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Mathematical Morphology Analysis of 3D MRA Images of Human Brain for Estimation of Blood Vessels Parameters

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***Abstract* — The aim of the described research is to develop brain blood vessels modeling algorithm on the basis of three-dimensional high-resolution magnetic resonance images. The geometrical model of vessels will be used to visualize arteries and veins and to determine their quantitative description. It is expected that the estimated geometrical parameters of vessels will significantly complement the results of medical examinations and contribute to a more objective and accurate medical diagnosis. Geometrical parameters need to be extracted from MRA image after segmentation. Most important parameters are: vessel diameter, local direction and location of vessel endings and bifurcations. In this paper, the estimation algorithms will be presented. They are developed on the basis of three-dimensional skeleton of vessels and vessel tracking techniques.**

***Keywords* — Magnetic Resonanse Angiography; blood vessels; image processing; parameter estimation; diameter; local direction; bifurcation**

I. Introduction

A. Problem description

Development of magnetic resonance technology enables one to acquire high resolution, three dimensional images. Time of Flight [1] and Susceptibility Weighted Imaging [2] techniques combined together in one measurement result in a full map of veins and arteries [3]. Typically, images have to be segmented for vessel extraction. There are many approaches to segmentation [4]. They are divided to two main groups: based on geometrical modeling and on mathematical morphology. This paper will focus on the processing step performed after segmentation witch is modeling. To produce reliable geometrical model of vessels one need an information about vessel tree parameters. Those parameters can be estimated from segmented MR images. Assumption is that estimation starts from binary, three dimensional image where all vessel voxels have brightness value equal 1 and background equals 0 (Fig. 1a). Another necessary input is skeleton of vessels which will be treated as center line of vessels (Fig. 1b). Morphological thinning has been chosen from a range of different skeleton methods. Morphological thinning is most suitable for vessel tracking purposes because of maximum reduction of vessel region. With this approach each voxel in the center line of vessel will have only 2 neighbor voxels which also are part of the center line in all-26-voxel neighborhood. Exceptions are bifurcation voxels (3 neighbors) and ending voxels (1 neighbor).

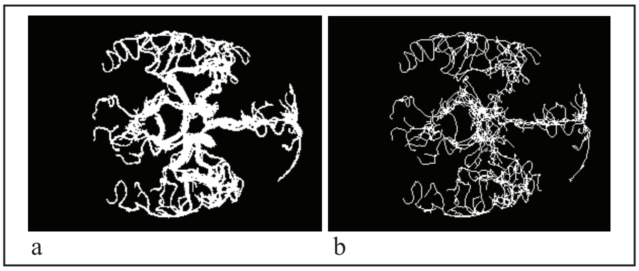

Figure 1. a)Maximum intensity projection of segmented 3D MRA image, b) maximum intensity projection of the result of thinning applied to image (a)

The most important vessel parameters, considered in this paper, are: vessel diameter, local direction as well as locations of vessel endings and bifurcations (Fig. 2). Estimation of vessel diameter can be performed by using both of those images.

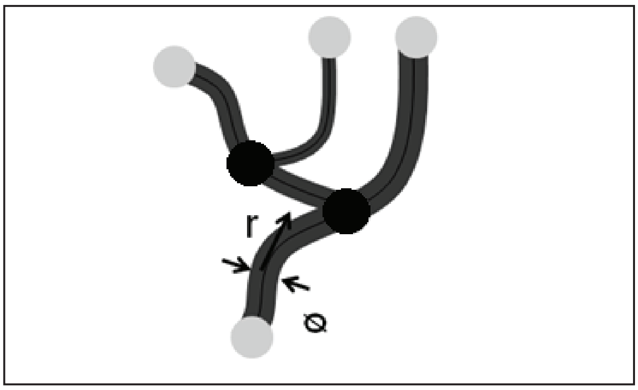

Figure 2. Parameters of vessel tree: diameter, local direction, location of endings and bifurcation

