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A novel statistical cerebrovascular segmentation algorithm with particle swarm optimization

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ABSTRACT

We present an automatic statistical intensity-based approach to extract the 3D cerebrovascular structure from time-of flight (TOF) magnetic resonance angiography (MRA) data. We use the finite mixture model (FMM) to fit the intensity histogram of the brain image sequence, where the cerebral vascular structure is modeled by a Gaussian distribution function and the other low intensity tissues are modeled by Gaussian and Rayleigh distribution functions. To estimate the parameters of the FMM, we propose an improved particle swarm optimization (PSO) algorithm, which has a disturbing term in speeding updating the formula of PSO to ensure its convergence. We also use the ring shape topology of the particles neighborhood to improve the performance of the algorithm. Computational results on 34 test data show that the proposed method provides accurate segmentation, especially for those blood vessels of small sizes.

1. Introduction

Stroke is the third common cause of death and a major contributor to long-term disability. Severe stroke is often caused by serious cerebrovascular diseases, such as the rupture of a cerebral aneurysm, carotid stenosis and arteriovenous malformations (AVM). Cerebrovascular segmentation plays an important role in early stroke diagnosis. Since manual segmentation is tedious and subjective with high error rate and low recurrence, many automatic approaches, such as the deformation model method, the statistical model method, the Hessian matrix based method and region growing method [1,2], have been proposed for cerebrovascular segmentation. All these methods are available in the visualization toolkit (VTK) and the medicine insight segmentation and registration toolkit (ITK). Among the main cerebrovascular medical images, such as digital subtraction angiography (DSA), computed tomography angiography (CTA) and magnetic resonance angiography (MRA), the TOF-MRA is widely used and analyzed in clinical. Therefore, our research focuses on the TOF MRA.

We make three contributions in this paper:

Firstly, by a comprehensive analysis of the brain intensity histogram of the TOF MRA, we observe that the accurate matching between the FMM and the intensity histogram does not always lead to an accurate vessel segmentation. Instead, the accurate matching in the cross region of the vessels and other tissues between the two curves is really meaningful.

Secondly, we model the observed volume data by a Rayleigh and two Gaussian distributions. This model can match the whole histogram, especially in the cerebrovascular region and the cross region between the cerebral vascular and the background. As a result, we can estimate the parameters in a more stable and easy manner than the other FMMs.

Thirdly, we propose an intelligent optimization algorithm, called particle swarm optimization (PSO), for estimating the parameter of the FMM. With statistic disturbance, our method is able to escape the local extremals of the swarm. Furthermore, we use the ring type neighborhood relationship to control the variations of the particles position. Experiments show that the improved PSO is faster and more robust than the traditional algorithms such as EM and Stochastic Expectation Maximization (SEM).

The remaining of this paper is organized as follows. Section 2 reviews the related work of cerebrovascular structures, with a focus on the stochastic algorithms. Section 3 develops a new FMM with two Gaussian distribution functions and a Rayleigh distribution function for fitting the intensity histogram of the brain TOF-MRA. Section 4 presents the improved PSO algorithm for parameter estimation. Section 5 shows the experimental results and analysis. Finally, Section 6 concludes the paper and discusses the future work.

2. Related work

Cerebrovascular segmentation algorithm for MRA medical images can be divided into four categories [3,4], namely the

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deformation model methods, the statistical model methods, the Hessian matrix based methods and the region growing methods.

The deformation model methods usually use various forces to drive the curves in images. Popular deformation models include the parameter deformation model and the geometric deformation model. Kass [5] pioneered the snake model, the first parameter deformation model. Chan and Vese [6] presented an active contour model without edges (the CV model), but it was difficult to solve the segmentation problems in the images with complex background or uneven intensity. Li [7] proposed the Local Binary Fitting (LBF) model , in which the local binary fitting energy term is replaced by a global binary fitting energy term. However, the LBF model is very sensitive to the initial contour and it is also ineffective to the images with uneven intensity. Tian [8] added the statistical information into the deformation model and proposed a novel approach for accurate extraction of the cerebral vascular tree with automatic setting the initial contour of vessels.

