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A concept of volume rendering guided search process to analyze medical data set

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Abstract

This paper firstly presents an approach of parallel coordinates based parameter control panel (PCP). The PCP is used to control parameters of focal region-based volume rendering (FRVR) during data analysis. It uses a parallel coordinates style interface. Different rendering parameters represented with nodes on each axis, and renditions based on related parameters are connected using polylines to show dependencies between renditions and parameters. Based on the PCP, a concept of volume rendering guided search process is proposed. The search pipeline is divided into four phases. Different parameters of FRVR are recorded and modulated in the PCP during search phases. The concept shows that volume visualization could play the role of guiding a search process in the rendition space to help users to efficiently find local structures of interest. The usability of the proposed approach is evaluated to show its effectiveness.

Keywords: Medical data set; Volume rendering; Search process; Focal region

1. Introduction

Over the past decades, great advances have been made in scanning techniques that produce volume data, such as CT and MRI. These developments have led to create higher resolution and larger volumetric data sets. However, structures of interest (SOIs) (tumors, metatarsal–phalangeal joints within the foot, etc.) in these data sets occupies a percentage of the voxels that is often below 10% of all voxels. In practical applications, the analysis of such data sets needs efficient extraction of SOI while preserving data structures around it to provide context information. In medical applications, the lung nodule, for example, is commonly diseased and surgeons doing lung surgery indicate that the spatial relationships between vessels and nodules are difficult to judge. A 3D visualization to provide spatial relationships and specifically focus on some SOIs would be helpful for this purpose. We believe that focal region-based volume rendering [1–3], which aims at making the visualization process more efficient by focusing on the effects or events the user is interested in, is a solution for this problem.

Furthermore, local SOIs are often occluded by outside structures because of their positions [4]. We name structures of interest being occluded as internal structures of interest (ISOIs). All SOIs to be analyzed in this paper refer to ISOIs except for thoes pointed out specifically. FRVR is particularly suited to depict SOIs during data analysis. Because it allows the user to "peel inside" the data set and enclose a local region separately to identify relationships between objects explicitly. The location, size, and shape of SOIs can be depicted through the use of the focal region. Further, it lets the user specify different transfer functions for different regions during data analysis. From the user's point of view, structures in context region are as significant as SOIs in focal region in FRVR. To navigate through volume using the focal region helps the user to improve understanding of SOIs. The properties of FRVR stated above enable it to be an appropriate tool to search SOIs. Thus a search mechanism based on FRVR is necessary to guide movement of the focal region inside the volume, so that SOIs are analyzed effectively.

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A framework for searching SOIs based on FRVR is composed of following components:

- An interface of fine control of parameters of FRVR during data analysis.
- An efficient search mechanism to be set up to find SOI.

In this paper, we firstly introduce the concept of *Parallel Coordinates* [5] into the rendering pipeline and set up a parameter control panel to control parameters of FRVR. In Section 3, we present a framework of volume rendering guided search process based on FRVR to find internal structures in volume data set. The parallel coordinates based parameter control panel is used to fine control parameters of FRVR during the volume rendering guided search process. Section 4 demonstrates implementation of the proposed approach. The presented approach is used to detect different SOIs in Section 5. The usefulness of the proposed approach is also evaluated in Section 6. Finally, we discuss the presented approaches and make conclusions.

2. Fine control parameters of FRVR

This section introduces the concept of parallel coordinates and its applications in FRVR. In order to show the integrity of this paper, a brief description of FRVR is given before presenting the details of fine control parameters of FRVR.

2.1. FRVR revisited

FRVR [1–3] is a rendering method that is used to "peel inside" data sets and depict internal structures of the data set. It divides the volume data into two parts by a geometry primitive (e.g. sphere, cube): context region and focal region. In the context region, the dominant features are extracted and rendered prominently while in the focal region, the detailed information of volume data is presented. Different rendering methods and transfer functions are used in different regions. Users could move the position and change the size of the focal region in order to explore different structures in volume data. The main information of FRVR can be found at http://medvis.webs.io/ and http://medvis.webs.io/Focalregion.htm.

Usually, there are four main parameters that need to be fine tuned in FRVR during data analysis: the transfer function for the context region, the transfer function for the focal region, the focal region position, and the focal region size. To fine control these parameters with the traditional approach is often time-consuming and difficult. It is highly necessary to develop a mechanism to effectively tune and control different rendering parameters of FRVR. Many researchers contributed different approaches to explore different rendering parameters [6–8]. Although these approaches can provide solutions for finding appropriate visualization parameters to some degree, they still have some challenges especially for FRVR:

- The user cannot easily combine different parameters of FRVR which have their own advantages for representing SOIs into a new rendering process.
- It is not easy for the user to keep track of different parameters of FRVR in different rendering processes.
- The effects of different rendering parameters of FRVR cannot be easily compared. It is difficult to effectively use the previous rendering results.

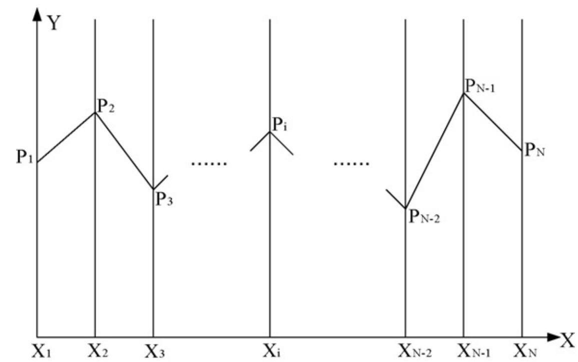

Fig. 1. The parallel coordinates for R^N.

