Visualization of neural network activity in the human brain based on fractal analysis

M Ya Marusina and M E Kalinkina
National Research ITMO University, Russian Federation, 197101, St. Petersburg, Kronverkskiy pr., 49, letter A
mariia_kalinkina@mail.ru

Abstract. Methods for the quantitative assessment of signals based on functional magnetic resonance imaging data when studying the activity of neural networks in the human brain are presented. The algorithm of computational and analytical methods is implemented in the MATLAB environment, fractal analysis methods are selected as methods. Based on the developed algorithm, the FracLab software complex was created, with the help of which the signals received during the recognition of stimuli by 13 subjects were processed.

1. Introduction
When processing large amounts of data, automated computational and analytical methods become working tools for the qualitative and quantitative analysis of medical images.

Functional magnetic resonance imaging (fMRI) is a powerful tool in studying the activity of neural networks in the human brain. Modern technical capabilities make it possible to study various types of neural network activity. One of the main tasks of data analysis in such studies is the search for areas of the brain involved in certain types of activity of neural networks. Therefore, the development of reliable image processing algorithms for qualitative analysis of fMRI data is a paramount task in digital visualization of neural network activity. To quantify the BOLD signal recorded by MRI when studying the activity of neural networks in the human brain, it was decided to use fractal analysis. BOLD (Blood-Oxygen-Level Dependent) is a signal when the maximum and minimum thresholds of activity are reached in various areas of the brain.

Most fMRI studies use BOLD contrast imaging as a method for identifying the most active parts of the brain, some researchers question the validity of this method because the signals are relative rather than quantitatively individual. In this case, a promising method for quantitative assessment is the description of disordered media based on the introduction of macroscopic quantities that depend on the averaging scale. The mathematical concept of a fractal developed by Mandelbrot and its applications to describing the shapes of various objects make it possible to construct models of a wide class of nontrivial random scale-invariant structures.

An analytical study of fractal models is not always possible, but the regularities of disordered processes in such models can be studied through computer experiments. Attention to the study of fractal models is based on the fact that a large number of different structures and processes have fractal properties.

In recent years, attention has begun to be paid to the possibility of using the advantages of fractal geometry in medicine, especially in cardiology and radiology. For example, in [1, 2], a method was proposed for classifying focal formations using multifractal analysis. Several studies have shown the
potential of fractal analysis as a characteristic of irregular structures of focal formations, relying on the fact that fractal geometry is a theoretical basis for studying and modeling irregular structures [3-10].

The aim of the study is to develop fractal methods for quantitative assessment of the BOLD signal recorded by MRI when studying the activity of neural networks in the human brain.

2. Research methods

Analysis of fMRI images was carried out by computational and analytical methods based on calculating the fractal dimension for images or their individual elements.

The fractal dimension of the image \( \dim_{box}(s) \) was chosen as diagnostic characteristics for tomographic images. Fractal dimension characterizes complexity, a concept associated with certain key characteristics of fractals: self-similarity and detail. The fractal dimension for regular fractals describes the repeatability of geometry, and for irregular ones, the repeatability of statistical characteristics when changing the scale [11].

To determine fractal dimensions often uses the box-counting method. Its popularity is based on rather simple mathematical calculations, empirical estimation, and the same efficiency of application for point sets, linear objects, regions, and volumes [12], which makes it ideal for working with digital images.

This method of calculating the fractal dimension \( \dim_{box}(s) \) is described as follows: first, the area containing the object under study is divided into cells at each stage of the study, the sizes \( \varepsilon \) of which change at each stage; for each size of the cells, their number \( N(\varepsilon) \) is calculated, necessary to cover the object studies, a graph of the dependence of the size of cells on their number is built, the slope of which is the cell dimension, which can be expressed as follows:

\[
\dim_{box}(s) = \lim_{\varepsilon \to 0} \frac{\ln N(\varepsilon)}{\ln \frac{1}{\varepsilon}}.
\]

For a 2D signal, the expression:

\[
H = 2 - \dim_{box},
\]

the determining Hurst coefficient characterizes the fractal properties of signals. The proximity of the Hurst exponent to 1 indicates the pronounced fractal properties of the object, and \( H = 0.5 \) characterizes a random process.

The successful application of fractal analysis as a tool for quantifying changes in the structure of images, both healthy and pathological tissues, was shown in [13-17]. The research results presented in [18, 19] indicate significant differences in fractal dimension for various types of tissues.

