Interactive Dual-Volume Rendering Visualization with Real-Time Fusion and Transfer Function Enhancement

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ABSTRACT

Dual-modality imaging scanners combining functional PET and anatomical CT constitute a challenge in volumetric visualization that can be limited by the high computational demand and expense. This study aims at providing physicians with multi-dimensional visualization tools, in order to navigate and manipulate the data running on a consumer PC. We have maximized the utilization of *pixel-shader* architecture of the low-cost graphic hardware and the texture-based volume rendering to provide visualization tools with high degree of interactivity. All the software was developed using OpenGL and Silicon Graphics Inc. Volumizer, tested on a *Pentium mobile* CPU on a PC notebook with 64M graphic memory. We render the individual modalities separately, and performing real-time per-voxel fusion. We designed a novel "alpha-spike" transfer function to interactively identify structure of interest from volume rendering of PET/CT. This works by assigning a non-linear opacity to the voxels, thus, allowing the physician to selectively eliminate or reveal information from the PET/CT volumes. As the PET and CT are rendered independently, manipulations can be applied to individual volumes, for instance, the application of transfer function to CT to reveal the lung boundary while adjusting the fusion ration between the CT and PET to enhance the contrast of a tumour region, with the resultant manipulated data sets fused together in real-time as the adjustments are made. In addition to conventional navigation and manipulation tools, such as scaling, LUT, volume slicing, and others, our strategy permits efficient visualization of PET/CT volume rendering which can potentially aid in interpretation and diagnosis.

Keywords: Visualization and Multimodality Display

1. INTRODUCTION

A Dual-modality scanner which combines two independent imaging modalities of functional PET and anatomical CT in a single session have been proven to be an effective approach in diagnosis and interpretation of certain medical conditions. In the visualizations of dual-modality PET/CT data, volume rendering is often employed. Volume rendering is a method of displaying three-dimensional (3D) data in a 2D format by using ray-tracing, and is able to produce rendition of complex and high-detailed medical data [1]. The ability to interactively navigate the rendered volume by "flying" the viewing window through the volume data is rapidly becoming a very attractive method for many medical imaging applications, including image guided surgery and computer aided diagnosis [1-5]. However, the ability to visualize the PET/CT images in volume rendering is limited by the high computational demand and expense, so is often restricted to dedicated workstations [5]. Moreover, visualization tools that are capable of interactive volume rendering are based on rendering a single volume, for instance, PET, CT, or the fused PET/CT [1-2]. The purpose of this study was to investigate a new visualization method for dual-modality PET/CT images, in order to allow interactive volume manipulations to be applied to individual volumes that are then fused in real-time. In particular, we introduce an "alpha-spike" transfer function which can be used to adjust the level of transparency of voxels in a non-linear function. The spike is designed to allow selective visualization of the PET/CT images, such that structure of interest in relation to its surrounding structures between two modalities can be interactively visualized. This can be used to eliminate or reveal

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details surrounding the volume of interest (VOI). Moreover, the visualization is optimized for a consumer PC notebook which provides mobility and cost-effectiveness.

2. METHOD

2.1. Dual-modality Volume Rendering

Currently, one of the most utilized and powerful image display and manipulation techniques is volume rendering by ray casting. This technique renders volumetric data (e.g. CT and PET) directly to a 2D image without the need for segmentation or surface extraction which is mandatory for surface-based rendering. The major advantage of this method over surface rendering techniques is that the values and context of the original image data are preserved rather than approximated. 3D visualization technique that is often applied in the medical imaging field is Volume Rendering by ray casting. This method is characterized by algorithms that have traditionally been too slow to allow effective interaction with the volume by a physician unless run on extremely expensive dedicated graphics terminals. With the advent of consumer based graphics cards for the computer game market, a new algorithm for ray-casting has been found to be effective by utilizing the fast download of *voxels* stored in dedicated texture memory.

