and different users (medical doctors) would probably produce quite different results.

The idea of employing distances in the specification of TFs has been presented by Kanda [KMM02] and Zhou [ZDT04] in order to focus visualizations on a particular region. In both publications, distances refer to a seed point specified by the user or given by the camera position. The methods presented here differ in considering distances to surfaces which is inspired by diagnostic processes where distances to anatomic structures guide the visualization. The term *spatialized transfer function* has been recently introduced [RBS05]. Spatialized transfer functions are special variant of local transfer functions where connected components are identified and the positional information is mapped to color. This allows to differentiate for example different objects of the same tissue type, such as different bones.

The work described here is based on our previous work on the diagnosis of CT thorax data [DWS$^+$03] where the idea of *anatomic reformation* (reformation according to the surface of an organ) was introduced. A short and earlier version of this work is [TPD05].

3 Distance-Based Approach

The expressiveness of volume rendered images is often limited by a lack of control over the mapping process. Visual parameters are usually defined globally for the entire dataset. However, in medical applications such as tumor surgery planning selected anatomic structures are relevant. Surrounding tissues serve as anatomic context only.
The distance-based approach is motivated by the fact that the interest of the user is often determined by the distance to reference structures. To improve local control over the mapping process, *distance* is introduced as a second dimension in the TF specification. In Fig. 1 an example of distance-based volume visualization is shown. Tissue in various distance intervals with respect to the lung surface is mapped to different optical properties. This is achieved by TFs specified in a 2d domain composed of intensity and distance to the lung surface. In this domain, four rectangular areas (distance $\times$ intensity ranges) were defined which map to opacity values unequal 0 and color values unequal (0,0,0).

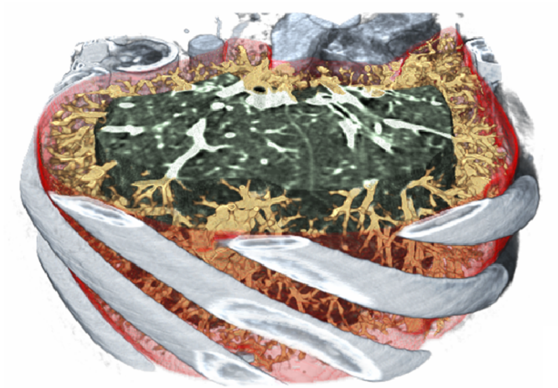

Figure 1: Distance-based visualization of a right lung lobe based on CT thorax data. The use of distance and intensity values enhances the discriminative power of structures well. Four distance intervals related to the segmented lung surface are used: bones [-40mm, 0mm], lung surface [0mm, 1mm], lung vessels [1mm, 23mm], lung tissue [23mm, 60mm].

To visualize bones, within the distance interval [-40mm, 0mm] and the intensity interval [100HU, 1450HU] a linearly increasing opacity from 0 to 1 and a linear grey value interpolation between black and white have been applied. Moreover, for visualizing the lung surface, lung vessels and lung tissue, three additional distance-intensity ranges were defined. Table 1 presents the parameters of the underlying TFs. To distinguish tissue inside and outside the reference structure, signed distances are employed with negative values representing positions outside the reference structure. With the specification presented in Table 1, bones are rendered white and light grey, the lung surface appears red, and the lung vessels are rendered yellow. Finally, lung tissue is rendered light green. This example is not clinically relevant, but it shows the flexibility to provide expressive and flexible volume visualizations. In Fig. 1, distances and intensity values are mapped to constant optical properties inside the related distance range. Also, it is useful to define distance-dependent color and opacity changes. The definition of distance-based TFs is discussed in the two following sections.