Compared with the traditional clustering algorithms such as Fuzzy C-Means (FCM), k-Nearest Neighbors(KNN) or parzen window, the parameter statistical model can naturally describe both the material homogeneity and heterogeneity. Moreover, these algorithms do not require any parameter and initial position. The core of these algorithms is to use a model to fit the intensity histogram distribution and estimate the model parameters. By analyzing the intensity histogram of the brain TOF-MRA images, we can find three regions in the medical images. The first region with the low intensity includes cerebrospinal fluid, cerebral bones, air and other organizations. The second region with medium intensity has cerebral gray matter and white matter. The third region with higher intensity consists of cerebral vessels and subcutaneous fat. Cerebrovascular segmentation is to label each voxel with vascular or non-vascular structure in essence. The intensity histogram reflects the number of voxels located in each intensity level. The probability density function of the finite mixture model reflects the possibility of a voxel belonging to a class. So finite mixture models can completely characterize the intensity distribution of medical image sequences, in which curve coincides with the intensity histogram distribution. That is to say the fitting result of a finite mixture model to the intensity histogram reflects the cerebrovascular segmentation result. Therefore, in order to achieve the labels of observed data or classify all the voxels, the finite mixture model has to be determined to fit intensity histogram, and the parameters of each probability density function need to be calculated. The segmentation algorithm based on a statistical model was first proposed by Wilson and Noble [9]. They used a uniform distribution function to fit the distribution of vascular voxels and two Gaussian distribution functions to fit the distribution of non-vascular tissue. The algorithm can segment the basic cerebral vascular tree and Wills ring structure, but it is difficult to obtain the cerebral vessels with small radius. Based on this statistical model, Chung [10] took a comprehensive observation on the TOF-MRA imaging technique and the hemodynamic effects on vascular voxels. They proposed the Maxwell–Gauss uniform distributed hybrid model, which can not only segment the cerebral vessels but also effectively avoid the noise from blood flow on the cerebrovascular segmentation. Hassouna [11] divided all the voxels in the TOF-MRA image into vascular class and non-vascular class. They used a Gaussian distribution function to fit the distribution of vascular voxels and two Gaussian distribution functions and a Raleigh distribution function to fit the distribution of other tissues with low intensity. Their model can accurately fit the overall intensity histogram distribution of medical images. However, because too many distributions were used in the model, the parameter estimation procedure became complicated, which made cerebrovascular segmentation difficult. Hao [12] used a partial observation model to replace the global observation model and presented an adaptive segmentation method for vascular tree to achieve more accurate segmentation of cerebral vessels. According to the prior knowledge that the proportion of vessels is very small, they improved the Iterated Conditional Modes (ICM) and greatly shortened the segmentation time of cerebral vessels. Xu and Wang [13] observed that the intensity distributions of vascular and non-vascular voxels approximately matched two Gaussian distribution functions and then proposed a double Gaussian model, which combined with Stochastic Expectation Maximization parameter estimation method to implement cerebrovascular segmentation. Gao [14] proposed a fast automatic vessel segmentation algorithm by combining the statistical model to improve curve evolution approach. It can extract the narrow cerebral vessels including the small vessels with the radius of one voxel in which intensity is similar to other brain tissues. But the segmentation process only concerns the intensity information, without considering the regional characteristics of vessels in medical images. Tian [8] proposed a flexible 3D cerebral vessel segmentation method based on statistical model, Hessian matrix and deformation model. They used four Gaussian distribution functions to fit the intensity histogram of medicine images. This method does not analyze the neighborhood information of vascular voxels. Ayman [15] chooses a joint Markov–Gibbs model to accurately describe the mapping from all the voxels to different categories in medical images. Besides, a linear combination of discrete Gaussian distribution functions was used to identify the boundaries of the vessel region. They achieved high-quality segmentation result finally. That method was applicable to various medical images with different formats. Afterwards, Fang [16] fused the statistical model based on intensity information and the Markov random field model based on the spatial correlation information. He proposed this hybrid model to finish vessel segmentation in TOF-MRA images. His method made full use of statistical dependence in voxels neighborhood and performed better in 3D medical volume data.

Since cerebral vessels have typical characteristics of tubes, the eigenvalues and eigenvectors of the Hessian matrix are often used in cerebrovascular segmentation. Koller [17] proposed a multi-scale vessel enhancement method based on the eigenvalues of the Hessian matrix. Frangi [18] presented a multi-parameter similarity function for vascular enhancement. Sato [19] proposed a three-dimensional linear enhancement filter based on the multi-scale method. He distinguished the cerebrovascular structures from other structures in medical images with this method. However, only two eigenvalues were used in Sato's measurement method, which made the bright and dark linear structure not be processed by a similar method. Manniesing [20] used the Hessian function to guide and control the spread instead of diffusion tensor. Later, he improved the nonlinear anisotropic diffusion algorithm and proposed multi-scale diffusion method to achieve vascular enhancement. From a new perspective, Xiao [21] made full use of the equivalence between stress tensor and Hessian matrix of images. He brought out a novel vascular segmentating formula, which added the concept of stress tensor in physics to the vascular segmentation.

The region growing methods [22] are a common cerebrovascular segmentation method. The resulting vessel voxels have a good connectivity and a complete topological structure, which is very important to further research and/or application on cerebral vessels. Yi [23] and Eiho [24] analyzed the local properties of vessel branches and developed some adaptive region growing methods.

Recently, there has been a trend of considering accurate, adaptive, robust and stable abilities in the cerebrovascular segmentation algorithms. The character of the vessels and the neighbor relationship of voxels were investigated in the segmentation.

3. FMM for brain TOF MRA data

The intensity histogram of the brain image sequence represents the frequency of intensity value of each voxel. The voxel intensity of one brain tissue should be uniform and has the same distribution from the