

# Mastering Transfer Function Specification by using VolumePro Technology\*

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## Abstract

A new user-interface paradigm for the specification of transfer functions is presented. The specification is usually a difficult task as mapping information for a number of different domains (data range, color, opacity, etc.) has to be defined. In the presented approach, the definition of the mapping information can be realized independently for each property domain. A set of specification tools is provided for each domain, enabling users with different levels of experience or demanding time restrictions to choose an appropriate approach for their needs. Real-time feedback during the manipulation of parameters has been proven to be crucial to the specification. An interactive direct-volume-rendering display is realized by utilizing dedicated hardware acceleration.

**Keywords:** Volume Visualization, Transfer Function Specification, VolumePro ray-casting system

## 1 Introduction

When employing direct-volume-rendering for the visualization of volumetric data sets, typically a transfer function is used to classify the data. Data values are mapped into optical properties like color or transparency information. During the rendering procedure the transfer function is evaluated for specific data values in order to gather the contribution of certain voxels or sampled locations to the resulting visualization.

In general a transfer function  $\tau$  is defined as a mapping from a cartesian product of scalar fields  $F$  to a cartesian product of optical properties  $O$ :

$$\tau : F_1 \times F_2 \times \dots \times F_n \rightarrow O_1 \times O_2 \times \dots \times O_m$$

Up to now the values of the dimensions  $n$  and  $m$  had to be kept small due to the overwhelming specification effort by the user. Typically a transfer function maps density values ( $n = 1$ ) to opacity

and color properties ( $m = 2$ ). All other parameters which are necessary for shading the rendered voxels are determined by a more or less sophisticated illumination model [8]. Transfer functions of higher complexity take usually the magnitude of the gradient within the volume-data set into account ( $n = 2$ ) [6]. Even for these restricted cases ( $n, m \leq 2$ ) the effort for specifying the transfer function is not to be neglected in daily clinical practice. Especially medical doctors with little experience in computers or the mathematical background of volume rendering are usually not able to handle complex paradigms for specifying high-dimensional functions needed for the visualization.

Several approaches to provide a more user-friendly methodology for the specification of transfer functions have been proposed. Some methods analyze input data [2, 5] or output images [1] to provide the user with an initial transfer-functions setup. When intuitive interaction mechanisms are missing, it is still hard for the user to fine-tune these proposed transfer functions to his needs. Other approaches generate an initial set of transfer functions, which is evolved for some generations by a genetic algorithms scheme [3]. It was also proposed to provide the user with an arranged display of previews, covering as much as possible of the entire domain of the transfer-function specification-parameters [7]. This approach proved to be very useful, as the user is just required to choose an appropriate region in the space of transfer function dimensions in order to gain an initial set of parameters for fine-tuning. The major drawback of this approach was the amount of preprocessing time needed for rendering the large number of previews covering the entire transfer function domain. With the rise of rendering hardware dedicated to generating direct-volume-rendering displays of large data sets with interactive frame rates [9], this problem can be overcome. In this paper a strategy similar to this approach is presented. With the possibility of high speed rendering, even more properties in the possible space of transfer function input dimensions can be explored. The goal of the developed approach is to provide medical doctors with a system, which can be used intuitively. Nevertheless the possibilities for the specification of transfer functions must not be restricted.

The following section describes the approach developed by the authors. Then the tools for the specification of contributions from the domains of data-value, color, and opacity are described. The results section discusses first feedback from medical doctors using

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the proposed system. Eventually conclusions and topics for future work are stated.

## 2 Advanced transfer function specification

The specification of transfer functions usually is a difficult task. Appropriate settings have to be found in several search domains of sometimes infinite resolution. Trying to find a useful transfer function by moving a single sample through this high-dimensional search space is not possible. The approach presented in this paper tries to define the specification step by step. If it is possible, the search-space domains are treated separately. Appropriate settings are found independently for these domains. The domains used as examples for the demonstration of the presented approach are:

- data range (center, width, and shape of contribution peaks)
- color (hue, luminosity, saturation)
- opacity (for different contributions to the visualization)

The presented approach is easily extendable by using different or additional specification domains, like gradient magnitude, principal curvature magnitude [4], etc.

