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Brain symmetry plane detection based on fractal analysis

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ABSTRACT

In neuroimage analysis, the automatic identification of symmetry plane has various applications. Despite the considerable amount of research, this remains an open problem. Most of the existing work based on image intensity is either sensitive to strong noise or not applicable to different imaging modalities. This paper presents a novel approach for identifying symmetry plane in three-dimensional brain magnetic resonance (MR) images based on the concepts of fractal dimension and lacunarity analysis which characterizes the complexity and homogeneity of an object. Experimental results, evaluation, and comparison with two other state-of-the-art techniques show the accuracy and the robustness of our method.

1. Introduction

Modern imaging techniques allow in vivo visualization of the brain providing vast amount of anatomical and functional information. Especially, the advent of high quality neurological MRI has the ability to produce three dimensional images with high soft tissue contrast. Precise clinical diagnosis and patient treatment can further be supported by quantitative image analysis techniques. However, despite the extensive research, visual interpretation is still the common method used in clinical practice [1]. Anatomical complexity of the brain has made automated brain image analysis a particularly challenging task.

A normal brain holds approximate bilateral symmetry. Highly convolved brain is separated into the left and right hemispheres by the inter-hemispheric fissure (IF) or the longitudinal fissure, which is a long and deep furrow (see Fig. 1). Although the real separation surface is not perfectly planar, the plane that passes vertically through this midline is considered to be the mid-sagittal plane (MSP) which also aligns with the plane dividing the body into two symmetrical parts. The symmetry plane of the brain is often considered as a first-order approximation to the MSP [2]. Knowing the precise location of the MSP is an important initial step in neuroimage analysis, and is of great interest in a number of medical applications. For example, it helps in identifying anatomical areas of interest for diagnosis, treatment and serves as a basis for asymmetry study of the brain [3]. MSP can bring multiple images into a common anatomical co-ordinate system like Talairach–Tournoux [4] thus reducing the degrees of freedom in multimodal registration of brain images. Usually, MSP is located manually by a neuroanatomy expert whose time is taken to process a massive number of scans. Moreover, manual methods suffer from operator dependency and the difficulty to achieve accurate reproducibility. Therefore, a robust and accurate automatic technique to identify the MSP can be useful in clinical practice.

Despite the variety of methods being proposed, MSP detection remains a challenging issue due to the natural anatomical complexity, the presence of various noise artifacts [5,6], pathologies, and tilted head scans. Most of the existing work has concentrated primarily on the image intensity analysis to detect the symmetry. However, it is the brain's structure itself which is symmetrical. To the best of our knowledge, none of the work on brain symmetry plane detection has tried to take advantage of the local self-similarity and bilateral symmetry in the structure present in brain images. Nevertheless, a recent work in [7,8] assumes the MSP to be the plane that best partitions the external surface of the head into two symmetrical parts. The brain has a complex geometric structure which cannot completely be described using only measures based on Euclidean geometry [9]. Such complex geometry can however be characterized by fractal geometry. Fractal dimension (FD) provides a way of quantifying the shape complexity of objects. Fractal analysis has already been successfully used in various areas such as mathematics, science, biology and medicine. The use of a fractal dimension to describe the convolution or the complexity of a line or surface is well established in several areas of biomedical research [10].

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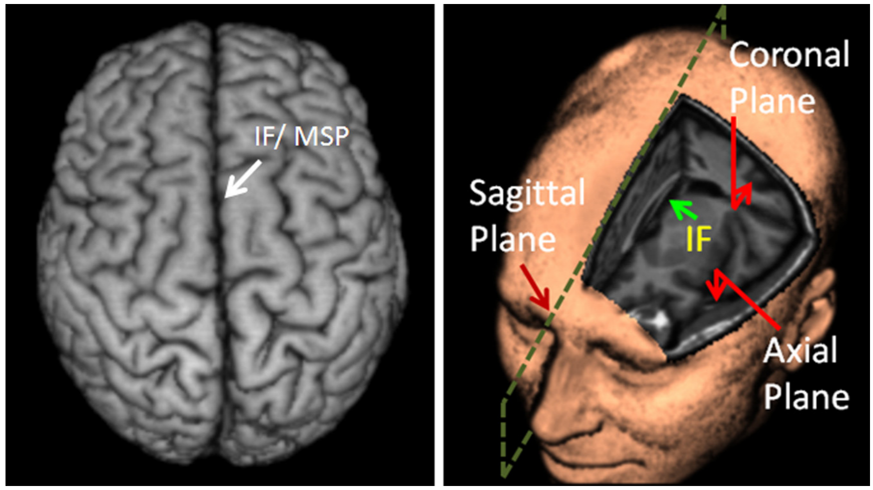

Fig. 1. Mid-sagittal plane [49].