B. Methods overview

There are many approaches of diameter estimation. Majority of them are using skeleton to obtain center line of vessel. Method proposed by Sorantin [5] is based on user interaction. Shortest path between two points determined by user is computed. Chillet [6] suggest to use normal plane and cross-section area. That approach can produce diameter information for every skeleton voxel. Another method, employing deformable sphere located at the center line, is proposed by Zhou [7]. Method proposed in this paper is similar, but based on binary ball structuring element. The center of the ball is placed at every voxel of center line, but in vessels image. Ball starts from smallest possible radius. When ball contains vessel voxels only, its radius is increased. This operation is repeated until some part of "growing" ball will contain background voxels. Local vessel diameter is computed based on number of iterations and percent of vessel voxels in last iteration. Tests were performed on digital tube phantoms with different position and diameter. The aim of the testing was to assess the accuracy of the estimated diameter.

Another important geometrical parameters are locations of bifurcations and endings of vessels. Bifurcation detection in vessel tree are usually designed for two dimensional images. To find bifurcation in this space, it is enough to use a set of masks [8] or count neighbors [9]. AdaBoost method of Gaussian filter and first and second derivatives of Gaussian filter[7] are used for three-dimensional images. Method proposed in this paper is based on fingerprint line tracking[10], but performed in three dimensional space. Only center line image is used to find locations of bifurcation and endings. Ending voxels are easy to find. Endings in center line image received from morphological thinning have only 1 neighbor. Voxels detected as endings are pending starting points for vessel tracking. The 26 voxel neighborhood is checked for center line voxels. When found it becomes next voxel to check. Traveled path becomes invisible for later tracking. When tracking finds more than one path to follow, the path is chosen randomly and start point of alternative path is added to an endings search queue. When tracking ends in a voxel not labeled as ending, then that voxel becomes labeled as bifurcation. In vessel trees with more bifurcations this is not enough. It may be necessary to search for endings in whole image after tracking and making traveled path invisible. Found endings will also be marked as bifurcations.

Finally, local direction of vessels is also an important parameter to find. Estimation method is in this case similar to the previous one. Vessel tracking is performed on center line image, but requires information about all previously estimated parameters (diameter, bifurcations and endings). Tracking starts from voxel which is labeled as vessel ending and has largest diameter. Tracking makes traveled path invisible like in bifurcation search. Local direction is determined in every voxel on centerline except for bifurcations and endings. When previous voxel in path is invisible, then examined voxel have only one neighbor. Location of that neighbor relative to examined voxel gives information about local direction. When tracking finds bifurcation it travels random branch. Beginning of second branch is added to queue as another starting point. Points from queue are used to start new tracking when previous one ends (when voxel labeled as vessel ending is found).

II. Parameter estimation

A. Estimation of diameter

Diameter estimation is performed in every voxel of vessel center line. Voxel index is taken from center line image and put into full vessel image as center of binary ball. Ball radius is equal to 1 voxel. Inner product of ball is computed. Brightness value of every vessel voxel equals 1 so inner product value is equal to number of vessel voxels inside ball (Fig. 3). When every voxel within given ball radius equals 1, then radius is increased. This process is repeated until the ball is fully filled with vessel voxels. Information about biggest ball radius without background voxels and percent of vessel voxels in larger radius is acquired by performing this procedure for every voxel of the center line.

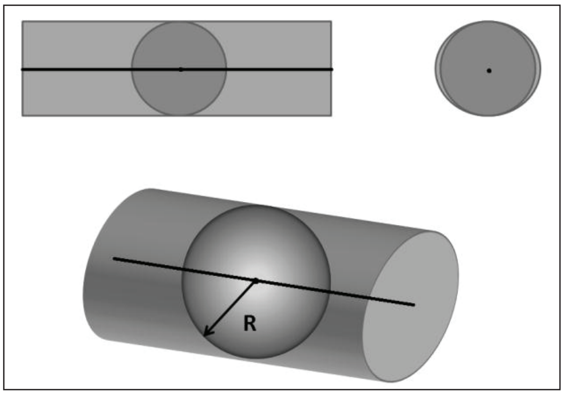

Figure 3. Visualization of diameter estimation

This information needs proper interpretation. This was done by using digital phantoms in tube shape. Tubes represents vessels with different radius (from 1 to 10 voxels) and different directions in three-dimensional space. Nearly 200 phantoms (Fig. 4) with known diameter were examined by diameter estimation algorithm.