For each specification domain, different user interaction approaches have been developed. A different approach will be chosen by the user, depending on the experience of the user, a-priori knowledge about the investigated volume data set, the dedication to fine-tuning, the need for efficient generation of the transfer function in time-critical fields of application, and the suitability of predefined settings.

The basic concept of our approach is shown in figure 1. Contributions to the visualization are composed by choosing a certain number of intervals in the domain of the data values (“peaks”), selecting colors for these ranges and have them combined with specified opacities into a single transfer function. If  $i$  contributions are to be used, then the transfer function  $f = \{f_o, f_c\}$  mapping data values  $d$  resolves to:

$$f_o(d) = \sum_i p_i(d) * o_i$$

$$f_c(d) = \begin{cases} c_i & p_i(d) \neq 0 \\ \text{black} & \text{else} \end{cases}$$

where  $f_o(d)$  is the opacity definition of the transfer function to be specified,  $f_c(d)$  the color definition of the transfer function,  $p_i(d)$  is the contribution of a certain region of the data domain,  $o_i$  the opacity combination values for the contributions, and  $c_i$  are the colors for single contributions. When peaks  $p_i(d)$  are overlapping, colors  $c_i$  have to be interpolated. An appropriate color space (like HLS) has to be used for the interpolation.

The core component of our specification scheme is a visualization display capable of rendering images of the investigated volume data set with real-time frame rates (see figure 2). Utilizing the VP500 hardware ray-casting system [9], this rendering performance can be achieved. Whenever the user is specifying a contribution from the different domains, the influence of the changes made to the 3D rendering are displayed in this window. Note, that not only the final transfer function will be used for the display, but also transfer functions composed by the partially defined contributions from the domains (like certain data only, colored data regions only, and finally the composed transfer function). Small preview images rendering the volume data set using the intermediate (or final) transfer-function components are generated. Clicking one

of these preview images, the user will activate the transfer function used for the preview. The rendering window will display the volume-data set classified with this transfer function, allowing the user to do further investigations by rotating and zooming the view. Using this approach, every manipulation of the transfer function by the user will result in immediate feedback of the changes in the 3D-rendering display (unlike other approaches, which try to give real-time feedback by classifying and coloring 2D slices).