In this paper, as the sequel of our previous work [11], we focus on detecting the MSP of the brain based on the fractal features of the textures present on neurological MRI. In our previous work, we proposed using fractal dimension as a symmetry measure for detecting MSP. The idea behind our approach is based on the assumption that the left and right hemispheres would be similar in structural complexity. In this paper, we exploit both fractal dimension and lacunarity for locating the MSP of three-dimensional (3D) brain volumes. We also carried out extensive experiments to test the viability of a fractal based method in MSP detection. Our results show that the method is robust to noise, applicable to different imaging modalities and is able to handle pathological cases. The method can also be applied on 2D axial or coronal scans.

2. Related work on MSP detection

A number of papers have tackled the brain symmetry plane estimation problem. A review can be found in [12]. These methods can be categorized based on two main approaches. The first approach [13–16] is to detect some anatomical feature like IF to estimate the location of MSP. In the method by Bergo et al. [15], it is assumed that IF contains the maximum area of CSF when ventricles are excluded. By creating a 3D brain mask that excludes ventricles, the CSF score of each sagittal plane is obtained by computing the mean voxel intensity in the intersection between the plane and the brain mask. The plane with a reasonably large brain mask intersection and minimal intensity score is taken as the best candidate for the MSP. Then, the CSF score is again calculated for all small transformations of the chosen plane and the plane with the lowest score is considered to be the MSP.

Volkau et al. [14] proposed another impressive method using Kullback–Leibler (KL) divergence. They assume that the entropy of MSP is lower than that of the neighbouring sagittal slices due to its large amount of cerebrospinal fluid (CSF). Let the probability distributions of the intensities of two sagittal slices be given by $P=\{p_i\}$ and $Q=\{q_i\}$, KL divergence measure is defined as

$$D_{KL}(p||q) = \sum_i p_i \log(p_i) - \sum_i p_i \log(q_i) = \sum_i p_i \log\left(\frac{p_i}{q_i}\right) \quad (1)$$

In their method, a volume of interest (VOI) is defined around the central slice in the sagittal direction and the KL measure is computed on all sagittal slices comparing each to the first slice of the VOI. By taking the slice that gives the maximum KL measure as the central plane for a new smaller VOI, a new search is performed until finally the MSP is estimated.

Methods in the first category are generally insensitive to pathological asymmetry. However, most of them are hard to extend to different imaging modalities and can be sensitive to noise and outliers. Existing methods also have some restrictions regarding the search area. Some prior assumption or knowledge about the approximate location of the MSP is needed to obtain good result.

The second approach defines MSP as a plane that maximizes the similarity of the two brain hemispheres [17–20]. Since brain is not perfectly symmetrical, several measures that quantify the degree of similarity between the two hemispheres have been proposed in the literature. Most of the work uses intensity based cross correlation. Cross correlation cc between two images P and Q can be calculated as

$$cc = \frac{\sum_i (P_i - \bar{P})(Q_i - \bar{Q})}{\sqrt{\sum_i (P_i - \bar{P})^2}\sqrt{\sum_i (Q_i - \bar{Q})^2}} \quad (2)$$

where P_i and Q_i are the intensity values in the ith pixel and $\bar{P}$ and $\bar{Q}$ are the respective means of the entire image.

Usually, the image is reflected across the estimated plane and the cc is measured between the original and the reflected images. The more recent edge based cc method [17,21] is different from the traditional intensity based cc technique in that it performs the cross correlation on an edge image in order to capture the anatomical structures of the brain and skull while ignoring intensity fluctuations. Although the method is capable of finding the MSP accurately on certain pathological images, the results could severely get affected by the initial estimate of the MSP computed on a lower brain slice, and the orientation of the image.

Methods in this second category can easily be extended to different imaging modalities. However, besides being computationally demanding, intensity based reflection approach is highly sensitive to the asymmetry caused by pathologies because of the similarity criterion used.

Despite the variety of work done in addressing the issue of MSP detection, there is still no method commonly accepted as the best. For an algorithm to be used in clinical practice, it has to be fast, robust and accurate [6,13]. Existing techniques leave significant room for applicability and accuracy. The closest related work to