2.2. The concept of parallel coordinates and FRVR

Parallel coordinates is a graphing technique which is used to represent relations of high dimensional data in a 2D plane [5]. As shown in Fig. 1, on the plane with XY-Cartesian coordinates, and starting on the y-axis, N copies of real lines, labelled $x_1, x_2, \ldots, x_N$, are placed equidistant and perpendicular to the x-axis. They are the axes of the parallel coordinate system for Euclidean N-dimensional space R^N. Tory et al. [9] presented a parallel coordinates style interface for exploratory volume visualization parameters. This interface is useful for the general volume rendering approaches. The work in this section is motivated by [9]. However, in FRVR, the most significant parameters are transfer functions for different regions, the focal region position, and the focal region size. The movement of the focal region is also significant for user understanding. It needs special mechanisms when adapting the concept of parallel coordinates into FRVR.

The obvious characteristics of rendering parameters of FRVR different from the traditional rendering approaches are that there are more parameters that need to be tuned, parameters depend on each other, and they have close relations with their previous states. Higher-dimensional parameters increase the complexity for tuning them. Close relations of parameters with their previous states require the user to compare these different parameters together in order to decide how to control parameters and understand their relations in the next step. The relations refer to dependencies of different parameters.

When using the parallel coordinates in FRVR, a point P, with coordinates $(p_1, p_2, \ldots, p_N)$ represented by one polyline, represents a FRVR-based analysis process with different parameters. Each coordinate of the polyline represents a parameter of FRVR. In this way, a one-to-one correspondence between FRVR and its different parameters on $x_1, x_2, \ldots, x_N$ is established through polylines.

In this paper, a parallel coordinates based PCP is set up to control parameters of FRVR in the rendering pipeline. The PCP is divided into two spaces: the parameter editor space and the rendering image history list space. The parameter editor space is used to edit parameters of FRVR as shown in Fig. 3. The rendering image history list space (see Fig. 3) is used to display rendering images based on parameters in the parameter editor space. The PCP gives the user an overview of dependencies between parameters and rendering images through polylines.

2.3. Parameter editor space

The parameters of FRVR to be controlled in the PCP include: the transfer function for the context region, the transfer function for the focal region, the focal region position, and the focal region size. Each of these parameters is represented with one parallel axis. We name one coordinate in the parallel coordinates as a *node*. After defining different parameters on each axis, a rendering process is set up through connecting nodes on different axis with polylines. The created rendering image is automatically added to the bottom of the rendering image history list. The polyline connects to the created image automatically in order to present dependencies between the rendering image and its parameters. The advantages of the parameter editor space are that it organizes all parameters in one space, and gives the user an overview of all parameters at the same time.

2.4. Rendering image history list space

In the rendering image history list space, each image corresponds to one polyline in the parameter editor space (see Fig. 3). The user could drag the vertical slide bar and loop through different rendering images. When the rendering image appears in the view port of the list space, a line is automatically connected between this image and its related parameter nodes. We set up a *Make Current* mechanism as shown in Fig. 3. When clicking a rendering image in the history display list, the clicked image and its related parameter polylines are highlighted. At the same time, the main renderer is synchronized to show the current rendering display. The *Make Current* mechanism allows the user to track back to any rendering states. The list space lets the user compare different renditions in one space. Through comparison, the user finds better parameters and settings for specific features from different images.

Based on these information, the user locates better parameters on each parallel axis through polylines, and then set up connections between the located better parameters to create a new rendering process. We name this process as the *parameter reorganization*. The explicit depiction of dependencies between rendering images and parameters enables the user to easily identify better parameters on different axes. It also enables the user to easily reorganize parameters into a new rendering process. In order to help the user to understand the relations of parameters in a continuous way, a movie based on previous rendering images is created using a *Movie Creator*. Through the movie, the user tracks the movement of the focal region dynamically.

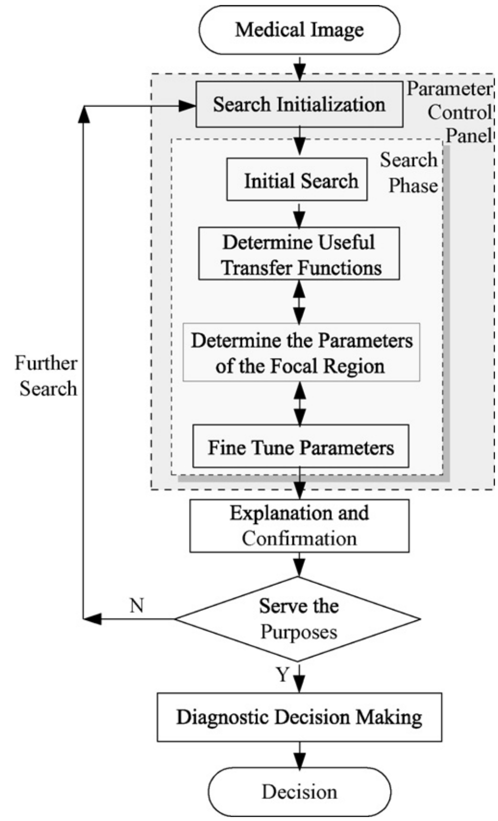

Fig. 2. The framework of volume rendering guided search process.