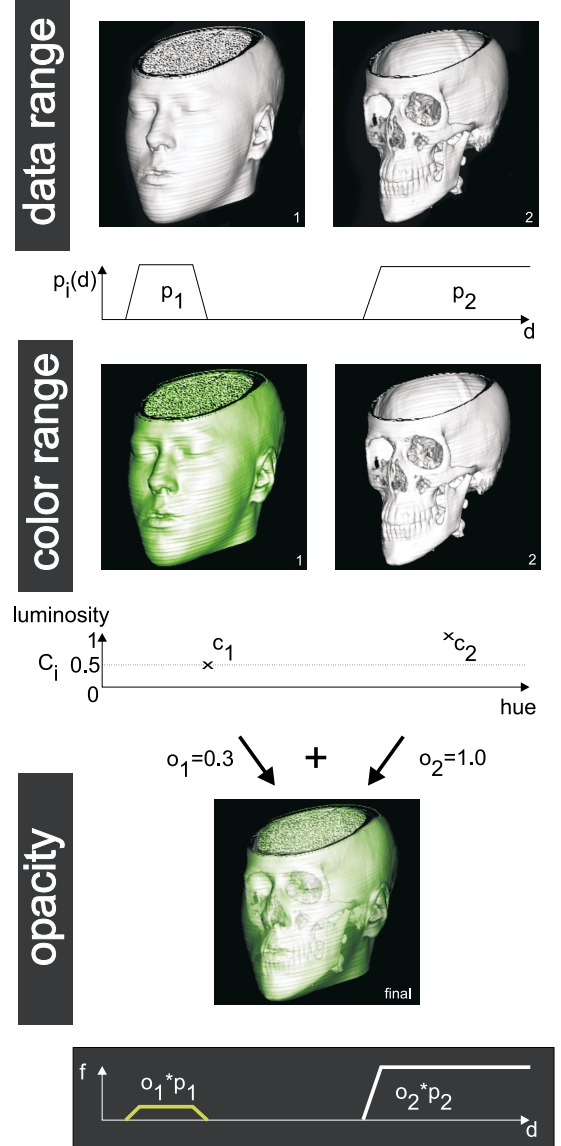


Figure 1: Two contributions are combined for the visualization. Parameters for the dimensions of the transfer function (data range, color, and opacity) are defined independently.

## 3 Data range

The first step in the composition of a visualization is the specification of certain data ranges  $p_i(d)$ , which shall contribute to the visualization (e.g. skin, bone, etc). In the current prototype-like implementation, the contributions are specified in the domain of the voxel values of the volume data set. Nevertheless, any scalar

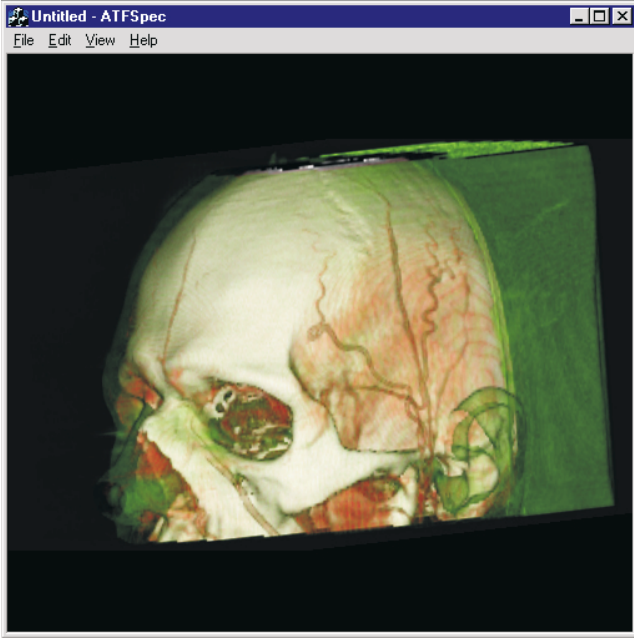


Figure 2: Real-time feedback for all modifications by the user is provided by a rendering window, using VolumePro technology for the calculation of the direct volume rendered image.

dimension of the data could be used for the selection, e.g. gradient, principal curvature magnitude, etc.

The contributing regions of the data domain are called *peaks* (see figure 3). The main properties of a peak are its location (*peak center*  $c$ ) and the range of its contribution (*peak width*  $w$ ). The contribution characteristic of specific data values within the range of a peak is defined by the shape of the peak. The following shapes have been proven to be useful:

- **Trapezoid:** The most common peak shape used with transfer functions is the trapezoid. Data values covered by the constant plateau around the center are mapped to full opacity, whereas the slopes are mapping data values to linearly increasing or decreasing opacity values. The width of the trapezoids slopes is an additional peak property definable by the user. The definition of a trapezoid-peak shape is as follows:

$$f(t) = \begin{cases} 0 & 0 \leq t \leq c - \frac{w}{2} \\ \frac{t - c - \frac{w}{2}}{s} & c - \frac{w}{2} < t \leq c - \frac{w}{2} + s \\ 1 & c - \frac{w}{2} + s < t < c + \frac{w}{2} - s \\ 1 - \frac{t - c - \frac{w}{2} + s}{s} & c + \frac{w}{2} - s < t \leq c + \frac{w}{2} \\ 0 & c + \frac{w}{2} < t \leq 1 \end{cases}$$

where  $c$  is the center of the trapezoid,  $w$  is the width (including the slopes), and  $s$  is the width of the trapezoids slopes.