Table 1: Distance and intensity ranges as well as opacity and color specification used to specify the visualization in Fig. 1. Intensity relates to CT Hounsfield units (HU). C refers to a constant behavior of the function; LI to a linear behavior

	distance (mm)	intensity (HU)	opacity	color
bones	[-40, 0]	[100, 1450]	[0, ..., 1], *LI*	black-white, *LI*
lung surface	[0, 1]	[-1024, 3071]	0.1, *C*	red, *C*
lung vessels	[1, 23]	[-824, -424]	[0, ..., 1], *LI*	black-yellow, *LI*
lung tissue	[23, 60]	[-1024, -424]	1, *C*	black-green, *LI*

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4 2d Transfer Function Specification

There are different requirements with respect to TF specification: sufficient flexibility on the one hand and reduced interaction effort on the other hand are desired. Moreover, the TF specification should be intuitive and goal-oriented. User interfaces which support users without long-term experience to generate expressive visualizations are thus desirable. The design of such user interfaces is more difficult the more dimensions are involved.
Sophisticated and evaluated approaches for 1d TF specification already exist. A widespread concept is the use of piecewise linear functions, which are defined based on component functions (hereafter CF) [CKLG98, KG01]. With the help of CFs, complex 1d TFs may be composed of simple basis functions such as ramps, boxes and tents. To specify a CF, the user has to adjust a small number of parameters. Often setting a center, a width and a maximum opacity is sufficient.

In principle, 2d TFs can also be generated by multiplying two 1d TFs. However, only a subset of the 2d TFs can be generated this way. For example, a 2d TF defined over a rectilinear grid allows to specify different distance ranges for which optical properties are specified in a distance-and intensity-based manner.

Rectilinear grids. To extend the CF specification to 2d TFs, we chose the composition of TFs based on predefined but adjustable templates similar to [KG01]. These templates are 2d piecewise linear functions which are defined by means of control points arranged in a rectilinear grid. Neither completely irregular grids nor regular grids are optimal representations for 2d transfer functions. A viable compromise is a rectilinear grid (see Figure 2). A rectilinear grid provides adequate flexibility for adapting the density of control points. On the other hand, it is appropriate to support the efficient transformation of the 2d TF to a lookup table by means of bilinear interpolation which can be accomplished with hardware support. Rectilinear grids are characterized by rectangular cells aligned with the coordinate axis. The size of cells however may be different (which permits a denser representation when required). Rectilinear grids can be stored as 2d arrays. The grid has an initial (coarse) resolution. If the user specified control points, either explicitly or by inserting component functions, additional cells in the grid are inserted. With rectilinear grids the insertion of a control point p in the 2d array with indices (i, j) requires to insert additional control points in the i-th row and j-th column (recall Fig. 2, right) to maintain the regularity of the grid.

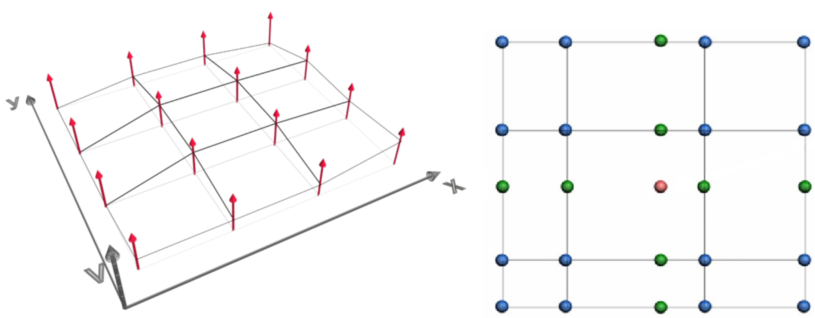

Figure 2: Control points are defined over a rectilinear grid to support the transformation to 2d lookup tables. The grid has a coarse initial resolution and is refined if additional control points are necessary. To maintain the rectilinear organization, the insertion of a control point (red point in the right figure) requires the insertion of another row and column of control points (green).

In order to limit the number of control points, the following strategy is employed: x_{min}, x_{max}, y_{min} and y_{max} determine the ranges, in which a CF is applied in the 2d domain. By means of a parameter e the slope at the border of the rectangular range is specified. Usually, we employ very small values for e. After the specification of the control point's locations at the rectilinear grid, values are assigned to each of them to determine the shape of the resulting 2d TF.