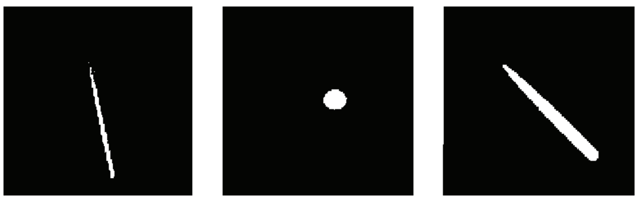

Figure 4.Maximum intensity projection of digital phantoms with different diameters and different orientation

Information about biggest radius of the ball fully filled with vessel voxels and information about percentage of ball voxels located inside the vessel at increased ball radius were compared with information about real radius of phantoms. Aim of composition was to reduce difference between real diameter and estimated diameter. After error reduction estimated diameter is over 90% correct. Usually mistakes are not greater than 1 voxel. Example results are shown on Fig. 5.

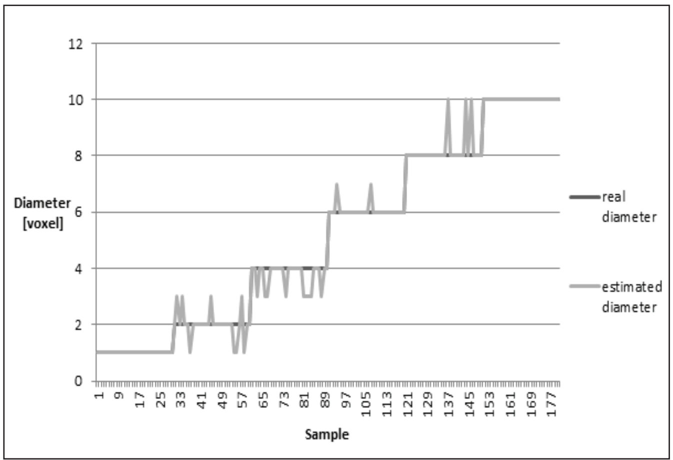

Figure. 5 Comparison of diameter estimated by the proposed method with correct diameter

B. Localization of bifurcations and ending

The algorithm is based on center line image only. Image is produced by morphological thinning. The algorithm returns another centerline image but with changed brightness values. Brightness value equal 3 means that a voxel has been labeled as vessel ending. Brightness value equal 4 means that voxel is labeled as point of bifurcation.

