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Fractal analysis of MR images in patients with chiari malformation: The importance of preprocessing

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ABSTRACT

As a popular method to meathe complexity of images and generally signals, FD analyses have been used in neuroimaging studies to evaluate the morphological complexity of brain structures. The aim of this study is to perform an FD-based complexity analyses of cerebellar tissues, such as cerebellar white matter (WM), cerebellar gray matter (GM) and cerebrospinal fluid (CSF) spaces around the cerebellum, on magnetic resonance (MR) images of Chiari Malformation type-I (CM-I) patients and healthy controls. Besides, to determine the noise effects on complexity of sub cerebellar structures, two common non-linear noise filters, median filter and bilateral filter, were applied to MR images and their performances were compared. Data of fourteen CM-I patients and sixteen normal subjects were used in this study. First, noise variance was estimated using a method based on skewness of the magnitude data. Second, as a preprocessing step, median and bilateral filters were applied on MR data separately to create different series of images for each filter. After the preprocessing, filtered brain images were segmented into three different tissues including WM, GM and CSF. Last, a 3D box-counting method was applied on segmented images to estimate the corresponding FD values. Our results showed that, while GM FD values was not significantly different between patients and controls ($p = 0.051$) in median filtering case, GM FD values in patients were found to be significantly lower than those in controls ($p = 0.007$) in bilateral filtering case. Additionally, in both cases, WM FD values in patients were found to be significantly lower than those in controls; however, this difference was more evident in bilateral filtering case ($p = 0.0003$) than that in median filtering case ($p = 0.013$). These outcomes indicated that bilateral filter was found to be more successful in discriminating CM-I patients from controls in cerebellar complexity analyses. In conclusion, results of this study revealed that noise removal is an important preprocessing step for a more successful analysis of digital images and bilateral filter is an effective filtering method for segmentation accuracy and FD analysis performance.

1. Introduction

Chiari Malformation type I (CM-I) is a serious neurological disorder, which was first described by Professor Hans Chiari in 1891 [1]. This condition is characterized by the downward displacement of the cerebellar tonsils, which are rounded lobule like tips of cerebellum under each of its hemisphere, into the spinal canal under the foramen magnum, which is the large opening in the base of the skull [2,3]. Radiological definition states that persons are diagnosed as having CM-I if they have a tonsillar descent of 5 mm or more below the foramen magnum [4]. Other parts of the hindbrain such as brainstem and fourth ventricle may also be affected in this disorder. They may be smaller in size or slightly deformed, however, their normal positions are not changed. Another condition associated with CM-I is syringomyelia, which is the abnormal development of a cavity that can involve a collection of cerebrospinal fluid (CSF) within the spinal cord. It may be observed in most of the CM-I patients [5].

The formation of CM-I syndrome may be triggered by several groups of conditions and disorders. These reasons include variations in the equilibrium of intracranial pressure because of altered CSF circulation dynamics [3], overcrowding of cerebellum due to small posterior fossa dimensions resulting from incomplete

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development of occipital bones [6–11]. However, the actual pathogenesis and the natural history of this anomaly have not been clearly specified [6,12]. CM-I patients may show several symptoms with different severity degrees. The most frequent symptom is severe headaches at the back of the head, which may result from the head movements such as coughing, laughing and sneezing. Another common symptom is the pain in shoulders and in the neck [13,14]. Additionally, a group of less frequent symptoms include sleep apnea [15,16]; nystagmus, which is a neurological condition involving rapid involuntary eye movements [17]; balance and gait problems [18] and dysarthria, which is a motor speech disorder causing disruption of speech quality [19]. Interestingly, some patients may not show any symptom, even though they have a tonsillar descent of more than 5 mm [20].

Midline magnetic resonance imaging (MRI) slices provide a suitable view of cerebellar tonsils; therefore, MRI is the preferred modality for the diagnosis of CM-I [21]. Besides, neurological tests, computed tomography (CT), and phase contrast (PC) cine MRI are additional diagnostic methods, which are used for the identification of this anomaly and for attainment of necessary information to make a suitable treatment plan as well [6,22–24]. Surgical operations are the only therapeutic methods to improve the conditions of patients. These operations, which are generally referred as posterior fossa decompression (PFD) [25], are aimed to restore CSF flow blockage between the brain and the spinal canal [26,27] or to enlarge the posterior cranial fossa (PCF).