The developed algorithm consists of several independent blocks: a block for loading data, preparing digital images, selecting information for processing, and outputting the received data. The algorithm was implemented using the MATLAB development environment using computational and analytical methods.

The data were obtained after studying the phenomenon of insight; the Gollin test was used as dynamic images, the work of which leads to a gradually increasing contour of randomly occurring fragments [20]. The Gollin test was constructed according to the following scheme: for the first five minutes the subject was presented with a point, after which 26 stimuli began to be shown, each stimulus was presented from 0 to 45%, 1% per second. The brain was scanned every 3 seconds (15 scans for one stimulus). The Gollin test is that the subject observes fragments of the drawing, expecting to see an object, but cannot guess what kind of object it is. Pattern recognition occurred unexpectedly, which evoked an emotional reaction in the subjects, which was recorded due to changes
in the BOLD signal, the registration and visualization of which was carried out using fMRI. We used fMRI images of the brain of 13 subjects in the NIfTI format (Neuroimaging Informatics Technology Initiative).

For automated fractal analysis of medical images, a software package (FracLab) was used, which provides the following functions: loading and viewing medical images, post-processing, highlighting areas of interest, calculating fractal dimension by the differential method (box-counting method), calculating the Hurst exponent [21].

3. Results
The fractal dimensions of the BOLD signal were obtained for Brodmann's zones of the medial parietal region (BA7), temporoparietal cortex (BA22), posterior temporal cortex (BA37), ventrolateral prefrontal cortex BA44, prefrontal cortex (BA46) on the left and right sides for 13 subjects.

To identify the dynamics of the activity of the brain zones, the normalized values of the fractal dimension were used, which were obtained by unifying the scale of values of the studied series: the new scale takes values from 0 to 1, for plotting in the new scale, the original row was divided by the maximum value of this row.

Figure 1 shows the dependence of the normalized values of the fractal dimension for 13 subjects on the time of presentation of the stimulus and the percentage of filling the contour; the average values of the fractal dimension for the entire sample are also shown – bold black line. The graph of the mean values of the fractal dimension of the images of the BA7 zone for 13 patients shows that the change in the fractal dimension has a general tendency. The abscissa shows the time and the corresponding percentage of the contour presentation. There is a noticeable dynamic during the time of presentation of the stimulus: on average, there is a tendency for bursts of activity at 10 seconds (10% of presentation of the stimulus contour), at 20 seconds and at 50 seconds from the beginning of the time of presentation of the stimulus. The minimum activity is observed at 30 seconds, which corresponds to the decline in activity observed after the insider. This dependence reflects the change in time of the fractal dimension of the BOLD signal in relative units, where it is possible to distinguish a pre-threshold state, a threshold state, and after a threshold state, which indicates the presence of a reaction of certain brain regions to test images. It is important to note that the moment of recognition in different subjects occurs at different times, and the range of the difference in activity for the same stimulus is different.

![Figure 1](image-url)

**Figure 1.** Normalized values of the fractal dimension in the Brodmann zone VA7 in the axial projection, for 13 subjects.
Let us consider in more detail the response of the brain in the medial region of the parietal cortex BA7. The inertia of the BOLD signal, which reflects the activity of the blood flow in the brain, does not allow us to accurately determine the time of arrival of the signal in a particular region, but the method of stimulus presentation allows us to record the dynamics of changes in the BOLD signal [20]. Table 1 shows brain scans in various projections now of recognition, or insight, and the type of stimulus presented to the subject at this moment in time. There are also examples of calculated fractal dimensions for the studied area of the brain and for the stimulus. The obtained values are a quantitative estimate of the BOLD signal, independent of the previous signal states.

| The axial projection of the brain | The coronal projection of the brain | The sagittal projection of the brain |
|----------------------------------|-----------------------------------|-----------------------------------|
| FD left 1.5685                   | FD left 1.5582                    | FD left 1.5838                     |
| FD right 1.5784                  | FD right 1.5720                   | FD right 1.2328                    |

Table 1. Fractal dimension for the BA7 zone on the left and right sides

Fractal dimension for the BA7 zone on the left and right sides

1.5839 1.5783

Figure 2 shows the dependences of the fractal dimension of stimulus images on the percentage of stimulus contour presentation, where the dashed line is the averaged values for all 26 stimuli. The abscissa shows time and the corresponding percentage of the contour presentation. All images of stimuli at the beginning of presentation have the same fractal dimension, but as the contour grows, the values diverge, which is associated with the formation of different patterns or different closed contours that have different lengths and shapes. The graphs have a generally linear relationship, but after presentation of 40-50% of the stimulus contour, the slope of the straight line’s changes, which is associated with the formation of the stimulus contour from chaotically scattered points.

