2D and 3D Complexity Analysis on MRI Images using Fractal Dimension

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***Abstract*— The brain, which is the most complex structure in the human body, has attracted attention of many researchers to study the possible fractal analysis application upon it. Current interest is seen directed more towards the utilization of complexity analysis as measured by fractal dimension in determining the pathologies effect and degenerative factor on the brain structure volume. In this paper, we used two box-counting methods: average 2D Fractal Dimension and 3D Fractal Dimension. 47 subjects (19 males, 28 females), aged ranging from 21 to 25 years, were recruited. Brain MRI images were acquired by using 3T MRI system. The images were then thresholded according to Otsu's method. The processed images were then calculated using fractal analysis, and the values obtained were statistically evaluated using Pearson's correlation test (r^2 = -0.106, p = 0.477). In conclusion, no correlation was seen between average 2D FD and 3D FD.**

***Index Terms*—Brain; Box-Counting; Fractal Dimension; Magnetic Resonance Imaging.**

I. INTRODUCTION

Human body is deemed to be one of the most complex structures that provides a vast field of interest to explore its wonder. The main regulator for this complex system is the brain, which function to ensure proper physical and physiological coordination within the body and external environment. However, the brain is also susceptible to changes on its structures. Reduction of gray matter (GM) volume in brain structures is always seen for patient with psychiatric disorder, such as schizophrenia and bipolar disorder [1]. Apart from that, the brain also functions as a reservoir for human memory. The structures of the brain varied according to the type of memory stored within the human brain. Brain, which has undergone robust memorization process, shows increased of regional GM in specific Broddman area with regards to memorization functions [2]. The increase of changes in GM volume could be detected by using Voxel Based Morphometry (VBM) analysis. Standard visual rating analysis for pathological identification is usually unable to detect subtle changes of the GM volume, due to lack of relevant assessment tools [3]. Since the shape and brain structures almost resemble self-similarities [4], a wide range of studies is currently being carried out by using Fractal Dimension (FD) to objectively quantify the brain structures as a single value.

Since its first introduction by Mandelbrot in 1983, FD has caught the interest of researchers in applying it as one of the tools to quantify natural phenomena which are typical but distinctive individually [5]. It has been used not only to characterize nature substance; it also has been applied into medical field among others for complex brain structures quantification. Its robust application enables detailed information being obtained within the brain morphology which is not limited to visual scale analysis only. Three present techniques for FD being used for brain complexity quantification are box-counting, surface-based algorithm and fast Fourier transform-based method [3]. Box-counting FD is usually used for its robust capability and directness [6]. Its ability to quantify the FD in the original image spatial domain makes it more preferred than its Fourier transform-based counterpart.

Several previous studies employed FD with regards to brain morphological specification and quantification. The interest of FD application for brain morphology has risen due to its superiority as compared to conventional Voxel Based Morphometry (VBM) method. While regional increased GM volume is detected in huffaz group, no significant different in total GM volume is found between huffaz and control group by using VBM [2]. FD has also shown to be more accurate than VBM for determining distant clinical phenotypes and detecting changes of white matter (WM) structure of several diseases, such as epilepsy and multiple sclerosis [7]. Liu et al. [5] employed FD in characterising changes of WM for human cerebellum in relation to disease development. They found FD to be helpful and sensitive to track the changes on the brain morphology during the developmental stage of the disease. This may help in early detection and good management to the patients. Squarcina et al. [1] in their study used 2D box-counting FD to characterise the brain morphology for subjects with psychiatric condition of bipolar disorder and schizophrenia. They found reduction of GM volume for bipolar disorder and schizophrenia subjects as compared to normal subjects. In a study of possible changes to WM in relation to age and sex [6], they used FD to investigate the changes of WM and found out that WM does reduce in complexity as age increases. They also concluded that FD is sensitive and accurate in detecting subtle structural changes within brain morphology.