3. Volume rendering guided search process

In this section, we set up a concept of volume rendering guided search process to find SOIs in a 3D data set. The framework of volume rendering guided search process is shown in Fig. 2. It is divided into four phases: the search initialization, the search phase, the explanation and confirmation phase, and diagnostic decision making. The search initialization phase initializes the volume rendering for the search process. The search phase performs the search based on FRVR. The explanation and confirmation phase explains and confirms search results. Based on the search results, the user makes diagnostic decisions. Each phase shows how FRVR is controlled and used to guide the search in order to find SOIs. The PCP plays the role as the control center during the search process. It provides two significant roles during the search process: compare different rendering parameters in one space, and create a new rendering process based on the previous rendering parameters.

3.1. The search initialization phase

In the search initialization phase, the user has some initial approximate ideas about SOI based on the anatomical knowledge and their experiences. For example, the user is aware of what kind of information about the data set is known before the search process. They are also aware of structures which are useful to guide their search process. Based on this information, the user often has assumptions:

- The assumption related to data value properties. In terms of volume rendering, this assumption is directly related to the approximate definition of transfer functions. It guides the user to approximately define transfer functions for different regions in the overall search process.
- The assumption related to the appearance of objects, e.g. the size and shape of objects. This assumption can help the user to optimize the transfer function in different regions.
- The assumption related to the relationships between objects, e.g. the location. This could also help the user to optimize transfer functions. In addition, it restricts the user to specific regions to detect SOI.

In summary, during this phase, the initial information and assumptions about the data set are transferred to the data analysis pipeline and recorded in the PCP. For example, transfer functions for different regions are specified based on the anatomical knowledge and recorded in the PCP. The initial focal region position is specified using the location where SOI possibly exists based on the anatomical knowledge and experiences. The recorded initial parameters in the PCP are used in the following search phase.

3.2. The search phase

After the search initialization phase, the user needs to find SOI and do further analysis according to their purpose. However, they do not know exactly where SOI is, how it looks like. So the search in the rendition is necessary in this phase. The search phase is divided into four sub-phases (see Fig. 2): the initial search sub-phase, determining transfer functions, determining parameters of the focal region, and fine tuning parameters.

(i) *The initial search*. In the initial search sub-phase, the input information are the recorded parameter nodes (e.g. see Fig. 4) which represent initial information and assumptions about 3D data set in the PCP. The user connects the recorded nodes on different axes in order to create different initial search renditions. The user gets an overview of the data set in this phase. However, it may be difficult to determine what is visible in the focal region because the parameters of the focal region may not be the optimal for showing SOI. So after this sub-phase, the user needs to modulate transfer functions and parameters of the focal region interactively.

(ii) *Determine transfer functions and parameters of the focal region*. A transfer function for the focal region is used to depict visual features of SOI purposefully. A transfer function for the context region allows the rendition to display guiding structures which orient movement of the focal region during the search process. Another significant search sub-phase is to determine good parameters of the focal region, and especially the location of the focal region. Usually, the initial location of the focal region is often determined based on the anatomical knowledge. In this sub-phase, the input information are different initial search renditions recorded in the PCP (e.g. see Fig. 5). The PCP enables the user to find good rendering parameters on each axis through comparing the recorded search renditions in the rendering image history list. If the user is not satisfied with the parameters on one axis, they could create new parameters based on the previous parameters.

(iii) *Fine tuning rendering parameters*. After a potential location of SOI is found, the user fine tunes parameters of the system and makes a display which shows SOI information clearly. During the volume rendering guided search process, the sub-phases of determining useful transfer functions, determining the parameters of the focal region, and fine tuning parameters of the focal region depend on each other (see Fig. 2). The input information of this sub-phase are the renditions created through reorganizing previous better parameters and newly created parameters. So during this search sub-phase, the user recognizes which rendering parameters of FRVR needs to be fine tuned in order to clearly display SOI. The changed parameters are recorded in the PCP, and the user only needs to connect other better rendering parameters with the new parameters using polylines to create new search renditions.

3.3. The explanation and confirmation phase

Once a SOI is found, the user needs to explain and confirm information obtained during the search process. After the explanation and confirmation phase, the user decides whether they should search other SOIs in a new search process (see Fig. 2). If the search results meet requirements and serve analysis purposes, the user then makes diagnostic decisions based on the search results. Otherwise, they begin another search process.

4. Implementation

We implemented a parallel coordinates based PCP, and set up the framework of volume rendering guided search process based on FRVR. The interface was built with QT [10], a cross-platform windowing toolkit. The rendering tools were implemented based on FRVR modules developed in our previous work. The presented approach was implemented on Windows XP platform on a standard PC with single 2.40 GHz Intel Pentium4 CPU and 1.0 GB memory. The graphics board is NVidia GeForce 4 Ti 4200 processor with 64 MB of data RAM.

Fig. 3 illustrates principal components of the PCP and the framework of volume rendering guided search process based on FRVR. Because Section 2 has already introduced some features of the PCP, this section gives a brief description of implementation of components in the PCP. A set of vertical parallel axis lines in the parameter editor space forms the central components, which represent different parameters of FRVR. Different nodes can be added on each axis from a corresponding popup dialog (or menu) or by manipulating a previous node to produce new parameter values. We implemented the following parameters: the transfer function for the context region, the transfer function for the focal region, the focal region position, the focal region size, and FRVR renderer. To the right of the parameter editor space is the rendering image history list space. We