There are two variation of the trapezoid-shaped peak, which have to be taken special care of: whereas the *tent* ( $s = w/2$ ) is useful to extract information which is represented in a very narrow region within the data volume, the *box* shape ( $s = 0$ ) should be avoided, as it usually produces artifacts due to the discontinuities at the vanishing slopes. Figure 3 gives a comparison.

- **Ramp:** Radiologists have been using the metaphor of *windowing* in 2D PACS software for years. A simple grey-level ramp (with certain center and width properties) is used to map data

values into luminosity values. Data values below the minimal extend of the window are mapped to black (zero intensity), whereas values above the range of influence of the window are mapped to white (full intensity). The users are moving this “window” through the range of data values in order to enhance the visual contrast for certain regions of the data domain. As this is a well established technique in 2D, it was desirable to adapt this approach for 3D. Using a ramp-shaped peak, 2D windowing can be simulated in 3D. As we are utilizing VolumePro technology, the same interactive frame-rates as for 2D-windowing are achievable.

Figure 3 gives a comparison of the influences of these peak shapes.

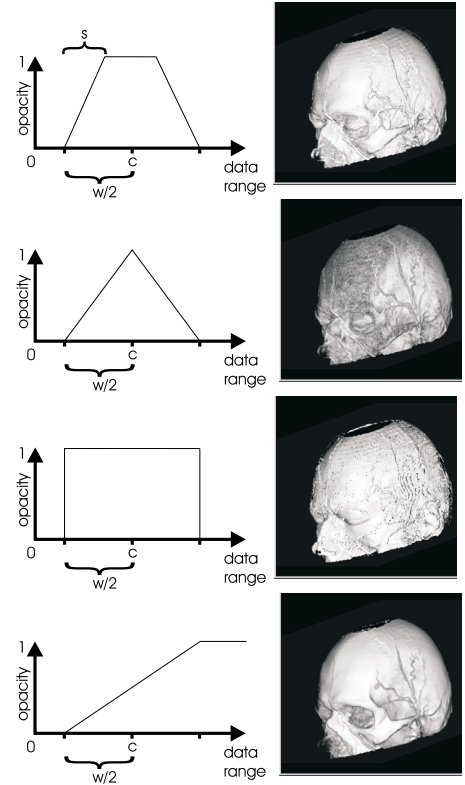


Figure 3: Different peak shapes (from top to bottom): trapezoid, tent, box, and ramp.

Several ways for specifying a peak have been included in the presented method. Depending on the task to be solved as well as on the level of experience of the user, a different approach may be chosen.

The central part of the user interface for this step is a bar displaying the range of data values (see figure 4). A grey-level ramp is displayed in this bar in order to give the user simple visual feedback which region of the data domain he is investigating.

When transfer function contributions (peaks) are displayed in the user interface, the numerical properties of a peak (center and width) are shown by plotted markers on this range bar, giving the user a hint, where the contribution he is investigating is located in the data domain.

By default the entire range of data values is displayed. Along with the bar, the limits of the currently active data range are given numerically (e.g. for a data set with a signal resolution of 12 bit the number 0 would be displayed at the left end of the bar, whereas 4095 would mark the right-most extent of the bar). When the user wants to “zoom” into the data range (in order to get a new set of

suggestions around an interesting region) the limits of the displayed range can be changed easily by activating a button and clicking the mouse into the spot of the bar, where the new limit should be. Another button would be used to “reset” the limits of the bar and display the entire range of data values again.

A histogram of the data set is painted into the range bar. Peaks in this histogram give hints where certain materials are to be found in the data domain.