Figure 2. Fractal dimensions of stimuli upon presentation from 0 to 90% of the contour.

Let us consider the responses of the brain around the occipital-temporal cortex BA37. The method of presentation of stimuli allows obtaining the dynamics of changes in the BOLD signal. Figures 3-4 shows the dependences of the fractal dimension and the BOLD signal for the BA37 zone on the
percentage of stimulus contour presentation. The abscissa shows time and the corresponding percentage of the contour presentation. Zone BA37, one subject, one stimulus. The ordinate shows the dynamics of changes in the BOLD signal in relative units (solid line) and the Z-estimate of the values of the fractal dimension of the fMRI image of the BA37 zone (dashed line). The results are presented for one subject upon presentation of the first stimulus for the left and right hemispheres. Differences between responses in the 20-30 seconds interval are statistically significant. The presented data showed that the activity of the right hemisphere exceeds the activity of the left when the stimuli are recognized. An increase in the BOLD signal for zone BA37 is observed 20 seconds after the start of stimulus presentation, which corresponds to the recognition threshold. The fractal dimension of the image of this zone also reaches its maximum after 20 seconds. The nature of the presented dependences for this zone repeats the dynamics of changes in the Z-estimate of the activity of the BA37 zone for the left and right hemispheres, given in the previously published work [20].

Figure 3. Z-estimates of fractal dimension and BOLD signal for the left hemisphere.
**Figure 4.** Z-estimates of fractal dimension and BOLD signal for the right hemisphere. The abscissa shows time and the corresponding percentage of the contour presentation. Zone BA37, one subject, one stimulus

### 4. Consideration

In [20], the results of studying the activity of large-scale neural networks were presented. It was shown that with insight there are differences in the activation of the left and right hemispheres and the maximum response is observed in the zone of the occipital-temporal cortex BA37. The registration of the activity of this zone by the BOLD signal presented by the authors showed that the maximum of the signal coincides with the moment of recognition or the emergence of insight.

The use of fractal analysis to assess the activity of different areas of the brain upon the onset of insight also showed that the activity of the right hemisphere exceeds that of the left hemisphere. The maximum response in the BA7 zone from 20 to 30 seconds of stimulus presentation, corresponding to stimulus recognition, coincides with the maximum of the fractal dimension of the fMRI image of the BA7 zone in the range from 20 to 30 seconds. The maximum value of the fractal dimension is observed at 24 seconds, and then decreases to a minimum at 30 seconds, which corresponds to the decline in activity observed after the insider (Figure 1).

The dependence of the Z-score of the fractal dimension of the stimulus image on time is linear, which is consistent with the way the stimulus is presented to the subject: the stimulus was presented from 0 to 45%, 1% per second. The greater the fractal dimension of the stimulus image, the less pronounced the fractal properties of the test image, the less the image contour is filled and, therefore, the more uncertain the picture in front of the subject.

### 5. Conclusions

Fractal methods have been developed for the quantitative assessment of changes in the structure of fMRI images during digital visualization of the activity of neural networks in the human brain.

For fMRI images of the brain using the box-counting method, fractal dimension values were obtained. Calculations were carried out for Brodmann's zones of the medial parietal region (BA7), temporoparietal cortex (BA22), posterior temporal cortex (BA37), ventrolateral prefrontal cortex BA44, prefrontal cortex (BA46) for the left and right hemispheres for 13 subjects, who were presented with 26 stimuli.

The results showed that the nature of brain activity during insight is different for the left and right sides. The data obtained allow us to assert that the time course of the responses (values of BOLD signals) of the BA37 zone and the time variation of the fractal dimension of the fMRI image of this zone have the same character. The results presented in this work proved the reliability and promise of fractal analysis for quantitative assessment of changes in the structure of fMRI images. Evaluation of the results obtained on larger samples is of interest for further studies of the activity of neural networks in the human brain.

