Magnetic Resonance Angiogram Processing and Modelling of the Cerebral Vascular Network

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***Abstract*—The main aim of the work is to develop an algorithm for creation of three-dimensional model of the cerebral vascular network on the basis of medical images. Two types of non-contrast enhanced magnetic resonance angiograms were used as input data. First of them, Time of Flight angiography, enabled visualization of the arterial tree, whereas the next one, Phase Contrast angiography, enabled visualization of both arterial and venous trees. Medical images stored in Digital Imaging and Communications in Medicine (DICOM) file format required pre-processing. This process included resizing of the images, segmentation of the brain area and morphological white top-hat transformation in case of Time of Flight images, for noise reduction and gamma transformation necessary for enhancement of the vessels. The main core of the algorithm consists of segmentation of the vessel sections, selection of the vessels centroids, and construction of graph structure storing branches and nodes of the network. Three types of segmentation algorithms were analysed: algorithms with automatic and manual threshold segmentation (where threshold is based on image histogram); and binarization with hysteresis. The vascular trees obtained from two types of images were compared with each other. The developed algorithm allows for creation of three-dimensional model of cerebral vascular network and is potentially useful for the diagnosis of various vascular system abnormalities/diseases of the brain , as well as for the scientific simulations of blood flow or prediction of the drug distribution in the brain.**

Keywords-Medical image processing; image segmentation; MRI angiography; cerebral vasculature.

I. Introduction

Contemporary Magnetic Resonance Imaging (MRI) technique allows for angiographic studies without the use of enhancing contrast agent. Cardiovascular imaging is crucial in diagnosis of vascular pathologies, *e.g.*, cerebral aneurysm. The most common sites of intracranial saccular aneurysms are anterior and posterior communicating arteries of the Circle of Willis.

The main aim of this study is to create an efficient algorithm for creation of the model of the cerebral blood vessels trees from three-dimensional medical MRI angiograms that reflects real structure of both venous and arterial vessels. The developed algorithm can be used not only for visualisation of the cerebral vascular system but also can be useful in detection of geometric deformations or abnormal narrowing of the blood vessels.

MRI images are stored in standardized DICOM file format [1]. Apart from the pre-processing improving the quality of the input data, the problem of extraction of vascular tree comes down to the problem of segmentation. There are many methods for medical image segmentation (see Chapter II in [2]). Segmentation techniques can be divided into classes in many ways, depending on classification scheme. The most commonly used segmentation techniques can be classified into two broad categories: region segmentation, and edge-based segmentation techniques. The most common region segmentation method is method of thresholding (*e.g.*, global or local (adaptive) thresholding) [2], [3]. Other region segmentation techniques include clustering, region growing, and watershed algorithms. Whereas, the edge-based segmentation algorithms include graph searching and contour following. The more sophisticated techniques use fuzzy clustering, neural networks, or deformable models.

Different segmentation techniques have different applications. Lesage *et al*. [4] review the techniques applicable for the vessel lumen segmentation. They also raise the topic of post-processing since initial extraction results may be lacking in different aspects: surface information may be missing or inaccurate, the vessels topology may be incorrect, non-vessel regions may be included, vessel segments may be disconnected or missing. An example of post-processing is skeletonization [5], which is used to determine the centerline of the vessel. In practice, image noise and the inherent limitations of 3D thinning algorithm may result in a skeleton that contains cycles and spurious spurs. Thus, it is necessary to perform skeleton pruning [6] in order to preserve unit-width skeleton without any bridges.

The rest of the paper is organized as follows: First, the research methodology is described in Section II. In Section III, we show the results of both image processing and algorytmic part of the work. Finally, in Section IV, we present the concluding remarks.

II. Materials and methods

Two types of non-contrast enhanced magnetic resonance angiograms were the input data of the developed algorithm. First of them, Time of Flight (TOF) angiography, enabled visualization of the arterial tree (see Fig. 1(a) and 1(c)), whereas