Volumizer (Silicon Graphics Inc.) is a well-established C++ library that provides implementation of volume rendering using volume-slicing algorithm [6] that is optimized for consumer based graphics cards. Volumizer was found to suit our visualization requirements and therefore was used to implement a prototype application that demonstrates our proposed method for dual-modality fusion, visualization and transfer function enhancement.

The Volumizer's texture-based rendering algorithm as explained in [6-7] utilizes the ability of modern graphics cards to perform extremely fast downloads of cached 3D textures (volumetric data sets) from specialized graphics memory and apply them to geometric surfaces. The outline of the algorithm is as follows: (1) The volume is sliced with planes aligned parallel to the viewing plane and then stacked perpendicular to the direction of view; (2) The planes from 1 are converted to polygons that are clipped to the edges of the volume geometry; (3) Each polygon is textured with the volume data from the 3D texture with which they intersect, forming a set of 2D images; and (4) The set of 2D images are *alpha blended* in back-to-front order to form a smoothed image. Under this algorithm it is possible for each slice of volumetric data to be downloaded from texture memory simultaneously.

2.2. Alpha Spike Transfer Functions

Transfer functions controls the transparency of the voxels to allow the user to have control over the intensity range which is made visible [6]. When rendering a voxel data set it is often important to store other data that characterizes how each voxel effects light which passes through it. There are many physical characteristics such as color, density, and translucency which all have an impact on the appearance of volumetric data, however since a voxel datum from such scanners as PET and CT is delivered as a single intensity value, from this we must interpret other physical characteristics. The physical property opacity is generally denoted by the Greek letter α and is defined as a measure of light absorption. Alpha values are typically decimal values in the range of $0 < \alpha < 1$ where an alpha value of 1 signifies a completely opaque voxel and 0 signifies one which is completely transparent.

For this study, the method for transfer function specification is based on alpha-spike, a non-linear function designed to work with the PET/CT images to simplify the process of feature selection for the physician. The aim of our feature selecting transfer function is to interpret voxel intensity values from volumetric image data to alpha values for use in the ray-casting algorithm. Therefore, let us define a linear function $f(x)$ which maps a single voxel intensity value x to the corresponding voxel alpha value such that

$$\alpha = f(x) \tag{1}$$

Now let us create a feature selecting spike in the opacity values using a continuous linear piecewise function where the effect of adjusting the transfer function is seen in real time so that when the width (W_L and W_R) and centroid (W_C) of the alpha spike (Fig. 1) is adjusted, it has the effect of selecting particular features within the volume while making others transparent. The level of alpha, α_{max}, and α_{min} can be used to set the level of opacity of the volumes. The α is also used to control the fusion ratio according to $\alpha_{PET} = 1 - \alpha_{CT}$.

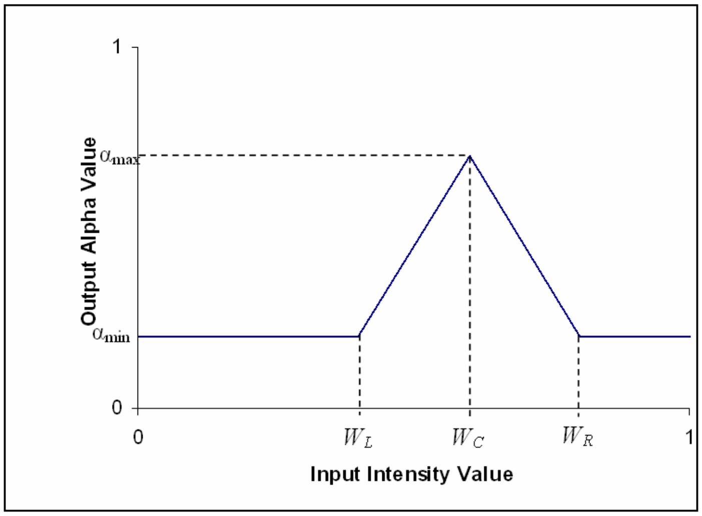

Figure 1. Alpha-spike transfer function. The window of the input intensity value can be adjusted by setting the window centroid, W_c, and the width for the left and right window, respectively of W_L and W_R. The alpha value can be controlled using the minimum and maximum thresholds.