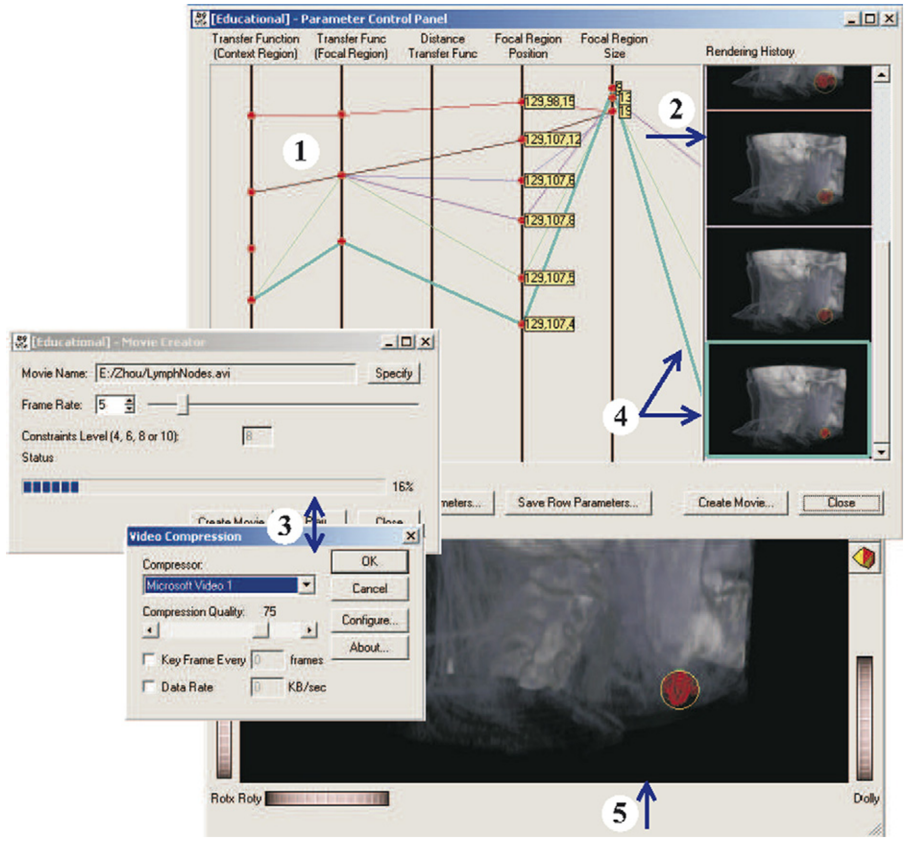

Fig. 3. The principal components of the PCP and volume rendering guided search process: (1) the parameter editor space; (2) the rendering image history list space; (3) the movie creator; (4) the make current facility; (5) the main renderer window.

included controls to save and reload parameters and polylines for the future search pipeline.

We also implemented additional features that help volume rendering guided search process more flexible and powerful. Firstly, a *Make Current* (see Fig. 3) facility allows the user to locate parameters used to render a rendition in the rendering image history list space. It also allows the user to synchronize the current rendering settings with the rendition in the main renderer window. It helps the user to track back any rendering states during the search process. Secondly, a *Movie Creator* (see Fig. 3) was implemented to help the user to percept the search process in a continuous way based on previous search history. In this way, the user can dynamically track the movement of the focal region during the search process. We also included controls to save rendering images and movies during the search process.

5. Experiments

The proposed approach has wide applications in medical image analysis. Firstly, it is used to analyze pathologies or small structures inside soft tissues, for example, lung nodules, brain tumors, solitary liver masses, and lymph nodes. The user needs to locate and differentiate these structures from their surroundings during data analysis. Secondly, local bone structures, such as metatarsal–phalangeal joints and local born fractures, need to be analyzed in detail while keeping structures surrounding them in order to provide context information. The proposed approach meets this purpose specifically. Further, the proposed approach can be used in orthopedics surgical planning and treatment, where FRVR is used to locate and depict local structures to be operated while surrounding structures provide context information. In this section, the presented approach is used to detect pathologies or small structures in soft tissues, and locate local bone structures, in order to show the effectiveness of the proposed approach.

5.1. *Detection of small structures and pathologies*

Small structures and pathologies in soft tissues are often occluded by other structures, and have low contrast with their surroundings. They need to be detected through a search process in order to get understanding and make diagnostic decisions. This subsection first uses the presented approach to detect lymph nodes in head and neck region. Lung nodules and brain tumors are also located and analyzed in this experiment.

5.1.1. *Lymph node analysis*

The lymph nodes in the head and neck region often have ellipsoidal bean shapes. The data values of lymph nodes are in the range between soft tissues and the contrast-enhanced blood vessels/bones. The lymph nodes are often laced along the lymphatic routes in certain regions and definitely occluded by other structures [11]. Any transfer function showing the lymph nodes will also show many other structures that have similar values using

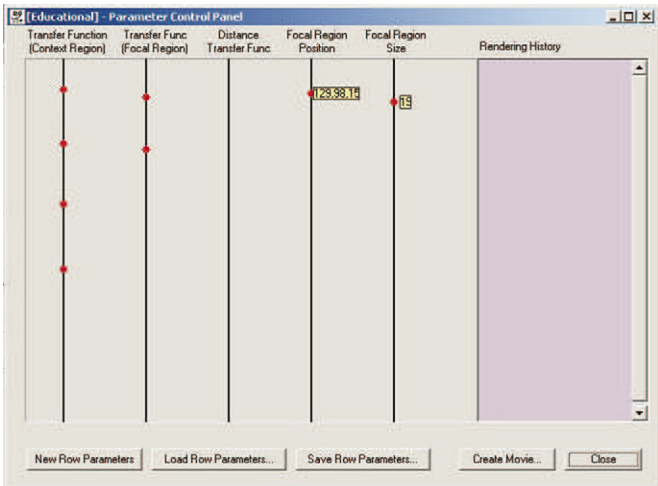

Fig. 4. The initial information and assumptions are represented using different parameter nodes.