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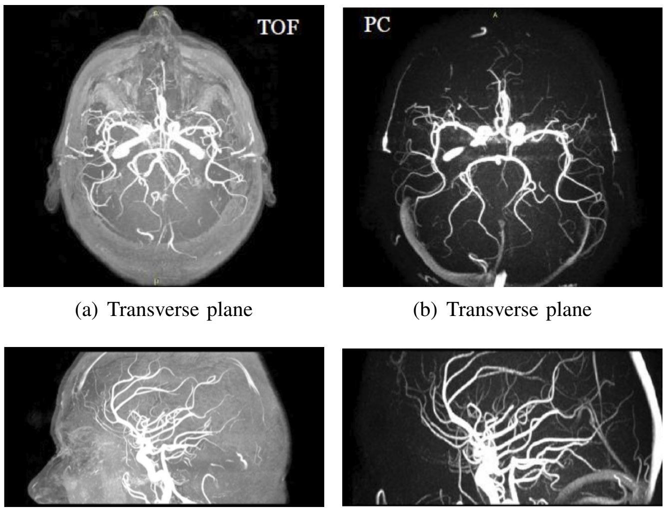
the next one, Phase Contrast (PC) angiography, enabled visualization of both arterial and venous trees (see Fig. 1(b) and 1(d)). An advantage of the TOF and PC techniques over the tradicional MRI angiography is that there is no need to use contrast agent, which may have adverse effects. Maximum Intensity Projection (MIP) of both types of images is presented in Fig. 1. The quality of the PC image data was higher then of the TOF images. The PC images were of size 1140 x 1140 voxels, whereas TOF were of size 256 x 256 voxels.



(a) Transverse plane
(b) Transverse plane
(c) Sagittal plane
(d) Sagitall plane

Figure 1: MIP projection of magnetic resonance images performed by means of TOF (a), (c) and PC (b), (d) techniques.

Medical images are often subjected to pre-processing, for increasing the quality of images. It enables for a more effective segmentation. In order to reduce the noise of the images, frequently median or convolution filters are applied. In this work, median filters ware used. Second step in pre-processing was application of the morphological White Top-Hat (WTH) transformation [7]. The WTH transformation is defined as the difference between the input image and its opening by some structuring element. The resulting images highlights the sections of blood vessels; since, their intensities have higher values than the image background. All images were also subjected to nonlinear gamma correction [8] in order to improve the contrast of the images.

Additionally, for the set of TOF images, it was necessary to remove the skull oval.

For the purpose of segmentation, either thresholding segmentation or binarization with hysteresis were applied. The thresholds were chosen experimentally or automatically by means of the image histograms.

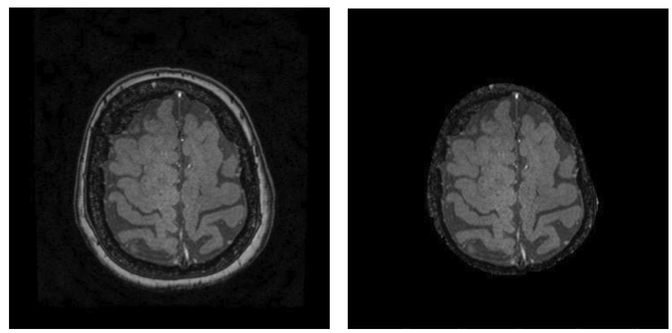
A significant part of the work was devoted to creation of object-oriented model of the vascular network structure. This work required:

- Selection of the vessels centroids on each slice,
- Iterative creation of branches from centroids, which subsequent cross-sections overlapped with each other,
- Saving the contours of subsequent sections for each branch,
- Capturing bifurcations, and storing it as node objects,
- Recursive attaching branches to nodal points.

The process of branches creation was complemented by a procedure of joining branches for those branches, which marginal cross-sections did not overlapped but were in close proximity. In such a case, changes in vessel circumference of subsequent cross-sections were analysed.

III. Results

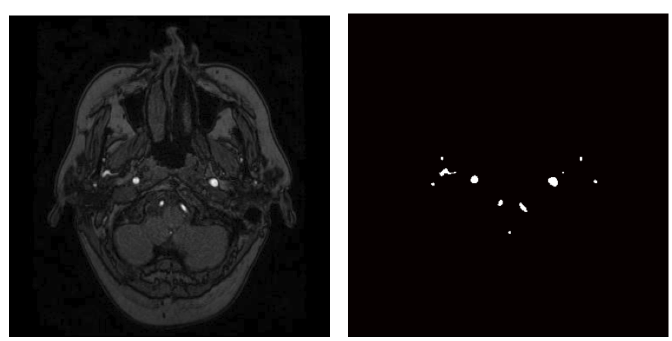
All of the calculations were carried out in Matlab environment. Input TOF and PC images were subjected to successive image transformations. Median filtering of the images is not shown but the best results were obtained for 5x5 size of the mask. Figure 2 presents the outcome of the process of skull elimination from TOF image.



(a) Original MRI image.
(b) Image after skull removal.

Figure 2: Process of elimination of the skull from the TOF images.