$$f(x)=\begin{cases}\alpha_{\min} & if \quad x \le W_L \\ \alpha_{\min}+\dfrac{(\alpha_{\max}-\alpha_{\min})(x-W_L)}{(W_C-W_L)} & if \quad W_L \le x \le W_C \\ \alpha_{\max}-\dfrac{(\alpha_{\max}-\alpha_{\min})(x-W_C)}{(W_R-W_C)} & if \quad W_C \le x \le W_R \\ \alpha_{\min} & if \quad x \ge W_R\end{cases} \tag{2}$$

In equation 1, the alpha spike is described by the five variables as shown in figure 1. The net effect of applying this alpha transfer function is analogous to selecting a particular intensity range to be semi-opaque and everything outside of that spike to be semi-transparent.

2.3. *Per-voxel Fusion*

In order to fuse the two volumes with depth perception, a "real-time per-voxel fusion" method was adopted which utilizes the *pixel-shader* architecture of modern consumer graphics cards to perform fusion calculations during the rendering of each pixel to the viewing raster. This method does not require any preprocessing of the volume data and thus allows real time adjustment of PET/CT fusion ratio.

A fragment program, an extension to OpenGL framework developed by ATi Technologies [8], is defined as a set of instructions that are applied to each *rasterized fragment* in the last stage of the OpenGL graphics pipeline. A *rasterized fragment* represents a set of assembled textures, pixel values and vertex operations. From these pieces of information a fragment program can be devised such that calculations including lighting, texturing and color mapping can be applied rapidly in the hardware in the final stage before being written to the frame buffer.

The instruction set provided by ATi Technologies for writing fragment programs used on their graphics cards is comprised of 33 instructions which perform operations such as applying a point in texture co-ordinates to a pixel, producing a vector cross products and performing linear interpolation between up to three vectors. The obvious advantage of this method is that the depth information is preserved. Another advantage which may not be as obvious is the lower instruction count required by this method which yields substantially faster rendering times. This is due to the fact that for each ray cast the sampling of the texture along the ray is done in tandem, thus utilizing the full potential of the memory bandwidth available on the new graphics cards like the Radeon 9800 Pro (used in this study).

3. RESULTS AND DISCUSSION

The application of the alpha-spiked transfer function and the per-voxel fusion was demonstrated to provide useful tools in the visualization of dual-modality PET/CT images which may improve the process of diagnosis. All FDG PET/CT images were acquired on a SIEMENS Biograph LSO scanner at the Hong Kong Sanitarium Hospital. The PET and CT images have been cropped and rescaled to the same volume of 256×256×263 at 16-bit with voxel dimensions of 1.953mm×1.953mm.

Figure 2 shows the clipped view of the lung from CT image. Detail of fine lung vasculature is blurred due to a single linear mapping of alpha values (a). By applying the alpha-spike transfer function with W_C set to the lung vasculature with broad W_L and $W_{R,}$ additional details are shown to be visible (b). This results in a vivid image where the outputted luminance range has been stretched to make use of the entire visual spectrum. Also note that the surrounding structures to the lung vasculature are visible without obscuring the selected structure. The orientation of the image is in rotated trans-axial view.