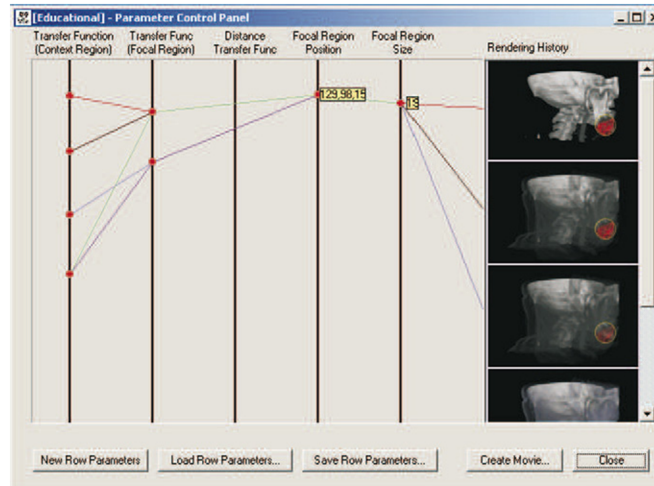

Fig. 5. The recorded nodes are connected using polylines to create initial search renditions in the initial search sub-phase.

direct volume rendering, which makes it difficult to detect and analyze lymph nodes based on direct volume rendering method. Our proposed approach is particularly suited to find and display the lymph nodes.

During the lymph node detection process, the user connects the search path for the lymph nodes to bones and typical tissues (e.g. vessels). The search path is restricted to the regions where the lymph nodes possibly exist. For example, we plan to find submental lymph nodes, the search path is restricted to the submental region in order to increase the search efficiency. We firstly use a focal region larger than the normal size of the lymph node. These initial parameters are recorded on different axes in the PCP as shown in Fig. 4, where the axis of “Distance Transfer Func” is used to control the distance transfer function [12] during rendering, and we do not use this axis in this experiment. Each circular node in the parameter editor space represents one initial parameter.

After aquiring the initial rendering parameters, we start the initial search phase. The input information of this phase are the recorded parameter nodes as shown in Fig. 4. We connect different parameter nodes on different axes using polylines. It creates different renditions in the rendering image history list as shown in Fig. 5. From these initial search renditions, we may not get useful features of the lymph nodes (e.g. boundary of lymph nodes) because of improper locations or large sizes of the focal region. So it is necessary to find better rendering parameters of FRVR based on the initial search renditions. This is done through comparing renditions in the rendering image history list. We recognize the better parameters on different axes, connect them using a polyline, and create a new rendering image.

Based on the created new rendering image, the focal region is moved with the help of guiding structures (e.g. the bones) and previous positions recorded in the PCP (see Fig. 6). In this image, although we do not see lymph nodes clearly in the focal region, the larger focal region allows us to gather information about the location of lymph nodes. For example, the object the arrow points to in this image is a part of ellipsoidal shape and possibly a lymph node based on its boundary shape. The focal region should be moved in the direction of the ellipsoidal boundary. The rendering parameters need to be fine tuned in the following processes to make sure that it is a lymph node in Fig. 6. So the size and location of the focal region are changed in the following steps. The fine tuning process is performed in the PCP through connecting newly created parameters and other better parameters.

A movie is created using the *Movie Creator* based on the recorded search states in the PCP (see http://medvis.webs.io/[Focalregion.htm#video]). It simulates the real-time search process for the lymph nodes, and helps to easily decide how to control parameters in the next step.

5.1.2. *Lung nodule and brain tumor detection*

Nodules are commonly diseased in human lungs. Radiologists usually use visual search method in 2D slices to detect and evaluate nodules. This kind of method has several disadvantages [4]. Traditional volume rendering cannot allow the user to peel inside the lung to show nodules and outside structures at the same time. It is also difficult for the user to better understand nodules if the same transfer functions are used for nodules and their surrounding structures (e.g. vessels) [13].

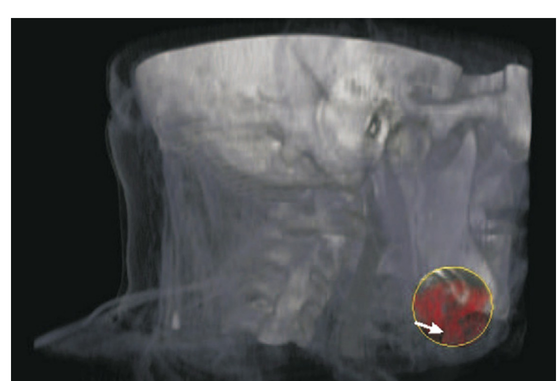

Fig. 6. The rendition shows cues of the lymph node in the search phase.

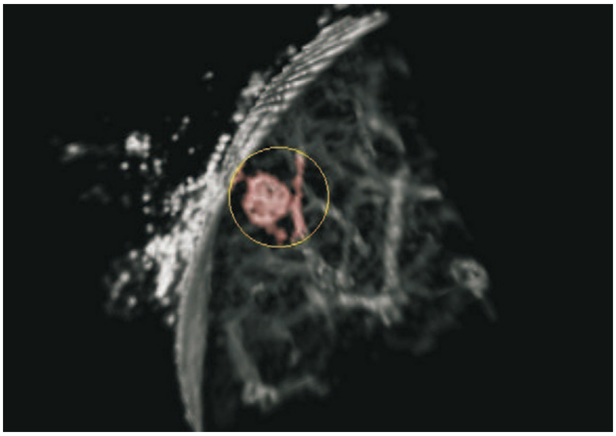

Fig. 7. The focal region is used to track lung nodules.