Zhang et al. [3] developed a 3D FD method to quantify in detail the inferior, surface and general structure of WM. Their method was proven statistically to be sensitive and accurate

in the detection of WM changes related to age. FD had also been used for tumor detection using a set of real CT and MRI images [8]. They found lower FD values presence on the tumor as compared to surrounding healthy tissues. This finding suggests the application of FD in tumor detection to help ease and alleviate burden from the radiologists making a diagnosis especially for a very tiny tumor. A bone imaging study by Akkari et al. [9] found the advantages of using 3D FD in diagnosing osteoporosis on trabecular pattern of the wrist. They concluded that the 3D FD is needed to assess osteoporosis, as 2D FD does not give sufficient information for radiologists. A more uniform distribution of data for osteoporotic patients were found in 3D FD as compared to 2D FD [10]. They suggested 3D FD to be used when assessing osteoporosis within the trabecular network. Suzuki [11] measured 3D tree model using 3D FD technique. Their technique successfully estimated 3D tree model using 3D FD.

In this study, we are interested in comparing the FD values between 2D and 3D box-counting method for brain MRI images. We thresholded the brain MRI images using Otsu's method [12], prior to calculating the FD. The FD values obtained were then analysed using the correlation analysis to investigate the relationship of the two methods.

II. Research Methodology

A. Subject Recruitment

A total of 47 voluntary subjects (19 males and 28 females), aged ranging from 21 to 25 years, were recruited. The subjects were right-handed, in a good condition of health with no known medical illnesses, no previous history of past head injury, and free from psychiatry, endocrine and neurological treatments. All subjects received the same level of tertiary education in the same public university. Any contraindications for MRI examination, such as the presence of metallic object and claustrophobic, were assessed prior to the commencement of the study. We sought approval from the local ethical committees IIUM Research Ethical Committee (IREC) prior to this study. The study complied with the ethical principles by Declaration of Helsinki. All the subjects were given explanation regarding the purpose, objectives and research methodology. Signed informed consent by the subjects was obtained, with the convenience for the subjects to withdraw from the study anytime.

B. MRI Image Acquisition

We obtained high resolution brain images of the subjects by using 3 Tesla Siemens Magnetom Spectra scanner (Siemens Medical Solutions, Erlangen, Germany) at Radiology Department, IIUM Medical Centre. Subjects were briefed on the MRI protocols prior to scanning, as well as other possible complications should they occur. The weight and height of the subjects were measured to ensure all subjects received the minimum Specific Absorption Rate (SAR) from the scanner. Specific instructions were given to subjects. They were required to rest still throughout the scanning procedure, not even moving their eye balls if possible to reduce the occurrence of artefacts on the MRI images. The protocol used throughout the study was T1-Weighted Three-Dimensional Magnetization-Prepared Rapid Gradient Echo (T1W-3D MPRAGE) sequence. This is the mostly used sequence for imaging high resolution brain images at this centre. The sequence parameters were: TR/TE = 1880/3 ms with Flip Angle of 15^0. Extend of view of the setup was 250mm, with voxel size of 1mm x 1mm x 1mm. The slice thickness was 1mm, with 121 contiguous slices of T1W-3D MPRAGE brain images. All the images generated were first checked for any presence of artefact before we processed it for the next level. The images were stored in an external hard disk after the retrieval process from the host computer (OSIRIX) at the department. At this moment, all stored images were in DICOM format.

C. Structural Brain Images Realignment, Segmentation and Normalisation.

Pre-processing was done using Statistical Parametric Mapping 12 (SPM12). The images which were in DICOM needed to be converted into NIfTI format first. Realignment, segmentation and normalisation processes were done according to our previous work [2].

D. Thresholding Technique

We employed Otsu's method for both our 2D and 3D box-counting FD measurements. Otsu's method is an automatic threshold selection technique, used extensively for picture segmentation [8]. The advantages of this Otsu's method are no supervision required during thresholding process and it is non-parametric. Otsu's method is easier to us as it only exploits the lower level orders of the grey-level histogram [8].

E. Fractal Dimension Measurement

Measurements for both average 2D and 3D Fractal Dimension were done by using the box-counting function under Matlab version 8.4.0.150421 (The MathWorks Inc., Natick, MA, USA). Figure 1 describes the overview of the flow.