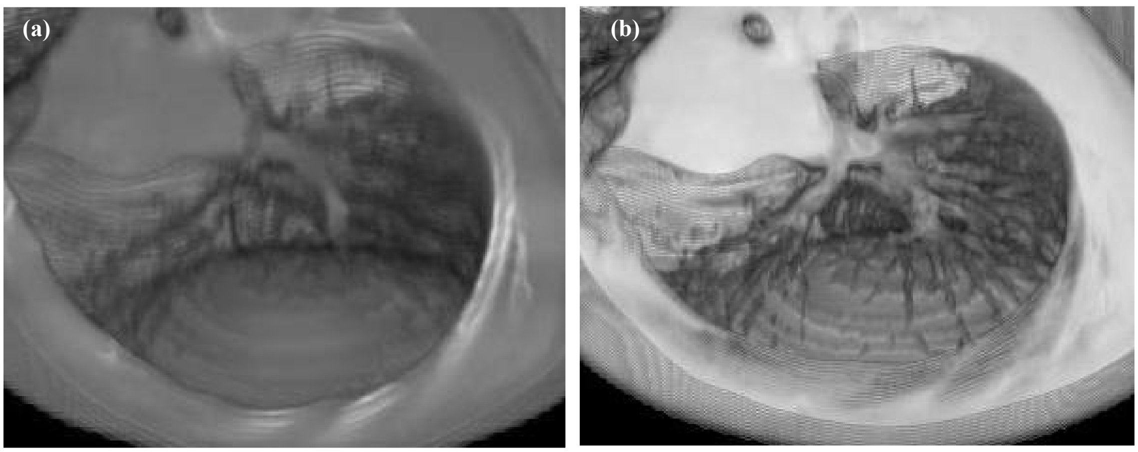

Figure 2. Alpha-spiked transfer function applied to a sub-section of a lung structure.

In figure 3, per-voxel fusion of the PET/CT images are shown. In (a), the skull (CT) encapsulating the brain (PET) is displayed which enable the visualization of the PET structures together with its anatomical surrounding structures. In (b), example of the lung section is shown. The low count areas from the PET image have been eliminated from view using the transfer function. In CT, transfer function was set at the bone level/skin structure. The fusion ratio was 70-30, respectively of PET/CT. Grayscale lookup table was used for CT, and "hot temperature" was applied to PET. As the transfer function and the fusion ratio can be adjusted to the same volume in real-time, these tools may improve the visualization of PET/CT images.

Examples of the application of transfer function to CT volume are illustrated in Figure 4. This demonstrates the ability of the transfer function to selectively visualize the boundary of the structures (a), and the bone structures (b), which may potentially be useful to threshold the unnecessary volume from the entire data to remove it from obstructing the view.

The proposed volume rendering can also be used in the conventional orthographically sliced views. Figure 5 presents the orthogonal views applied to PET/CT using Per-Voxel fusion. The volume rendered data can be viewed in traditional viewing planes for Coronal (a), Axial (b), and Sagittal (c). More over, since the data are volume rendered, the viewing angle from any of these views can be adjusted, such as in (d). In this example, the equal fusion ratio for the PET and CT data were applied. The volume consisted of slices from the lung to the brain of a human patient data. It should be noted that since this is a real CT data set it is subject to real problems that currently have not been solved in CT image reconstruction. In (a) and (b), dark lines across the volume can be noticed, this is part of the data set and is a result of a metal false tooth disturbing the attenuation settings of the scanner.