In the human lung, nodules and vessels often have close relations (i.e. the nodules are often near vessels). The relations between nodules and the main structure of vessels in the lung can be used to guide the movement of the focal region during FRVR-based search process. Fig. 7 shows the result of using the proposed approach for lung nodule detection. During the search process, rendering parameters are recorded in the PCP in order to be used in the following phase. A movie is created to show the analysis process of lung nodules using the proposed method (see http://medvis.webs.io/Focalregion.htm#video). From the experimental results, we see that our approach has the following advantages compared with traditional approaches: nodules are dynamically tracked using the focal region, and vessels are used as the guiding structures to track nodules in order to let the user more easily locate and better understand nodules.

The proposed approach was also used to locate brain tumors. When opening a channel from the skull to the actual location of the tumor inside the brain, a surgeon needs to take proper planning to avoid major blood vessels. Through the volume rendering guided search process, brain tumors can be visualized by navigating the focal region inside the volume. At the same time, the context information (e.g. skull) are displayed to provide comprehensive information for surgery. In this experiment, tumors can be screening detected in 2D slices (see Fig. 8). During the brain tumor analysis using the proposed approach, parameters in different search phases are recorded in the PCP. The user reorganizes parameters recorded on different axes and get the final analysis result. Fig. 9 shows the result of brain tumor analysis using the presented approach.

5.2. Local bone structure depiction

In medical imaging, an SOI often resides in local areas (e.g. bone fracture and bone joint). It is useful if the SOI is rendered in detail with its surrounding structures at the same time. This kind of presentation is helpful for the user to understand the SOI and its relative position during diagnosis and surgical planning. In this experiment, CT foot data set is used to demonstrate how the proposed approach is used to analyze part of large structures. Fig. 10 uses FRVR-based 3D data analysis to analyze

Fig. 8. A brain tumor is detected in a 2D slice.

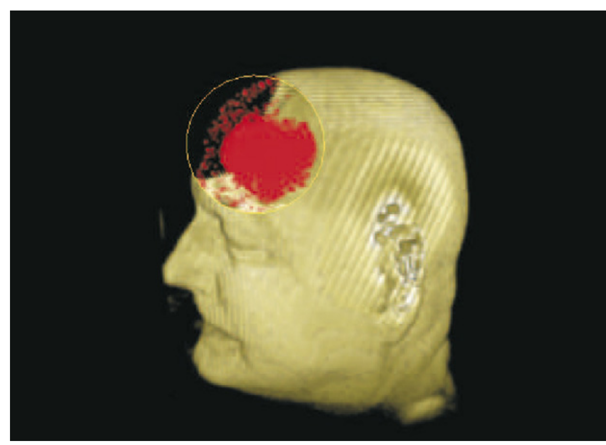

Fig. 9. The focal region is used to locate a brain tumor.

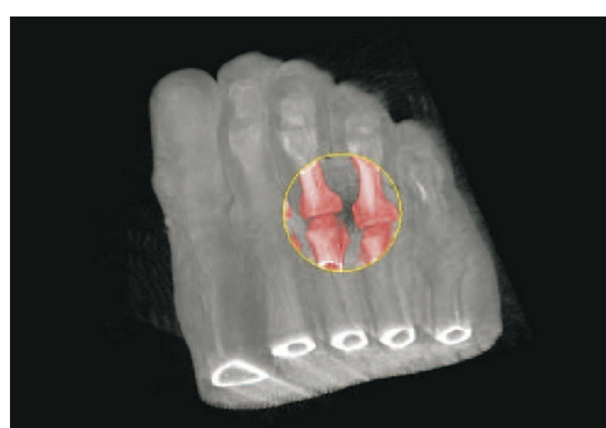

Fig. 10. Rendering of bone joint structures and their surroundings at the same time.

metatarsal–phalangeal joints of the foot data. In this figure, joints and their surroundings (e.g. skin) are presented in the rendition at the same time. This allows the user to be more confident for pathological structures and their positions during diagnosis and treatment planning.

6. Usability evaluation

We conducted a usability evaluation in order to show the effectiveness of the proposed approach by comparing it with other traditional approaches (e.g. cine-looping, direct volume rendering) for searching SOIs. We collected quantitative and qualitative rating scales on several items that were designed to evaluate whether the volume rendering guided search process met our objectives (helping users to improve searching and understanding of internal structures in a 3D data set).

6.1. Evaluation set-up

The evaluation procedure was set up based on the followings: six observers assessed the volume rendering guided search process for analyzing internal structures in medical data sets. Observers are from a wide variety of backgrounds: two observers are end users who are radiologists with expertise in medical imaging. Another two observers are researchers in the field of volume visualization of medical data set. The other two observers are researchers in the field of computer graphics. We expected these different backgrounds of observers to provide a wide variety of opinions and insight into the proposed approach. For example, radiologists are more knowledgable at finding SOIs and understanding them; visualization researchers focus their attention more on understanding rendering parameter space; graphics researchers are more interested in the user interface.