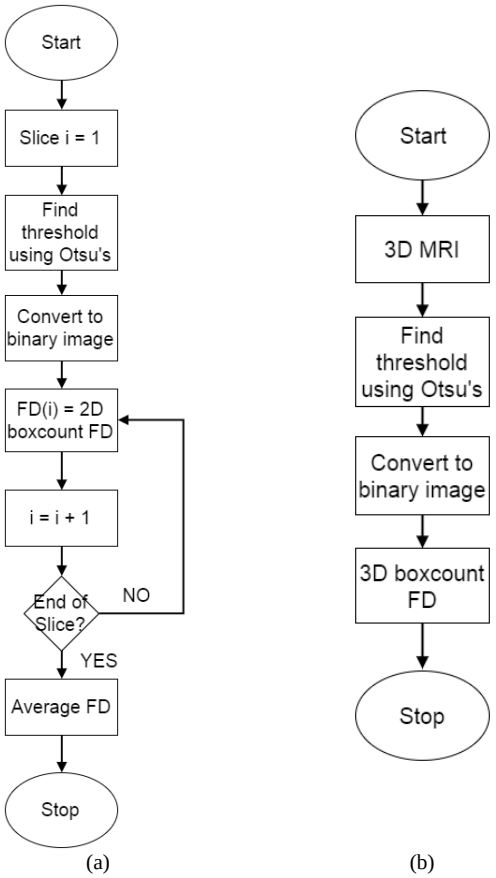

Figure 1: (a) The steps for average 2D FD, (b) The steps for 3D FD quantification.

F. Averaged 2D Fractal Dimension

All the images underwent thresholding technique using Otsu's method individually. The thresholded images were then converted into a binary image. This conversion is deemed necessary for box-counting FD. The FD was then calculated for each slice (Figure 2) based on the following relationship:

$$n \, \alpha \, r^{-FD} \quad (1)$$

Box-counting FD requires the box size to be varied. For each box size, *r*, the number of box that overlaps the white pixels are counted and recorded as *n*. The magnitude of the slope from *log(r)* versus *log(n)* was taken as the FD value. This step was done repeatedly until the FD for each slice was recorded. Upon completion of FD calculation, the FD obtained was averaged and the values were used for further statistical analysis.

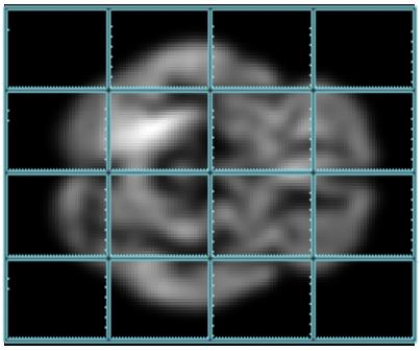

Figure 2: Box-Counting Method for 2D FD

G. 3D Fractal Dimension

Using 3D images, we run 3D FD to study the differences between averaged 2D FD and 3D FD. The thresholding technique used is the same as averaged 2D FD, which is Otsu's method. 3D images were then converted into binary images, and 3D box-counting FD was performed using Matlab, as shown in Figure 3. The process was similar to the 2D FD, with the exception of the box being counted is the one that overlapped with the white voxels in three-dimensional space.

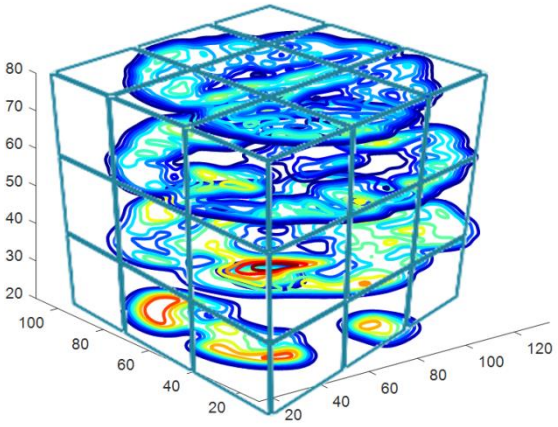

Figure 3: Box-Counting Method for 3D FD

H. Statistical Analysis

We ran thePearson's correlation test to determine the possible correlation between averaged 2D and 3D FD. In this study, we used the FD values obtained between average 2D FD and 3D FD from the GM region. The statistical test considered to be significant at the 5% level.

