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Semi-Automated Skeletonization of the Pulmonary Arterial Tree in Micro-CT Images

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ABSTRACT

We present a simple and robust approach that utilizes planar images at different angular rotations combined with unfiltered back-projection to locate the central axes of the pulmonary arterial tree. Three-dimensional points are selected interactively by the user. The computer calculates a sub-volume unfiltered back-projection orthogonal to the vector connecting the two points and centered on the first point. Because more x-rays are absorbed at the thickest portion of the vessel, in the unfiltered back-projection, the darkest pixel is assumed to be the center of the vessel. The computer replaces this point with the newly computer-calculated point. A second back-projection is calculated around the original point orthogonal to a vector connecting the newly-calculated first point and user-determined second point. The darkest pixel within the reconstruction is determined. The computer then replaces the second point with the XYZ coordinates of the darkest pixel within this second reconstruction. Following a vector based on a moving average of previously determined 3-dimensional points along the vessel's axis, the computer continues this skeletonization process until stopped by the user. The computer estimates the vessel diameter along the set of previously determined points using a method similar to the full width-half max algorithm. On all subsequent vessels, the process works the same way except that at each point, distances between the current point and all previously determined points along different vessels are determined. If the difference is less than the previously estimated diameter, the vessels are assumed to branch. This user/computer interaction continues until the vascular tree has been skeletonized.

Keywords: micro-CT imaging, 3D image processing, 3D image analysis, angiography

1. INTRODUCTION

High-resolution micro-CT scanners permit the generation of three-dimensional digital images containing extensive vascular networks such as found within the lung. Segmentation of these vascular tree structures for quantitative vascular morphometry can be difficult and time consuming. This is due, in part, to the complexity of the networks and the fact that the vessel axis has no distinguishing features in a fully reconstructed 3D image. The proposed method is based on the premise that the latter problem can be circumvented by using the original planer images at different angular rotations to locate the central axis within the contrast-enhanced vessels. This method is exemplified on images of the pulmonary arterial tree.

2. METHODS

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2.1. Development Environment

The algorithm runs under the Windows 95,TM Windows 98,TM Windows 2000TM or Windows NTTM operating systems. The computer program is written in Microsoft Visual C++ Version 6.0. Visual C++ was chosen for its portability between different PC platforms, its rapid, user-friendly development environment and its ability to generate efficient code running under the well-understood Microsoft WindowsTM user-interface.

2.2. Image Acquisition

The lung preparation has been described previously¹. A lung from an anesthetized rat was isolated and placed within an x-ray lucent tube on a computer driven turntable between the focal spot of an x-ray source (FeinFocus FXE100.20) and an image intensifier (North American Image Intensifier Corp.) so that it could be rotated 360°. The pulmonary arterial tree was filled with perflouroctylbromide at 20 mmHg with the airway pressure fixed at 6 mmHg. As the rat lung was rotated over 360 degrees, images were recorded using a digital CCD camera connected to a computer via a parallel RS422 interface. Each monochrome image was 512 x 512 x 8 bits. The set of 360 images was stored on the computer's hard disk.

2.3. Identification of a starting point

The software allows the user to cycle through the 360 planar images to choose a vessel segment from which to begin following the central axis. At any given view, the user identifies (mouse-clicks) a point on the vessel. The computer constructs a projection vector (v_1) through object space originating at the x-ray source and ending at the image intensifier. This vector, when viewed edge-on, appears as a point on the planar image (Fig. 2). An overhead representation of the same vector is shown (Fig. 3).

Figure 3. Schematic representation of a vector originating at the x-ray source, passing through a vessel of interest, and terminating at the image intensifier (II).

The user then chooses an image captured at a different angle of rotation. The computer superimposes v_1 , which now appears as a line, onto this rotated image (Figs. 4-5).

Figure 4. Schematic representation of vector v_1 rotated along with object.

Figure 2. X-ray planar image of a left rat lung lobe. Pulmonary arteries have been filled with contrast media and appear dark. The dot v_1 represents a view through the axis of a vector originating at the x-ray source and ending at the image intensifier. The dark region at the bottom center of the image is a calibration phantom near the center of rotation of the object stage.

Figure 5. A different orientation of the rat lung rotated approximately 70 degrees by the user. As a different orientation of the lung image is displayed v_1 appears to rotate with the object.

The same location of the original vessel is identified (second mouse-click) where it intersects the projection of v_1 . The computer constructs a second projection vector (v_2) originating at the x-ray source and ending at the image intensifier.

A three-dimensional point (p_0) is constructed at the intersection of v_1 and v_2 . p_0 represents the user-initiated initial guess of the three-dimensional coordinates of the vessel center point. This process is illustrated graphically in figures 6 and 7.

Figure 6. Schematic of vectors v_1 and v_2 and the point at their intersection, p_0 .

Figure 7. Three-dimensional point p_0 is superimposed on the image. Here p_0 is the intersection of vectors v_1 and v_2 .