There are a number of possibilities to specify a peak. Depending on the a-priori knowledge about the data set, the experience of the user or the special demands of the visualization task, a different approach can be chosen. The following techniques have been proven to be useful:

- *Accept a suggestion:* The system renders a certain number of preview images, using peaks covering the entire range of data values. Small thumbnail images are displayed (see figure 4). The user is free to activate one of the thumbnails by clicking on it and investigate the visualization created with this transfer function peak in the rendering window. Due to the rendering speed of the VolumePro board, the visualization parameters (like camera position and orientation, lighting, shading, etc.) can be modified in real-time. If one of the suggested peaks renders, what the user is looking for the suggestion can be chosen as a result for this step.
- *Modify a suggestion:* If none of the suggestion shows exactly the features of the data set, the user is interested in, the suggestion suiting the users needs best can be fine-tuned. Using his mouse the user drags one of the previews below the bar displaying the range of data values. The suggestion is turned into a modifiable peak. Its center can be moved through the range of data values by holding down the middle mouse button and moving the mouse horizontally. By moving the mouse vertically (again with holding the middle mouse button) the width of the peak can be modified. This approach has been chosen in analogy to the method of “2D-windowing” described above. Radiologists are used to select a certain range of the domain of data values and suppress the rest from rendering by holding the middle mouse button and dragging around the mouse. After a bit of training, this approach allows to fine-tune peak-parameters efficiently without being aware of the actual numerical properties of the selection in the data domain which is currently rendered. This approach also allows to quickly browse through the entire data domain and therefore gain a fast overview on the features present in the volume. Without the real-time frame-rates provided by the VolumePro hardware, this approach would not be usable intuitively.
- *Use standard values:* For certain types of data sets, it is possible to directly derive the material scanned by the modality from the signal value. For instance, for CT-data sets there is a linear mapping from voxel values to material densities. Certain materials are identifiable by their Hounsfield numbers. For this reason, predefined transfer function peaks can be used to display certain combinations of materials, which are interesting to the user. Common combinations include the display of bone, soft tissue and contrast media (injected into vessels before scanning). The presented approach includes the possibility to load predefined sets of peaks and to save peak combinations the user wants to reuse. This approach is less suitable, when data sets acquired by MR or other non-xray-based modalities shall visualized.
- *Numerical specification:* Another possibility is the specification of peak properties by their numerical representations. When for instance contrast medium of a certain manufacturer is used, its signal representation in the volumetric scan is

known. The center and width values (and slope for trapezoids) for the peak rendering this feature may be entered manually by the user.

Whichever approach is chosen by the user, the goal of this specification step is one selected contribution from the range of data values for every feature, which has to be distinguished in the final visualization. Therefore this “data selection” step will be repeated by the user until the set of objects to be visualized is complete (and represented by thumbnail images in the user interface). The following step (described in the next section) yields similar selections from the domain of color values.

## 4 Color range

The next step in the specification process deals with the assignment of color information  $c_i$  to the ranges selected in the first step (see figure 5). For each peak defined in the first step, colors can be assigned independently. Color assignment is investigated for one “active” peak at a time, which is marked with a red frame in the user interface.

The main part of the user interface for color specification is a bar representing the hue and saturation domain of possible colors. Whenever a preview image is displayed in this user interface, it is connected to this color domain bar by a thin line, marking the color parameters for the color used to create the rendering. This enables the user to associate hue and saturation information with the presented color representation quickly. For the sake of convenience, the leftmost part of the color domain bar does not represent hue, but a grey-level ramp of entirely de-saturated colors with varying luminosity. Using this approach the usually three-dimensional color space of a HLS-color system has been reduced to a two-dimensional specification scheme. As the quick specification of transfer function colors usually does not need other luminosity than an average value (0.5 is in the middle of full and no intensity in the HLS-color system), this approach seems to be sufficient. If the user wants to specify colors with other luminosities, other approaches can be used (see below!).

Again a number of approaches are presented to the user:

- *Accept a suggestion:* The system renders a certain number of previews for the active peak, using colors covering the entire range of color hues. Small thumbnail images are displayed (see figure 5). The user is free to activate one of the thumbnails by clicking on it and investigate the visualization created with the active transfer function peak and the color represented by this preview in the rendering window.
- *Modify a suggestion:* If none of the suggestion shows exactly the color the user wants to see the investigated feature of the data set in, the color suggestion suiting the users needs best can be fine-tuned. Using his mouse the user drags one of the previews below the bar displaying the range of color values. By holding the middle mouse button and moving the mouse horizontally, the user changes the hue of the suggestion. Moving the mouse vertically changes the saturation values of the selected color. This approach has again been designed in analogy to 2D-windowing.
- *Specify hue or luminosity only:* If the user knows beforehand what color he is going to use for the peak in question, it is very convenient to “drag & drop” the peak-preview image right onto the color bar. If the user releases the mouse button in the leftmost part of the bar, a color-preview image in the grey-level range with a luminosity according to the mouse position is chosen. If the user drags to the right part of the color bar,