We used the CT data of the head and neck region, lung nodule data set, brain tumor data set, and foot data set in the evaluation. The observers were asked to perform two sample tasks during the evaluation: (1) explore the data sets, and (2) search for an identifiable SOI (e.g. lymph node, nodule, tumor, joints) in different data sets, respectively. Besides using the proposed volume rendering guided search process to perform these tasks, the observers were required to use two other medical image analysis methods (cine-looping 2D slices and direct volume rendering) to conduct the same tasks in order to compare effectiveness of different methods.

The observers conducted evaluations separately. During the evaluation, the observers were first introduced to the PCP and the concept of volume rendering guided search process based on FRVR, cine-looping 2D slices, and direct volume rendering. Initial search parameters were set-up ahead of time. Then they were asked to perform two tasks as described above. The observers were provided directed information for searching SOIs. We developed evaluation guidelines based on a questionnaire for 3D data analysis tasks. These guidelines are motivated by the guidelines used in [9]. The observers were required to complete a report to answer the following assessments based on 5-point rating scales (1, poor; 5, good) for three different analysis methods:

(i) Learning: ease of learning to use the technique.
(ii) Analyzing: ease of analyzing the data using the technique.
(iii) Understanding structures: ease of understanding the found SOI in the rendition.
(iv) Finding structures: ease of finding SOI.
(v) Parameter space: ease of understanding the parameter space (rendering options).
(vi) Tasks straightforward: ease of tasks that can be performed in a straightforward manner.
(vii) Anatomical knowledge: ease of the anatomical knowledge that can be considered in the search process.
(viii) Overall understanding: ease of understanding SOI and overall data set at the same time.
(ix) Further analysis: ease of using search results for further analysis (e.g. segmentation).

These evaluation items were designed in order to show the effectiveness and usefulness of different methods for searching internal structures and overall understanding of 3D data set. Because the time for the search process using different methods depends on hardware performance and data size, we did not evaluate the time performance. However, we simulated the volume rendering guided search process using movies as discussed in the previous sections to show its powerfulness for data analysis when it is performed in real-time.

6.2. Evaluation results

Table 1 shows the rates for successfully finding SOIs using different analysis methods, where VRGS represents volume rendering guided search process and DVR denotes direct volume rendering method. We only show the successful rates of finding lymph nodes and lung nodules. They are two typical examples of using the proposed approach for 3D data analysis. From the table we can see that volume rendering guided search process shows higher success rates in finding SOIs than other two methods, and cine-looping shows higher success rates in finding SOIs than direct volume rendering. But we found that cine-looping requires more time and anatomical knowledge for searching SOIs. Further, it shows that the success rates for finding the lung nodule is higher than that of finding the lymph node. During the evaluation, we found that radiologists showed higher success rates than other two observer groups, and visualization researchers showed higher success rates than graphics researchers.

Two principal reasons result in these evaluation results: The first comes from the data set itself. In this evaluation, the lymph

Table 1
The rates for successfully finding SOIs using different methods

SOIs	VRGS (%)	Cine-looping (%)	DVR (%)
Lymph node	66.7	50.0	16.7
Lung nodule	83.3	83.3	16.7

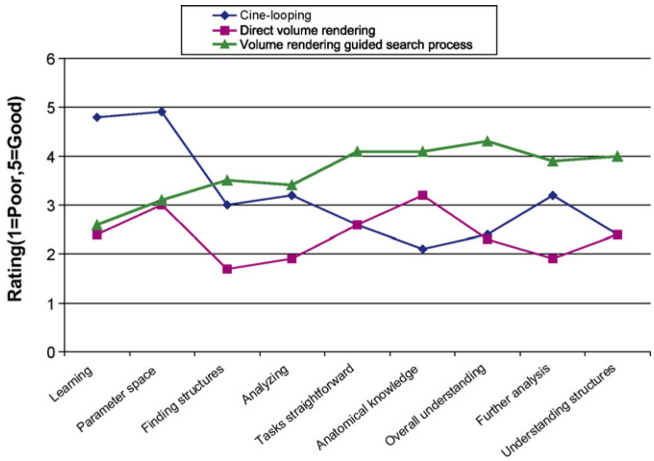

Fig. 11. Average ratings in the usability evaluation.

node in the CT data set of the head and neck region has lower contrast compared with the lung nodule data set. So the lung nodule is more easily identified than the lymph node. Secondly, each observer has different backgrounds and strengths as described in the previous subsection. This allows the participant, who has more anatomical knowledge and is knowledgable on rendering options, to have higher success rates in finding SOIs. Furthermore, because cine-looping requires more anatomical knowledge during evaluation, radiologists show higher success rates for finding SOIs using this method. And because of occlusions, it is often difficult to find SOIs using direct volume rendering, and the success rates for finding SOIs using direct volume rendering are low. From the statistical results in Table 1 we see that more knowledge on anatomical structures and visualization options help to improve the search efficiency and success rates in finding SOIs.

Fig. 11 illustrates average ratings from the usability evaluation. Qualitatively, we can see that the proposed approach rates higher than the other two methods, except that volume rendering guided search process needs more time to be learnt and has more complicated parameter space. Because cine-looping only requires the user to change z-axis coordinates and windowing function to find SOIs, it is easier to use than direct volume rendering and volume rendering guided search process. The figure shows that it is easier for volume rendering guided search process to find SOIs and consider anatomical knowledge into the search process than the other two methods. Volume rendering guided search process is a more straightforward method to search SOIs. It also shows better overall understanding of the data set than the other two methods. The search results from volume rendering guided search process and cine-looping can be used more easily for further analysis (e.g. segmentation) because they both explicitly provide position information, but direct volume rendering cannot meet this point.