The same simultaneous vector technique is applied to create a second estimation of the vessel's center axis (p_1). The user has the ability to confirm the points' position by rotating through the set of planar images as p_0 and p_1 are continuously projected onto the images. Rotated image of vessel tree with p_0 and p_1 projected onto image is shown (Fig. 8).

2.4. Back projection

The computer calculates coefficients of a plane orthogonal to the vector passing through p_0 and p_1 . Points on this orthogonal plane, centered at p_0 , are back-projected in 360 orientations to create an image in which the true vessel axis lies. The back projection is carried out on a bounded subset of image-space encompassing the whole vessel cross section. The user interactively specifies the diameter of this orthogonal plane, typically approximately twice the diameter of the back-projected vessel's image.

The minimum intensity within this back projection is determined and the XYZ coordinates corresponding with minimum intensity are stored as the improved approximation to the point on the central axis (p_0^*). The back projection process and 3D plot of pixel intensities are shown (Fig. 9). A key element of the method is that the unfiltered back-projection results in a single point of minimum intensity located very near the central axis of the vessel.

Figure 8. User has selected two three-dimensional points p_0 , and p_1 within the vicinity of the vessel center. These points are projected onto the original planar image

Figure 9. Top: Back-projections centered on p_0 , lying in a plane orthogonal to vector between p_0 and p_1 . Bottom: three-dimensional representation of pixel intensities along back projected plane after 360 projections. Pixel with minimum intensity (p_0^*) is assumed to be true center of vessel.

2.4. Determining second point (p_1^*)

Having computed p_0^* , a vector originating at the newly determined point p_0^* and ending at the original user defined point p_1 is determined. The plane orthogonal to this vector is computed and p_1^* represents the XYZ coordinates of the minimum pixel within this plane.

2.5. Automated Skeletonization of entire vessel

All subsequent points (p_n^*) are determined based on a moving average of vectors derived from previously determined points ($p_0^* - p_{n-1}^*$). An orthogonal plane generated around p_n and p_n^* is calculated from the XYZ coordinates corresponding to the minimum intensity pixel on that plane. This skeletonization process continues in user-defined increments until stopped by the user (Fig. 10).

Figure 10. First vessel has been skeletonized

2.6. Diameter Estimation

The central axis of any arterial branch can be obtained in the same manner. However, to interconnect the central axes of neighboring vessels at branch points, a boundary, centered along each vessel's central axis and proportional to the vessel's diameter is required. This boundary is obtained by beginning at the central point p_n^* , and working outward. All pixels within the back-projection plane are replaced with brightest pixel for every given distance. The radius of this boundary is the distance between the center point and a ring located at the level of steepest descent. This is graphically depicted in Figure 11.

Figure 11. **Top:** Pixel intensities within back projection surrounding vessel. **Bottom:** All pixel intensities at every distance from center have been replaced with brightest pixel at that distance. The method computes boundary radius as the distance between center pixel and a ring located at the level of steepest decent.

2.7. Connecting subsequent vessels

The user identifies two 3D points (using methods described above) along a different vessel and skeletonization is once again performed. However, as each point is determined, the distances between points on all previously skeletonized vessels and the current point are determined. If this distance falls within the radius of the previously determined vessel boundary, the skeletonization process for the current vessel ends and the new point's coordinates are changed to the coordinates of the point on the existing vessel corresponding to the smallest distance. This is shown diagrammatically in Fig. 12.

Figure 12. Connection process. New points along a vessel axis are determined (in direction of arrows). Distances between all new points (open circles), and points along central axis of previously determined vessels (filled circles) are determined. If distance (dashed line on right diagram) falls within previous vessel's boundary, this new point's position is set to the coordinates of the vessel axis point corresponding with the nearest distance.

3. Results and Discussion

Figures 13-14 shows the 3-dimensional skeleton of several orientations of a left rat lung obtained as described.

The concept upon which this method is based is illustrated in Fig. 15 which compares the image of the vessel cross section generated by cone beam reconstruction using a Feldkamp algorithm with a vessel cross section generated by simple unfiltered backprojection. A graph of pixel intensities along a line transecting the central axis of the vessel image is also shown. While the unfiltered back projection has an easily discernable center, the fully reconstructed CT image (top) has no easily discernable center.

Many approaches have been proposed based upon, to the best of our knowledge, a completed CT reconstruction²³⁴⁵⁶. This present approach uses raw images and unfiltered back-projection to reconstruct the central axis of vessels within the pulmonary arterial tree. Because the method does not rely on CT reconstruction, it allows a rapid "turn around time" between data acquisition and data analysis. Also, only a few images (usually < 10) captured at differing rotations are necessary to differentiate vessel from non-vessel and to identify the central pixel. Therefore, fewer image acquisitions may be necessary. This may facilitate faster data-acquisitions during studies requiring more physiologic conditions. Finally, once skeletonization information has been obtained, it can be superimposed on the full 3D reconstruction to aid in morphometric measurements.

Figures 13, 14. The central axes of several skeletonized arteries of a left rat lung. Two different orientations are shown

Figure 15. Comparison of vessel cross sections slices across identical location of vessel. **Top** slice taken from full CT reconstruction. **Bottom** slice from back projection.

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