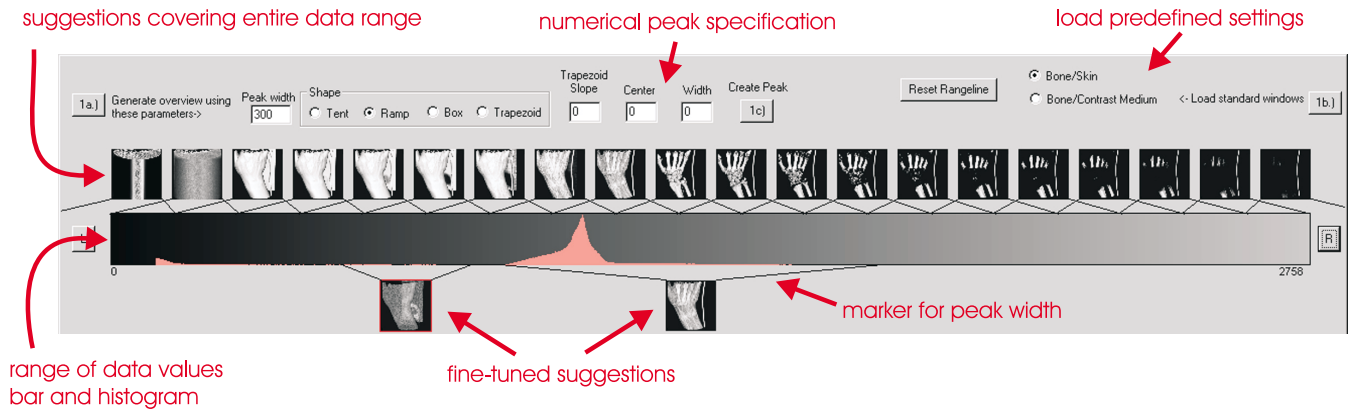


Figure 4: Specification of contributions from the range of data values.

the selected color is determined by the mouse position in the hue / saturation range. Luminosity is set to “middle”.

- *Choose a standard color:* By clicking a button, a set of standard colors is presented to the user. By choosing one of these, a color-preview image is created, which renders the volume data set using the selected peak (as opacity information) and the hue/luminosity/saturation value selected by the user.
- *Choose color parameters from graphical representation (color editor):* A standard color selection dialog is used to give the user the possibility to specify all parameters of a color (represented in different color spaces, like RGB or HLS) in an easy way. In the HLS-color space the user would for instance move the mouse around the hue/saturation circle and adjust the luminosity of the selected color by clicking into a region displayed with varying intensities. Figure 5 (lower right hand corner) shows the user-interface dialog used for this approach.
- *Numerical specification:* If the user is experienced with the usage of different color systems, there is also the possibility to enter the characterization values of a certain color numerically.

The goal of this specification step is the assignment of color properties for every data-range peak selected in the first step. The final step will deal with the appropriate combination of these “colored peaks” in the opacity domain.

## 5 Opacity range

The final step in the specification process deals with the combination of the color-assigned data-range peaks prepared in the first steps into a single visualization. Different opacities  $o_i$  are assigned to the single peaks, when they are combined into a single transfer function, which is used on the volume data set. The specification of these opacities  $o_i$  is the contribution of this step.

Again a user-friendly interface with real-time rendering feedback and a number of different approaches for the specification is provided (see figure 6).