In the case of gamma correction, the best results for TOF images were obtained for $\gamma = 1.2$, whereas for PC images it was $\gamma = 1.4$. For the white top-hat transformation different structural elements were analysed. The best element turned out to be a square element with 30 pixels side length.



(a) Original MRI image.
(b) Segmented vessels.

Figure 3: Process of vessel segmentation from TOF images with applied method of binarization with a hysteresis.

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Different types of segmentation methods for vessel extraction were analysed. Those implemented were compared with methods implemented in graphical programs, *e.g.*, Yen method [9]. Nevertheless, those more advanced methods did not show any significant difference in comparison to the methods described in Section II. For the TOF images the best results were obtained for the binarization with hysteresis (see Fig. 3). While for the PC images the best segmentation results were obtained for binarization with threshold based on the image histogram.

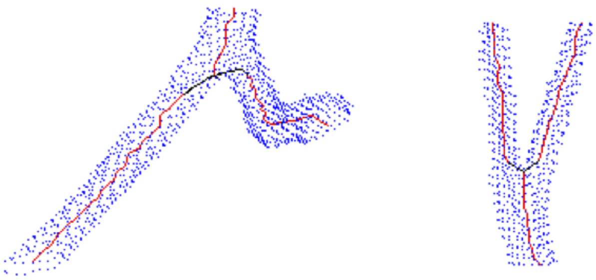
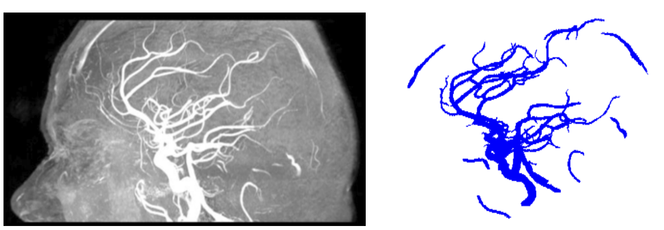


Figure 4: Visualization of two branching vessels with visible skeleton (in red) of the vessel.

The implemented algorithm for creating the object-oriented model of the vascular network structure is working properly. An example of two enlarged network segments is present on Fig. 4. One can see three-dimensional visualisation of the branch objects in red colour connected with nodal points by black lines, together with successive vessel contours presented in blue colour.



(a) MIP projection from TOF images.

(b) Visualization of the blood vessel network.

Figure 5: Comparison between input TOF data (a) and the result of developedalgorithm (b).

The comparison between input TOF data and visualisation of the model of arterial network for the whole brain is presented in Fig. 5. The selected method for the segmentation was binarization, with the threshold based on the image histogram. The advantage of the model is that one can selectively visualize only a part of the branches of the vascular network (or distinguish it with a different colour). Thanks to the model, the statistical analysis of the network parameters may be significantly reduced.

The comparison between the structure of the vessel network obtained by means of two different techniques is presented in Fig. 6. Images complement each other. Interestingly, despite the TOF images are of much lower resolution and contain more noise, this angiography technique gives more dense arterial network.

(a) Vessel structure obtained from TOF MRI.

(b) Vessel structure obtained from PC MRI.

Figure 6: Comparison between two vessel network obtained from TOF (a) and PC (b) MRi angiographies.

IV. Conclusion

The developed algorithm allows for creation of three-dimensional model of cerebral vascular network and is potentially useful for the visualisation and diagnosis of various vascular system diseases of the brain, as well as for the scientific simulations for blood flow or prediction of the drug distribution in the brain. The best segmentation results for TOF images were obtained by means of the binarization with hysteresis, whereas, the best segmentation results for the PC images were obtained for binarization with threshold based on the image histogram. Beyond the image processing, the work required the development of the algorithm of creation of blood vessel skeleton. The way of merging centroid points in the branches and bifurcations was no always trivial (in particular due to vessel twisting). The present work is still under development, it requires a quantitative analysis of the results. Application of two types of non-contrast MRI imaging is performed in order to extract the veins, which are present only at PC images together with the arteries. Therefore, the goal is not to improve the visualization of the entire vessel network but correct estimation of both 3D structures. The quality of the final model of cerebral vascular network depends strongly on the quality of the input data provided. Pre-processing and choice of segmentation method play an important role, however breaks in branches are mostly caused by imperfection of the acquisition method.

Applicability of the method is very broad. Visualization of the three-dimensional vascular network may have clinical applications, and the same network model can be used in further research. The obtained vascular tree structure of the brain can complement for example mathematical model describing vascular growth of tumours, mathematical modelling of blood flow, or models describing creation and growth of the blood vessels (*e.g.*, angiogenesis).

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