The CFs are scaled by the amplitude of the desired optical property, e.g. the opacity. Several CFs can be flexibly placed in the 2d TF domain. Often, several channels, such as color and opacity, are needed. If different specifications in these channels are desired, CFs are specified in each channel separately.

The introduced approach to specify 2d TFs can be applied to different domains. We applied the described specification method for creating TFs in the intensity $\times$ distance-domain, intensity $\times$ gradient magnitude-domain [SPD05] and intensity $\times$ subvolume (local TFs) domains. For a common support, the component representation of TFs is transformed into a lookup table. This process is guided by the available graphics hardware. On an NVidia Quadro4 - graphics board for example, a lookup table of a maximum size of 256×256 is available; on other graphics boards hardware, such as NVidia GeForce FX - graphics, support for 4096×4096 lookup tables may be utilized. The generation of 2d lookup tables is carried out by interpolating between control points of the CFs.

5 Interactive Specification of Distance-Based TFs

The definition of distance-based 2d TFs is initiated by selecting a reference object which must be segmented before. Subsequently, the distances of all voxels to the selected object are computed and stored in a separate volume data (further details in Sect. 6). The distance volume is required to support the definition process and to compute the distance-based visualization. Based on the distance volume, the user starts to create the TF, by defining parameters for one or more CFs traversing the following sequence of interactions:

- selection of *intensity range* and *distance range*,
- selection of a *template*, which describes the behavior of the CF (similar to the selection of a tent or a ramp shape for 1d TF definition), and
- selection of *opacity* and *color*.

5.1 Selection of Intensity Range and Distance Range

The intensity and distance range (distance to the reference structure) of a CF define the visibility of different tissues. To specify the intensity and distance ranges, four values have to be defined which represent the borders (i_{min}, i_{max}, d_{min}, d_{max}). The adjustment of these values requires feedback which can be accomplished in different ways.
Slice-based: An important aspect is to convey to the user the relation of the current TF settings to slice-based visualizations which are familiar to radiologists. For this purpose, 2d views of the original radiological data are combined with colored overlays indicating which pixels are affected by the currently selected intensity and distance range (see Fig. 3). All tissue which is light blue colored (intensity range) and located between the two red lines in Fig. 3, right (distance range) will be visualized by the related CF.

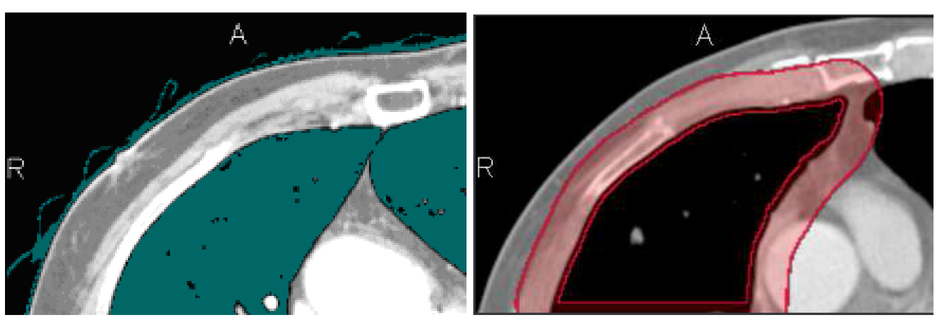

Figure 3: The 2d view provides feedback for an intensity selection and a distance selection. Both images are based on the same dataset as Fig. 1. The selected intensity range (left) [-980HU, -420HU] and the distance range (right) [-14mm,1mm] are emphasized in the slices.