- *Choose suggestion:* The system is rendering a certain number of combinations of the “colored peaks” in discussion. When two peaks are to be combined, sixteen combinations with different amounts of opacity are displayed in a 4-by-4 matrix. The opacity contribution for the first peak is increasing in horizontal direction, whereas the opacity for the second peak is increasing vertically (see figure 6, left hand side). If three or

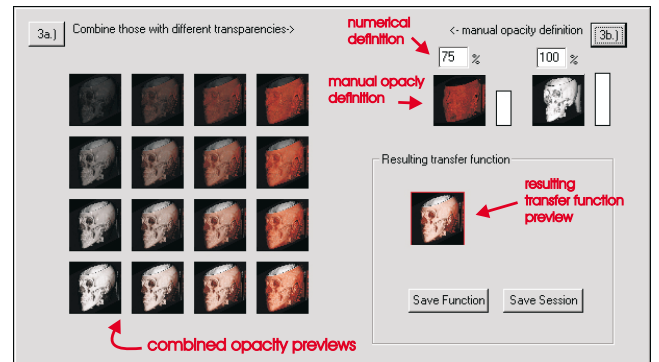


Figure 6: User interface for the combination of “colored peaks” by assigning opacities.

more peaks are to be combined, more sophisticated schemes for the arrangement of the preview images have to be provided (e.g. sorted by dimensions).

The fastest way for the user to specify an appropriate combination is to simply select one of the preview images by clicking it with the mouse cursor.

- *Modify suggestion:* If none of the suggested combinations entirely satisfies the user, he may choose one of the preview images to have it put into “fine-tuning” mode. Modifications to the amounts of opacity used for the combination of the colored peaks can be made with the same interaction techniques as described below.
- *Manual definition:* The system displays the preview images for the prepared colored peaks along with small bars, representing the opacity contribution of the peaks (see figure 6, upper right hand corner). The user adapts the opacity contribution by simply clicking the middle mouse button into the bar and dragging the mouse in a vertical direction. Depending on the direction of the movement, the opacity contribution along with the graphical representation through the height of the bar is changed. Furthermore, the rendering window displays the changes to the final visualization in real-time during the modification of opacity contributions.
- *Numerical definition:* Finally, the user is able to enter the values for the contribution of the single colored peaks in numerical terms, giving the opacity as percentage of fully opaque.

suggestions covering entire color range



Figure 5: Specification of contributions from the range of colors.

The user usually modifies the opacities until the visualization rendered with the final transfer function fits his needs. Whenever settings defined in the first two steps seem not to be appropriate, the user would go back to data range or color specification and do some modifications to the definitions there. Changes will of course be reflected in the definitions done in later steps.

## 6 Results

The concepts presented in this paper have been implemented in a prototype software system. A standard PC system (500MHz, 512MB RAM) was used as the hardware platform. It is equipped with a Real Time Visualization VP500 VolumePro board in order to provide interactive direct volume rendering performance. The prototype was developed using MS Visual C++ 6.0 running under Windows NT 4.0 SP5.

Figure 7 shows the entire user interface of the system. This screen shot has been taken after a user has defined three different contributions: skin, vessels (with contrast medium), and bone. These contributions have been assigned the colors green, red, and white. The user has chosen the opacity value of 24% for the skin, 40% for the vessels, and 100% for the bone. The volume-data set rendered with the final transfer function is shown in the lower left hand corner.

Other images created with the presented system can be viewed in higher resolution at the web page <http://www.cg.tuwien.ac.at/ATFSpec>.

## 7 Conclusions

A new user interface paradigm for the specification of transfer functions in the field of medical volume visualization has been presented. The specification task is simplified by realizing the definition of mapping parameters for each search domain independently. A prototype software implementation (supporting data range, color, and opacity as search domains) has been used to prove the usefulness of the presented concepts. Several specification tools for each search domain were presented to a group of medical doctors. Depending on the users experience and special demands of the visualization, different tools can be used. VolumePro technology has been used to provide the direct volume rendering performance crucial for

interactive feedback to the users when modifying the transfer function.

Topics for future work include the investigation of the usefulness of additional search domains (gradient magnitude, principal curvature magnitude, shading coefficients, etc).