Evaluators felt that the proposed approach would be more powerful and effective if the system provided more intuitive interaction devices for the focal region. This could be one of our future studies. Some evaluators suggested to combine 2D slices and the proposed approach together in order to guide the movement of the focal region and provide more understandable information. This is more useful for radiologists, who are used to analyzing 3D data set in 2D slices, to use volume rendering guided search process in practical applications. Overall, the evaluation study indicates that volume rendering guided search process is a positive and promising idea for finding SOIs in a 3D data set. Our evaluation process also identified directions for future research.

7. Discussion

Control of rendering parameters in volume rendering especially in FRVR is often difficult because of their complexity and high dimensions. The disadvantages of the approach by Tory et al. [9] are that, it is not useful to integrate camera position as well as zoom and translation of the scene into the parallel coordinates style interface. Because these parameters are more easily controlled in the renderer directly through the mouse interaction. They are also not the main factors which affect the effectiveness of the rendering. The PCP shows advantages for fine control parameters of FRVR during data analysis. It can combine different parameters of FRVR into a new rendering process. Different parameters can be easily compared and tracked during data analysis.

The proposed concept of volume rendering guided search process finds SOIs based on the 3D object displays, but not on the pixel information in a 2D slice as in cine-looping mode. Because volume visualization provides content-based representations of data set rather than pixel-based representations, it is a more natural way for the user to find SOIs using this concept. Compared with the method of cine-looping mode often used by radiologists, the concept proposed here has the following advantages:

- The user searches SOIs in 3D rendition space. He interacts with the data set at an organ or tissue level, rather than at a voxel level.
- The concept allows the user to find SOIs in a certain region in the rendition space, but not in all slices as in the cine-looping mode.
- The content-based representations of data set in the rendition space allows the user to more easily evaluate and find SOIs.
- It is a good representation to evaluate complex anatomical structures and find SOIs.

The concept bridges the gap between volume rendering and applications. It considers volume rendering not only as a visualization tool to display structures, but also as a search tool to find SOIs in a 3D data set when meeting some requirements. So from this concept, another role of volume rendering for data analysis could be added besides the roles demonstrated by Tory and Möller [14]: volume visualization could allow the user to incorporate the anatomical knowledge into a data analysis pipeline, and guide a search process in the rendition space to help users efficiently find SOIs in a 3D data set.

8. Conclusions

This paper firstly contributed the parallel coordinates based PCP in order to fine control parameters of FRVR during data analysis. Then the concept of volume rendering guided search process based on FRVR was proposed to find internal structures in a data set, which is one of the principal contributions of this paper. The PCP is used to control parameters of FRVR during the search process. The concept shows that volume visualization, which meets some assumptions and techniques, can be used to guide the data analysis and help the user to get search results more effectively and faster, where SOIs are detected, recorded, and ready for the further analysis. The concept allows the user to semi-automatically analyze medical images — by developing generalizable tools for incorporating medical knowledge into a volume visualization-based analysis system.

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References

[1] Zhou J, Hinz M, Tönnies KD. Hybrid focal region-based volume rendering of medical data. In: Proceedings of the Bildverarbeitung für die Medizin", Leipzig. 2002. p. 113–6.

[2] Zhou J, Hinz M, Tönnies KD. Focal region-guided feature-based volume rendering. In: Proceedings of the first international symposium on 3D data processing visualization and transmission (3DPVT). 2002. p. 87–90.

[3] Zhou J, Wang Z, Tönnies KD. Focal region-based volume rendering. Int J Pattern Recogn Artif Intell 2006;20(5):665–77.

[4] Preim B, Peitgen H-O. Smart 3D visualizations in medical applications. In: Smart graphics conference. 2003. p. 343–52.

[5] Inselberg A, Dimsdale B. Parallel coordinates: a tool for visualizing multidimensional geometry. In: Proceedings of the first IEEE conference on visualization (Vis '90). 1990. p. 361–78.

[6] Pfister H, Lorensen B, Bajaj C, Kindlmann G, Schroeder W, Sobierajski AL, et al. The transfer function bake-off. IEEE Comput Graph Appl 2001;21:16–22.

[7] Hahn H, Preim B, Selle D, Peitgen H-O. Visualization and interaction techniques for the exploration of vascular structures. In: Proceedings of IEEE visualization 2001. 2001. p. 395–402.

[8] Weiskopf D, Engel K, Ertl T. Volume clipping via per-fragment operations in texture-based volume visualization. In: Proceedings of the IEEE visualization'02. 2002. p. 93–100.

[9] Tory M, Potts S, Möller T. A parallel coordinates style interface for exploratory volume visualization. IEEE Trans Vis Comput Graph 2005;11(1):71–80.

[10] Blanchette J, Summerfield M. C++ GUI programming with Qt 3. Prentice Hall, PTR; 2004.

[11] Richter E, Feyerabend T. Normal lymph node topography: CT atlas. 1st ed. Springer; 2004.

[12] Zhou J, Döring A, Tönnies KD. Control of object visibility in volume rendering—a distance-based approach. Int J Image Graph 2005;5(4):699–714.

[13] Calhoun PS, Kuszyk BS, Heath DG, Carley JC, Fishman EK. Three-dimensional volume rendering of spiral CT data: theory and method. Radiographics 1999;19:745–64.

[14] Tory M, Möller T. Human factors in visualization research. IEEE Trans Vis Comput Graph 2004;10(1):72–84.

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