Support by 2d histograms: In conventional TF specification the histogram of intensity values is a valuable support. Similarly, 2d histograms of intensity and distance data aid the selection of ranges effectively. The brightness of a point in the histogram represents the quantum of tissue which has the related intensity and distance. Fig. 4 presents a 2d histogram based on intensity and distance information, and a visualization of selected ranges. The intensity range is encompassed by two vertical bars, the distance range by two horizontal bars. These bars may be modified interactively using a pointing device. The structures in the histogram guide this process. Each structure represents tissue in a limited distance and intensity range.

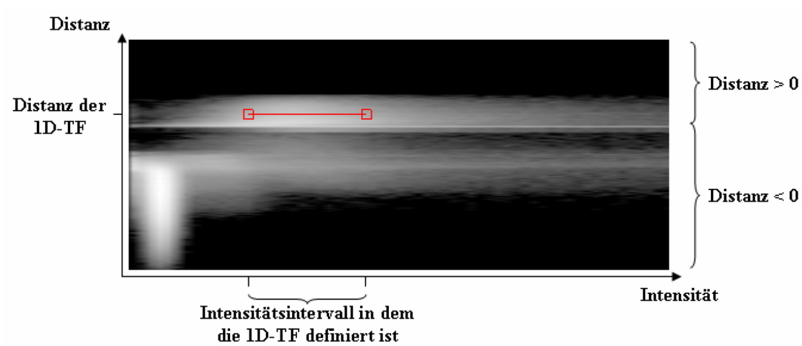

Figure 4: 2d histogram of distance and intensity distributions based on the same dataset as Fig. 1. The selected ranges have been used to visualize bones in Fig. 1.

5.2 Templates

Templates are used to define the values at the supporting points of CFs. The template type strongly affects the shape of the CF and the resulting 2d TF. The following list contains the templates which turned out to be useful after careful discussions with colleagues and medical doctors. We describe each of them in the following.
The template of a CF defines the optical properties. It is adaptable by the selected intervals of $[d_{min}, d_{max}] \times [i_{min}, i_{max}]$. For the description of these templates, we need two additional variables. The following list contains a selection of useful 2d templates (see Fig. 5).

1. *2d extension of a 1d box*: This template assigns a constant level in $[i_{min}, i_{max}] \times [d_{min}, d_{max}]$. At the border lines the template decreases to 0 with high slope. This template displays tissue inside the 2d interval with a constant opacity and/or color.

2. *2d extension of a 1d ramp, increasing by intensity*: This template is linearly increasing from 0 to a maximum between i_{min} and i_{max} and constant between d_{min} and d_{max}. With this template it is possible to visualize tissue by linearly increasing opacity or color. It is useful to attenuate low and emphasize high intensity tissue.

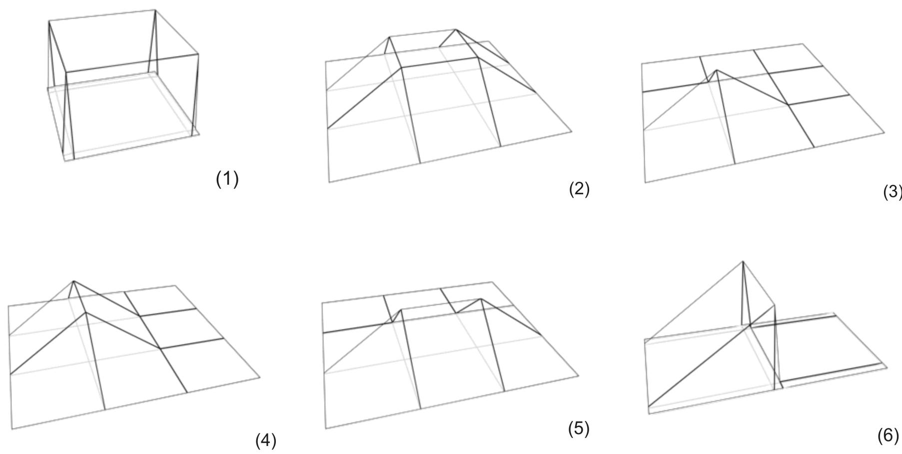

Figure 5: Templates which describe different adjustments of color and opacity values. (1) 2d box, (2) 2d-trapezoid, (3) pyramid, (4) elongated tent in *d* direction, (5) elongated tent in *i* direction, (6) 2d ramp

3. *2d extension of a 1d ramp, decreasing by intensity*: This template is linearly decreasing from a maximum to 0 between i_{min} and i_{max} and constant between d_{min} and d_{max}. This template is similar to template 2 and is useful to emphasize low and attenuate high intensity tissue.