Previous MRI studies related to CM-I research mainly dealt with morphological assessment of hindbrain structures such as cerebellum, fourth ventricle, PCF, brainstem and entire brain as well [6,8–10,28,29]. Several linear and volumetric analyses were carried out using sagittal MRI slices to evaluate the structural features of PCF. An essential measurement is the determination of the length of cerebellar tonsils under foramen magnum. Additionally, measurements related to occipital bones including lengths of clivus and supraocciput and calculation of the slope of tentorium were performed for linear analysis of PCF [6]. Furthermore, several volumetric assessment of this syndrome were also carried out using total volume of brain, PCF and CSF regions [6,8–10,28,29]. All these studies were related to size of the brain tissues and bone parts that surrounds it. To investigate the variations in inner structures of cerebellar tissues in CM-I patients, we have performed a 2D fractal analysis of cerebellum after segmenting it into white matter (WM), gray matter (GM) and CSF using a single sagittal MRI slice [30]. On the other hand, evaluation of CSF flow characteristics were also performed to determine the relation between CM-I symptoms and CSF flow patterns and to distinguish symptomatic cases of this disorder from asymptomatic cases [31–33].

A popular method for performing quantitative evaluation of morphological complexity is fractal dimension (FD) analysis [34–42]. A numerical value is generated by this method to process the structural details in complex objects [34–36]. FD analysis was used in a broad category of studies in neuroscience such as evaluation of the morphology of the brain cortices in neurological disorders [37], structural and functional changes in complexity of neural system during development or degeneration of brain [35,38–40]. Therefore, this analysis was applied in many neurological disorders such as multiple sclerosis (MS) [35,41], schizophrenia [34], Alzheimer's disease [42], multiple system atrophy [36], obsessive-compulsive disorder [34] and CM-I [30].

Accurate segmentation of brain tissues that includes complex structures in various neurological disorders such as CM-I is considered as an important step for the diagnosis. In previous studies, it has been reported that there are difficulties in finding edges or boundaries between different regions in MRI images, which have small intensity variations among pixels [43,44]. Another important problem in image analysis is segmentation of noisy images. Particularly, to classify three main brain structures, such as WM, GM, and CSF, intensity-based segmentation algorithms, that divide each pixels/voxels based on their intensity, are used. In the intensity-based segmentation, the intensity values of brain tissues in MRI images are modeled by a mixture of Gaussian and Rician probability distribution functions [45]. However, it has been reported that these types of segmentation require some tools for artifact elimination such as noise [46]. Because MRI images include various sources of noise, such as salt and pepper noise, speckle noise, Gaussian noise and Rician noise; these types of artifacts must be removed from MR data using filters to decrease misclassification problems and unrealistic results [44]. Therefore, in some of the previous studies on other neurological disorders such as MS, extensive pre-processing algorithms have been implemented on MRI data for noise removal [47].

The main purpose of the present study is to determine the effects of pre-processing on FD analysis of sub-cerebellar tissues in MRI data obtained from CM-I patients. To this end, two common nonlinear filters, median and bilateral filters, were employed and compared. The effects of denoising were evaluated using the results of FD analyses on WM, GM, and CSF, respectively. To our knowledge, no study has yet analyzed and compared the effects of pre-processing on FD analysis results of MRI. Thus, this research represents one of the first studies that investigate the effect of applying different noise filtering techniques on structural complexity analysis of MRI data from CM-I patients and healthy controls to achieve better statistical results.

2. Material and methods

2.1. MRI data

Brain MR images of 15 CM-I patients (4 males and 11 females, 16–55 years age range) and 16 healthy subjects (5 males and 10 females, 16–50 years age range) were obtained from databases of the radiology departments of two hospitals: Mehmet Akif Ersoy Cardio-Thoracic Surgery Training and Research Hospital and Medicana International Hospital, Istanbul. These data, which were taken in the period between 2013 and 2015, were selected from already existing MRI records at the hospitals mentioned above. The experimental procedures of this study were approved by the Ethical Committee of Fatih University. Three-dimensional high-resolution MRI data were recorded using a Siemens Symphony Magnetom Aera 1.5 T MR scanner (Erlangen, Germany). MR image parameters include: A matrix size of 512×512 pixels and in-plane resolution of $0.5\,\text{mm} \times 0.5\,\text{mm}$, flip angle 90°, TE (echo time) 9.8 ms, TR (repetition time) 511 ms, FOV 25 cm, 24 contiguous 5 mm sagittal slices.

2.2. Noise characteristics of MRI

Thermal effects originated from the stochastic motion of free electrons are a major noise source in MRI. This noise can be assumed to be white, additive and described by a Gaussian distribution with an equal variance and zero mean [48]. The real and imaginary components of an MR image are reconstructed applying Fourier transformation to the acquired raw complex MR data. Since the Fourier transform has linearity and orthogonality principles, the data in real and imaginary parts continue to follow Gaussian distribution [49]. Magnitude values are obtained for each pixel by calculating square root of the sum of two independent random variables from the real and the imaginary images to produce the Magnitude image. The noise features of the obtained magnitude