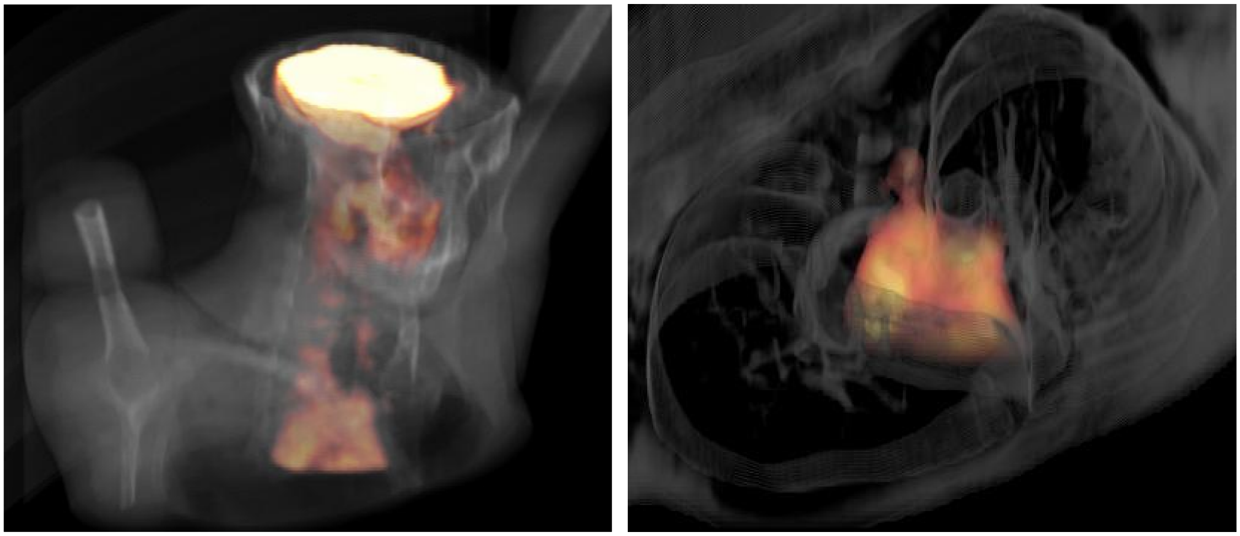

Figure 3. Per-voxel fusion of the PET/CT images.

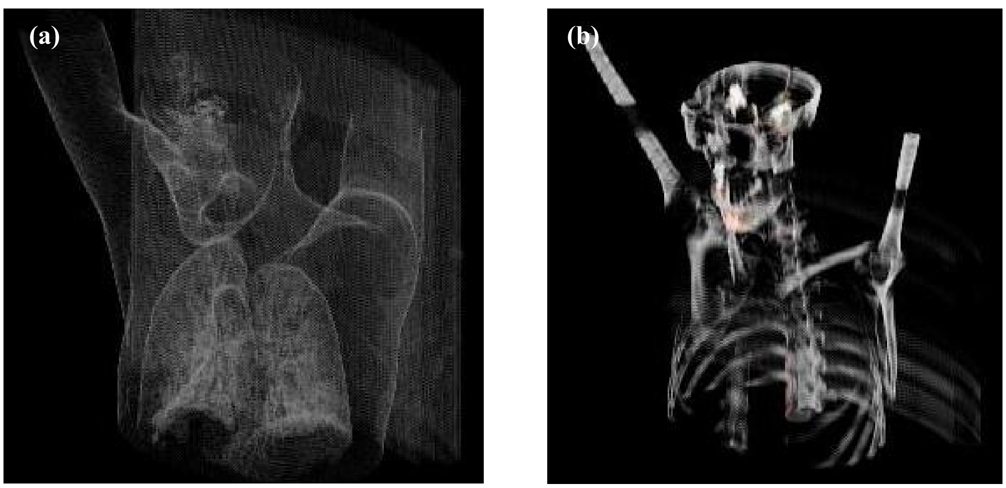

Figure 4. Transfer function applied to CT volume.

A major goal of the research was to provide real-time volumetric rendering of PET/CT data allowing interactive manipulation of the volume. In order to facilitate this, the time that is taken to render the entire volume must be reduced to a sufficient level as to ensure that smooth animation of a user interaction occurs. From studies of the human visual system (HVS) [9] it has been established that a frame rate of >25Hz is perceived as very smooth animation, between 12Hz and 25Hz is noticeably less smooth, and below 12Hz is perceived as progressively more "jumpy".