4. *2d extension of a 1d ramp, increasing by distance*: This template is constant between i_{min} and i_{max} and linearly increasing from 0 to a maximum between d_{min} and d_{max}. With template 4 it is possible to visualize tissue by increasing opacity or color depending on the distance to the reference object. It is useful to attenuate low and emphasize high distances to the reference object.

5. *2d extension of a 1d ramp, decreasing by distance*: This template is constant between i_{min} and i_{max} and linearly decreasing from a maximum to 0 between d_{min} and d_{max} . This template is very similar to template 4 and is useful to emphasize tissue close to the reference structure and attenuate structures with increasing distance. As an example, this template may be employed to focus on the region around a tumor and explore different margins around it.

6. *2d extension of a 1d tent, increasing-decreasing by intensity*: This template is linearly increasing from 0 to the center between i_{min} and i_{max}, decreasing from center to 0 and constant between d_{min} and d_{max}.

7. *2d extension of a 1d tent, increasing-decreasing by distance*: This template is constant between i_{min} and i_{max}, linearly increasing from 0 to the center between d_{min}

and d_{max} and decreasing from the center to 0. It is useful to convey distances to the reference structure.

The choice of a template is determined by the desired behavior of opacity and color TF. Based on our experience, in most cases the same template for opacity and color is chosen.

5.3 Selection of Color and Opacity

Colors can be selected conveniently by means of color palettes. The selected color dyes the tissue whose intensity and distance are inside the chosen ranges. If a linear increasing template is selected for color, color is interpolated linearly between black and the chosen color. On the other hand, a constant template dyes the tissue by one color. Opacity can be defined by a scalar value between 0 and 1. This value describes the opacity of the tissue whose intensity and distance are inside the chosen ranges.
After the selection of ranges, template(s), color and opacity the definition of a CF is complete. A TF can be flexibly composed of several CFs (Fig. 6). For example, for the visualization in Fig. 1 four CFs are combined. CFs can be placed freely inside the distance and intensity domain. For overlapping regions (Fig. 7 one of the involved CFs is prioritized. In principle, in overlapping regions the resulting TF may be generated by blending individual CFs. In our implementation, one CF is selected and the influence of others is neglected. The user can select a CF or its footprint in the joint histogram and assign "top" or "lowest" priority to influence the prioritization. In case, nothing is specified, the least frequently defined CF "overwrites" other CFs relating to the same region in the TF domain.

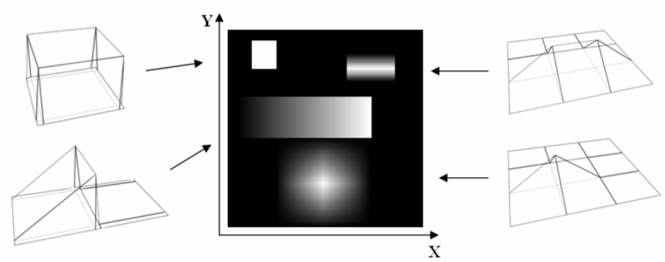

Figure 6: A distance-based TF is composed of 4 CFs. The image in the central part indicates which regions in the 2D domain are affected.