### References

[1] Landini G, Rippin J W 1993 Fractal dimensions of the epithelial-connective tissue interfaces in premalignant and malignant epithelial lesions of the floor of the mouth. *Anal Quant Cytol Histol* 15(2) 144–149

[2] Hemsley A and Mukundan A 2009 Multifractal measures for tissue image classification and retrieval. *Proceedings of the 11th IEEE International Symposium on Multimedia*, pp 618-623

[3] Mandelbrot B 2002 Fractal geometry of nature (Moscow: Institute for Computer Research)

[4] Kronover R M 2000 Fractals and chaos in dynamical systems. Fundamentals of the theory (Moscow: Postmarket)

[5] Džuričić GJ, Radulovic M, Sopća JP, Nikitović M and Milošević NT 2017 Fractal and Gray Level Cooccurrence Matrix Computational Analysis of Primary Osteosarcoma Magnetic Resonance Images Predicts the Chemotherapy Response. *Front. Oncol.* 7 246
[6] Wąsik P, Seddon A M, Wu H and Briscoe W H 2019 Dendritic surface patterns from Bénard-Marangoni instabilities upon evaporation of a reactive ZnO nanofluid droplet: A fractal dimension analysis. *Journal of Colloid and Interface Science* **536** 493-498

[7] Marusina M Ya 2004 Invariant analysis and synthesis in models with symmetries (SPb: SPbGU ITMO)

[8] Flegontov A V and Marusina M J 2009 The Comparison Method of Physical Quantity Dimensionalities. *Lecture Notes in Computer Science*. **5743 LNCS** 81-88

[9] Marusina M Ya and Kaznacheeva A O 2006 Modern types of tomography, Textbook (SPb: SPbGU ITMO)

[10] Marusina M Ya, Kostenikov N A and Kaznacheeva A O 2010 Physical basis and equipment for positron emission tomography. National guidelines for radionuclide (Tomsk: STT)

[11] Hurst H E 1951 Long-term storage capacity of reservoirs. *Transactions of the American Society of Civil Engineers*. **116** 770-799

[12] Lopez T, Manjarrez J, Plascencia N et al 2009 Fractal analisis of EEG signal in the brain of epileptic rats, with and without biocompatible implanted neuroreservoirs. *Applied Mechanics and Materials*. **15** 127-136

[13] Marusina M Y, Sizikov V S and Volgareva A P 2015 Noise suppression in the task of distinguishing the contours and segmentation of tomographic images. *Journal of Optical Technology*, **82** 10 673-677

[14] Marusina M Y, Mochalina A P, Frolova E P, Satikov V I, Barchuk A A, Kuznetcov V I, Gaidukov V S and Tarakanov S A 2017 MRI Image Processing Based on Fractal Analysis. *Asian Pacific Journal of Cancer Prevention*, **18**(1) 51-55

[15] Kiryakova T N, Marusina M Ya and Fedchenkov P V 2017 Automatic methods of contours and volumes determination of zones of interest in MRI images. *REJR* **7**(2) 117-127

[16] Marusina M Ya, Karaseva E A 2018 Automatic Segmentation of MRI Images in Dynamic Programming Mode. Asian Pacific journal of cancer prevention: *APJCP* **19**(10) 2771-75

[17] Marusina M Ya and Karaseva E A 2018 Application of fractal analysis for estimation of structural changes of tissues on MRI images. *REJR* **8**(3) 107-112

[18] Marusina M Y and Karaseva E A 2019 Automatic analysis of medical images based on fractal methods. *Proceedings of the 2019 IEEE International Conference “Quality Management, Transport and Information Security, Information Technologies”* (IT & QM & IS), September, 23-27, 2019, pp 349-352

[19] Marusina M Y and Karaseva E A 2019 Application of the box-counting method for the evaluation of medical images. *Proceedings of the 2019 IEEE International Conference “Quality Management, Transport and Information Security, Information Technologies”* (IT & QM & IS), September, 23-27, 2019, pp 353-355

[20] Shelepin K Yu, Trufanov G E, Fokin V A, Vasiliev P P and Sokolov A V 2018 Digital visualization of the activity of neural networks in the human brain before, during and after insight in image recognition. *Optical Journal*. **85** 8 29–38

[21] Karaseva E A, Marusina M Ya and Andreev Yu S 2019 The Certificate on Official Registration of the Computer Program. Software package for automated fractal image analysis (FragLab). No. 2019614337, 2019.