In computer graphics frame rates are measured in *frames per second* (FPS). Although mathematically equivalent to the Hertz measurement, FPS is a measure of how many times the graphics hardware writes to the frame buffer per second, as distinct from the number of times per second the frame buffer is delivered to the user, i.e. the monitor refresh rate (measured in Hz). In order to test the frame rates for various manipulations a user can affect on the volumetric rendering process, the time elapsed (at millisecond resolution) between frames was recorded. Performance of our method is tabulated in Table 1, measured in frames per second (fps) using a windows size of 500×500 pixels and volumes cropped to 100 axial slices. Although the application of our method to whole-body PET-CT resulted in satisfactory result, significant performance gain was possible by reducing the volume size. Note that the performance of the visualization is improved when down-sampled (8-bit). The volume rendering was tested on a *Pentium mobile* CPU on a PC notebook with 64M graphic memory.

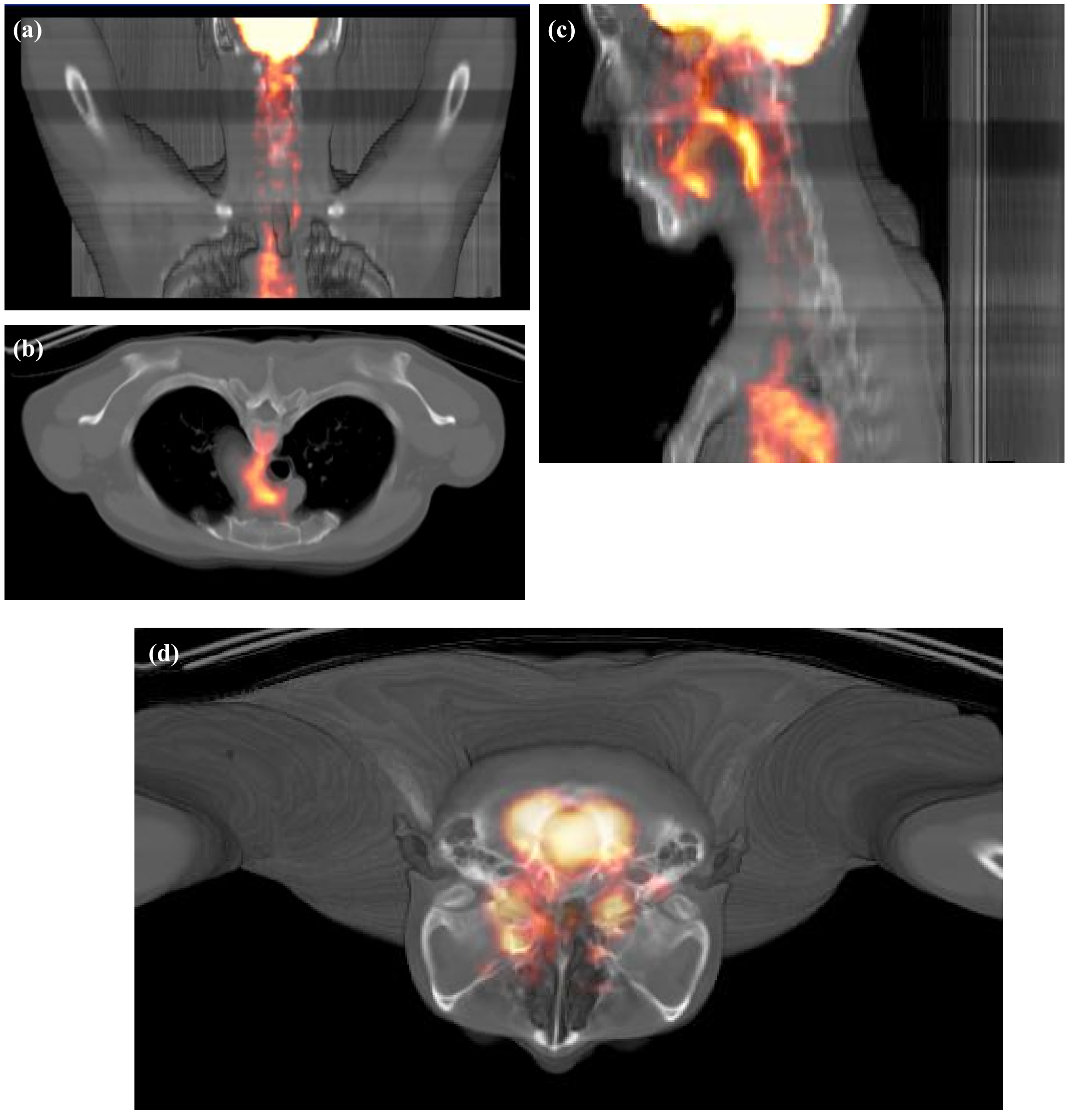

Figure 5. Orthographically sliced views of PET/CT using *Per-Voxel* fusion.

Table 1. Frames per second (FPS) measurement of manipulations applied to the PET/CT volume rendering on the examples (Figures 2 to 5) used in this paper.

Manipulation Performed	Average Frame Rate	
	8-bit Data	16-bit Data
Rotation (x-, y-axis)	22.35 FPS	15.20 FPS
Transfer Function	17.27 FPS	11.93 FPS
Fusion Ratio	19.46 FPS	12.28 FPS
Clipping Plane	33.10 FPS	29.10 FPS
Zooming	31.53 FPS	30.76 FPS

One problem which sometimes arises using the volume slicing method to perform volumetric rendering is “Ring” artifacts. These occur when the view port is positioned very close to the volume. A solution to this problem would be to dynamically adjust the sampling rates for the volume slicing algorithm dependent on how close the first set of visible voxels are to the view port. This would most likely be implemented as a linear function mapping first-hit voxel depth in a ray-casting algorithm to the sampling rate used for the next ray-cast. Special care would need to be taken when designing this function so that over-sampling does not occur, as this would cause substantial slowing of rendering speeds.