6 Computation of the Distance Volume

A crucial issue in applying distance-based TFs is the representation of distances to the target structure T. For this purpose, an additional volume V_{dist} is required which contains the Euclidean distances to T. Different metrics might be employed for the calculation of

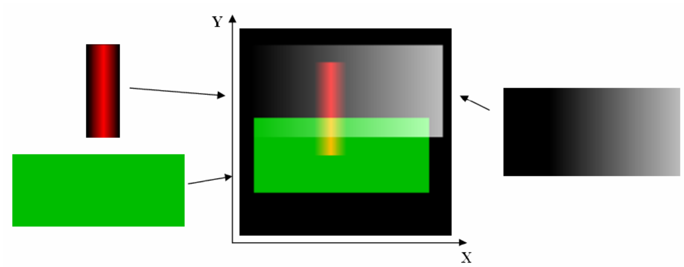

Figure 7: A TF is composed of several CFs which overlap in the 2D domain. The CF on the lower left was the least recently specified and is assigned the highest priority.

V_{dist}. We employ the Euclidean distance metric where the distance D of a voxel p to the reference shape T is calculated as:

$$D(p) = min\{||p-t||t \in T \tag{1}$$

The computational effort of Euclidean distance computation is considerable. If a small error can be accepted, distance computation may be considerably accelerated by approximative methods, e.g. with the Chamfer metric which operates on integer values and approximates distances with an error up to 5% [Loh98]. We chose to compute accurate distances, taking into account that it takes some seconds (the Euclidean computation of a distance volume based on a 256^3 dataset using a standard PC system (*1.7 GHz CPU, 1GB RAM*) requires approx. 20 seconds). If the reference structure is not changed, V_{dist} has to be calculated only once which can be performed as a preprocessing step. As an example, in thorax diagnostics, the segmented lung serves as reference structure for many diagnostically relevant questions. It is important to compute signed distances in order to distinguish structures inside and outside the target structure. This is accomplished by assigning a negative sign to all voxels which are outside of T. The reference structure is usually one connected component but it may also consist of several structures which are not locally connected. It is not necessary, that the reference structure is closed since the distance computation only relies on a certain set of voxels representing the reference structure.

7 Applications

The application of distance-based TFs requires that relevant objects are segmented in advance. In therapy planning scenarios, this assumption is reasonable since segmentation information is required for different reasons, such as quantitative analysis.

7.1 Anatomic Reformatting

One application of distance-based TFs is based on organ surfaces as reference shapes in order to explore inner structures. Here, the idea of anatomic reformatting (recall [DWS$^+$03]) is extended: the visualization of slices where each pixel is equidistant to an organ surface where lung nodules occur with higher probability. A clinically relevant example is the search for lung nodules in the vicinity of the organ surface. With distance-based TFs, different distances can be evaluated within one view by interactively modifying the represented distance (see Fig. 8). This application can be enhanced by generating animations which slice through a given range of distance values, such as the two used in Fig. 8. The continuous movement makes it easy to discriminate whether bright spots belong to vasculature or to a lung nodule.

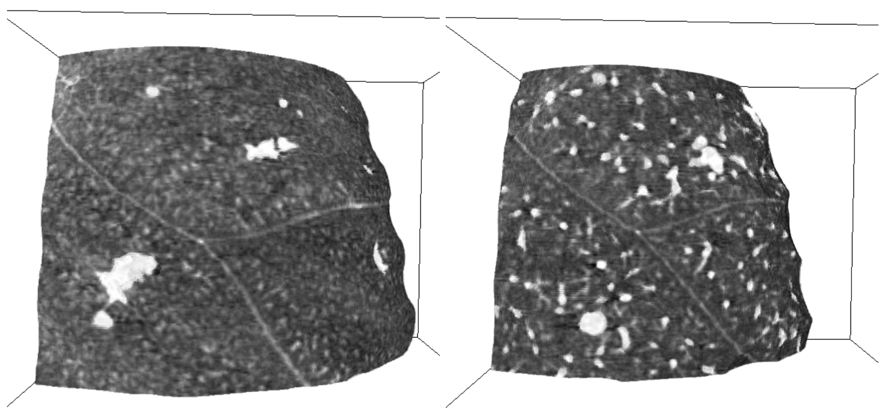

Figure 8: Visualization of slices equidistant to the lung lobe surface. Distances are 3.6 (left) and 20 mm (right).