III. Results

The values of the calculated average 2D and 3D FD of GM is shown in Figure 4 scatter plot. We can see that there is no correlation between average 2D and 3D FD of GM. The Pearson's correlation test gave r^2 value of -0.106 and *p*-value of 0.477, strongly indicates that there is no correlation of FD values between average 2D FD and 3D FD.

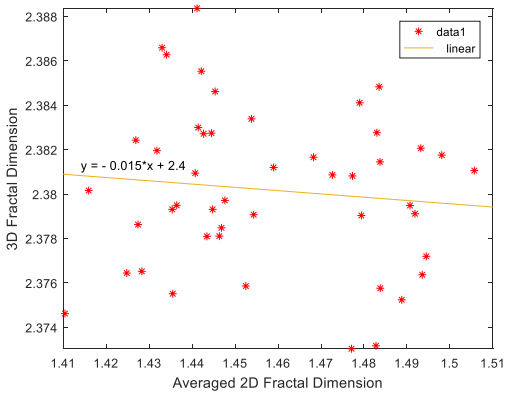

Figure 4: Scatter-Plot of 3D FD vs Average 2D FD

2D FD has proven to be reliable in measuring the fractal values of human anatomy such as brain, bone, breast and molecular structures [13]. As compared to our previous work [2] where we used VBM, FD allows us to calculate the fractal value for every single subject [1]. This in turn gives better information as the calculation of FD truly represents each single subject. In this study, we want to see the possible correlation between average 2D FD and 3D FD. 3D FD has been used among others in brain structure calculation [7], [14] and bone imaging [9], [10].

Our result shows no correlation between average 2D FD and 3D FD. This may be due to two reasons: first, the different process of calculating FD between average 2D FD and 3D FD. In average 2D FD, the calculations of FD were made on slice-to-slice basis on 3D structure, which in our case the brain. Different FD values from different slices do not correspond to the whole brain anatomical structure [1], [9]. On the contrary, 3D FD technique calculates the FD values in a volume, thus preserving the original brain structure and may better represent the 3D anatomical structure. This is proven by the work on brain [7], [14] and bone [9], [10] region. The differences of the plane directions in average 2D FD and 3D FD resulting in no correlation between average 2D FD and 3D FD [9].

Another reason for no correlation seen between average 2D FD and 3D FD values is due to limited range of age for our subject's profile. Our subjects aged between 21-25 years old. Farahibozorg et al. [6] in their study recorded an increased in FD values for young to mid-age group, whilst a decreased of FD values for mid-age to old group. This shows the wider the range of age between subjects, the greater the FD values differences. Since our subjects are in a young group (21-25 years old), it makes sense why we found no correlation in our FD values. They [6] also suggested that degenerative changes to the brain structures that lead to decreasing of FD values is age-related, as supported by earlier studies [15], [16].

In view of FD practicality for clinical field, both average 2D FD and 3D FD have their advantages. If the specification of specific abnormalities or pathology in the brain is required, average 2D FD will give a comprehensive FD values calculation but it may miss the possible progression of the pathology to the other parts of the brain [1], [9]. Meanwhile the application of 3D FD may give better calculation of FD values as it produces a more uniform data distribution over a 3D structure [10], giving an overview information of pathological progress that might be missed by using the average 2D FD technique.

IV. CONCLUSION

In conclusion, the application of average 2D FD and 3D FD on human structure opens for further venture and expansion in the future. Both techniques, if be used together may really alleviate the burden of radiologists in making a diagnosis to the patient. Future study should emphasize on optimizing the capability of average 2D FD and 3D FD on a wide spread of pathologies, as it has proven to be useful in clinical field by previous studies [17], [18], [19], [20]. The memory and cognitive function of the brain may also be the field of interest for fractal analysis application in the future.

ACKNOWLEDMENT

The authors would like to acknowledge the input and idea provided by Dr. Mohd Arshad Sideek from the Kulliyyah of Allied Health Sciences, and Azmir Ahmad from the Kulliyyah of Nursing, International Islamic University Malaysia.

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