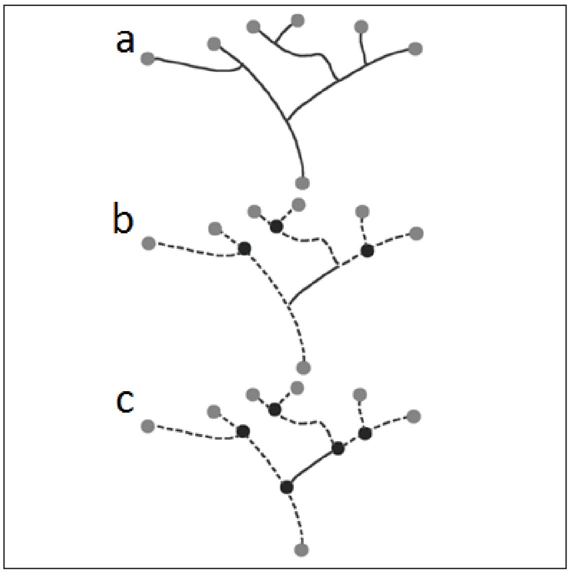

Figure 6. Bifurcations and endings estimation steps

First task (Fig. 6a) in the proposed algorithm is to find endings of vessels. Thanks to morphological thinning, the ending voxels have only one neighbor in full 26-neighborhood. Brightness value of those voxels is set to 3. Second step (Fig. 6b) is vessel tracking. Purpose of tracking is to find bifurcation voxels. All indexes of ending voxels are put into a queue as start voxels for tracking. Tracking changes brightness value of current voxel to 2 if current voxel isn't labeled as ending or bifurcation. Thanks to that traveled path is labeled and other tracking won't follow that path. Neighborhood of currently examined voxel checking is performed in every step of tracking. Usually only one unlabeled neighbor is found. In that case, a found neighbor becomes next voxel to check. When tracking arrive to crossroads (two unlabeled neighbors found in neighborhood) further path is chosen randomly. Third case is end of road (no unlabeled neighbors found). In this case it can be another ending voxel. If it is (current voxel brightness value equals 3), then tracking ends and another tracking starts from next start point from queue. If current voxel isn't labeled as ending it means that this is bifurcation or voxel next to bifurcation. Current voxel is labeled as bifurcation. It may happen that not all bifurcations are found. Because of that third step (Fig. 5c) repeats searching of ending voxels, but operates only on unlabeled voxels. Found voxels are labeled as bifurcations.

There is one issue with the algorithm. Sometimes voxel labeled as bifurcation isn't really a bifurcation, but some neighbor is. This issue requires correction which is realized by simple loop. If voxel labeled as bifurcation has only two neighbors, neighborhood of that voxel is searched to find voxel with tree neighbors. If such neighbor was found, then it becomes labeled as bifurcation and voxel previously labeled as bifurcation becomes part of center line. This procedure is enough to detect all bifurcations in real MRA image. Algorithm testing on more complicated digital vessel tree phantoms showed that when number of bifurcations in vessel tree is large then not all of them are detected. Because of that estimation algorithm became iterative and is repeated on unlabeled voxels until there are no unlabeled voxels left in entire image. Thanks to that, localization of bifurcations works well regardless of vessel tree complexity.

C. Estimation of local direction

Local direction estimation results in new image of vessel center line with changed brightness values just like in bifurcation estimation. In this image brightness value represents local direction in every center line voxel except for endings and bifurcations. Spectrum of those values is from 1 to 26 just like number of neighbors in three dimensional space. Information about previously estimated parameters like diameter, endings and bifurcations is required to create such image. Local direction is estimated through tracking similar to that used is bifurcation estimation. Tracking starts from voxel with biggest diameter which is labeled as ending. Traveled path is labeled to make it invisible. Examined voxel usually has one unlabeled neighbor. Position of that neighbor in one of 26 directions is written as brightness value in output image and found neighbor is set as next voxel to examine. If currently examined voxel is labeled as bifurcation then randomly chosen unlabeled voxel is set as next voxel to check and index of other is put into a queue. When tracking arrive in voxel labeled as ending, then next voxel index is taken from queue and new tracking starts. When queue becomes empty and some unlabeled voxels are still in image, whole process is repeated only on unlabeled voxels. This is necessary because in real MRA image of brain there are two main arteries without any connection.

III. FUTURE WORK

Proposed solutions need further improvements. Bifurcation and ending estimation still generates minor mistakes and must be reviewed. Another important modification will be diameter estimation performed on gray scale images by computing standard deviation inside ball radius. This will allow to express diameter as real number instead of natural number. When all parameters will be estimated correctly then vessel modeling can be started.

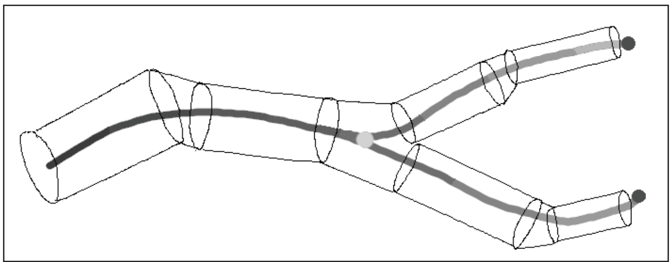

Figure 7. Model based on cylinders and trapezoids

Model will be based on cylinders and trapezoids like in Fig. 7. All gathered information about vessel parameters will be useful while building model. Reliable 3D model of real brain vessels can be used for blood flow simulations

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