7.2 Distance-dependent Context Visualization

In many cases, relevant structures should be presented along with important context information which serves as orientation aid. With conventional direct volume rendering this is often not possible since relevant and context structures can not be distinguished. Distance-based TFs support such a separation. We illustrate this with another example which also relates to the diagnosis of CT thorax data. In Fig. 9, vessels and the lung surface are visualized. Here the TF for the lung lobe is specified such that two distance ranges are rendered: the surface [0 mm,2 mm] and the inner vessels [2 mm,160 mm]. For both ranges, different opacity and color properties are used. In principle, a similar effect could be achieved with gradient-magnitude weighted opacity specification. The interaction, however, would be more tedious. Besides, TFs are easier applicable to different datasets (gradient-magnitude between two tissues varies considerably depending on the CT device and the reconstruction filters).

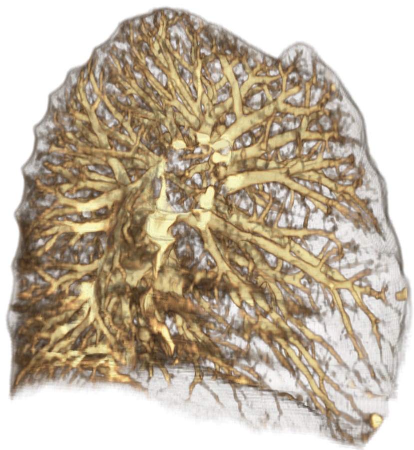

Figure 9: 3d visualization of vessels within a lung lobe. The distance-based TF was adjusted such that the surface of the lung lobe and the vascular structures inside are visible.

7.3 Distance-based Visualization for Tumor Surgery Planning

Another application for distance-based TFs is surgery planning where the distance from (malignant) tumors to vascular structures is crucial. With distance-based TFs, colors may be employed to convey the distance of a tumor to vascular branches. Such visualizations provide an overview of vascular branches in certain security margins around a tumor, which is shown in Fig. 10 for a lung tumor.
Beside the discussed applications in thorax diagnostics, distance-based TFs are applicable and probably useful in other medical applications. As a general application, distance-dependent removal of distracting tissues is often needed for diagnostic procedures as well as surgery planning.

8 Discussion

Distance-based volume rendering is closely related to focus and context rendering [BGKG05]. Indeed, distance-based TF specification provides additional facilities for focus and context rendering, see Fig. 11. The major difference is that the visualization properties are adapted to specific distances. This is crucial for clinically relevant tasks, such as tumor surgery planning, where acceptable safety margins are based on established guidelines.

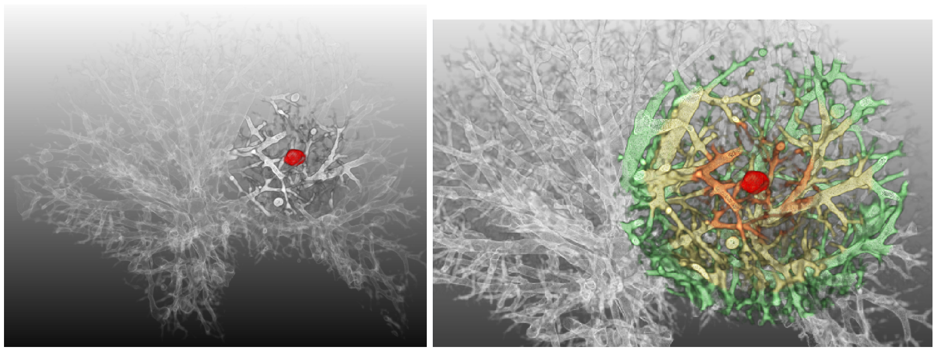

Figure 10: Distance-dependent visualization for lung tumor surgery planning. Left: Opacity increased for vascular structures in the 20 mm security margin around the tumor. Right: Four distance ranges are used: tumor red [0mm,3mm], vessels red [-15mm,0mm], vessels yellow [-30mm,-15mm], vessels green [-45mm,-30mm].