The *alpha spike* transfer function used for feature selection works well for performing boundary detection in volumetric rendering. It utilizes linear interpolations between fixed points on the graph defined by dual-axis user input. An alternative method of interpolation is *Gaussian Spline* which is derived from statistical theory. This is a type of interpolation often used in graph theory to provide a line of best fit between points on a graph. Using Gaussian Splines to connect the user specified points in a transfer function would be beneficial in circumstances where the feature that is selected does not require edge definition, and is especially useful for rendering features which have a larger range of intensity values [10]. More experimentation with the visual effects of Gaussian Slpines would be required before it could be determined whether they yield a significant improvement in visual filtering.

The volumetric rendering approach to visualization has the primary aim of assisting physicians in diagnosis. Another avenue for further research in this area is to explore how volumetric rendering techniques can be used in other clinical tasks such as surgical planning and surgery itself. Image guided surgery is another promising application for volumetric rendering.

The program Simian [11] performs volumetric rendering utilizing higher-order multi-dimensional transfer functions and can produce images of immaculate and even photo realistic quality. However, research into ways for users to be able to easily specify these transfer functions is ongoing, due to the complexities in the order to operate the user interface, where the user must have a relatively deep understanding of visualization and volumetric rendering principles.

In a clinical setting it would probably only be feasible to use these multi-dimensional transfer functions if there was a method for automated, or semi-automated, transfer function generation. These methods would need to interpret that used only semantic descriptions of features such as “skin-air boundary” then used mathematical models and heuristic approaches to establish what transfer function is likely to best portray the specified feature [12].

4. CONCLUSION AND FUTURE WORK

This paper investigated a new approach for visualization and enhancement of dual-modality PET/CT images running on consumer hardware. The proposed alpha-spike transfer function to PET/CT volume rendering was shown to be able to enhancement the visualization capabilities. As the PET and CT are rendered independently, and then fused together in real-time, manipulations could be applied to individual volumes. This introduced a new approach to visualizing volume rendering of multi-dimensional data. The preliminary results are encouraging and further investigation will be conducted.

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