## 8 Acknowledgements

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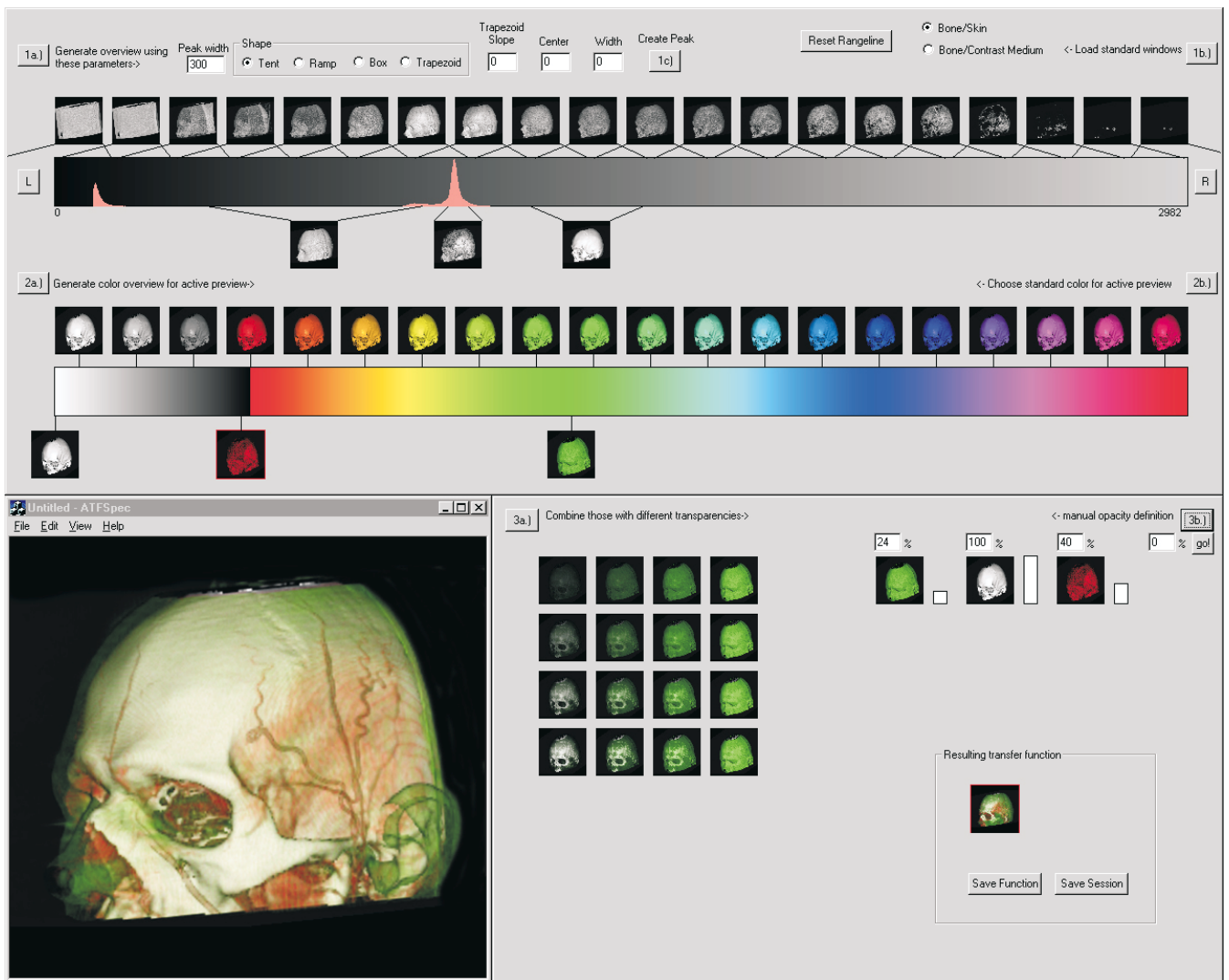


Figure 7: Specification of a transfer function with three contributions

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