For clinical applications of distance-based TFs, an efficient interaction is crucial. Predefined 1d TFs (presets) are wide-spread in radiological workstations for all common tasks, such as assessing skeletal structures, vascular structures or lung tissue in CT data. Presets are also essential for the distance-component of the TF specification. In this work, presets for distance-based TFs were defined for some tasks in CT thorax diagnostics (including all discussed applications). The presets are applicable to different datasets similar to presets for 1d TFs. For the visualization of MRI data, intensity ranges have to be adapted since no standardized scale is available such as the Hounsfield units. This task is less complex than setting completely new CF parameters and can be supported again by presenting appropriate histograms.

9 Implementation

We integrated distance-based TFs into the MeVisLab platform (http://www.mevislab.de/) which comprises an efficient volume renderer (Gigavoxelrender, based on multiresolution rendering techniques described in [LHJ99]). We used an efficient 3d texture-based approach. The visualization process will be executed almost completely on graphics hardware. The scalar volume data (CT or MRI), a distance volume and a distance-based 2d lookup table provide the basis for the visualization. These data are transferred to the volume renderer, which adds proxy geometry, texture coordinates, and other features required for 3d texturing. For distance-based volume rendering two aspects are essential: a volume renderer, which supports 2d lookup tables, and a graphics board with 3d texturing facilities. Also 2d (multi) texturing can be used, but the rendering quality decreases due to rendering artifacts and switch effects while changing of texture volumes.
The transfer function is specified within an appropriate editor which contains some viewers

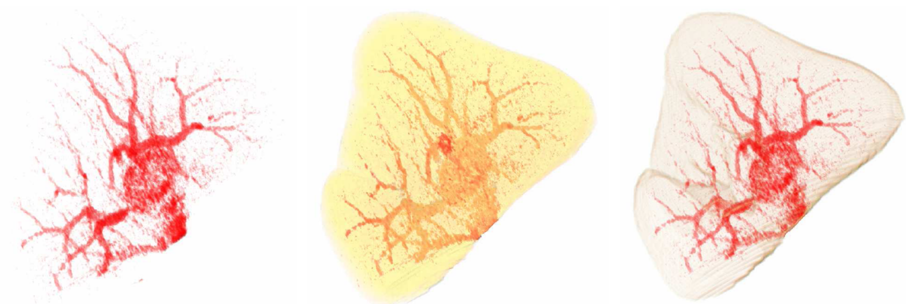

Figure 11: Using distance-based specification for focus and context rendering. The intrahepatic vasculature (left) is the focus object and the liver represents the context. With conventional tagged volume rendering, the visualization of the vasculature is hampered by many occluding liver voxels (middle). In the right image, only the [0...1 mm] distance range of the liver surface is rendered.

like 2d-histogram viewer, slice viewer, and a volume viewer. These support the user while setting visualization properties (selection and adaptation of templates). Beside, the interactive definition concepts, discussed in Sect. 5, are included. In addition there is a facility to handle presets, which allows a fast definition of an initial visualization.

10 Concluding Remarks

The visualization by means of distance-based transfer functions allows to hide, emphasize or color structures based on their distance to a relevant reference structure. We described an efficient realization of distance-based transfer functions with dedicated hardware support. For example, it permits to peel an organ which is useful for a directed search concerning lesions near an organ's surface. In principle, the presented techniques can be applied broadly. Reference objects are not restricted to segmented objects. Arbitrary geometric shapes, such as spheres or planes, may also be employed. The specification techniques based on 2d CFs are not restricted to distance-based TF design. They are applicable to other kinds of TF design on a 2d domain such as intensity and gradient magnitude-based TF definition.

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