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Nataliia Maryenko, Oleksandr Stepanenko

Fractal dimension of cerebellum in acute cerebellar infarction (magnetic resonance imaging study)

Zastosowanie badania wymiaru fraktalnego móżdżku w diagnostyce ostrego udaru móżdżku (badanie z zastosowaniem rezonansu magnetycznego)

Department of Histology, Cytology and Embryology, Kharkiv National Medical University, Kharkiv, Ukraine
Correspondence: Nataliia Maryenko, Department of Histology, Cytology and Embryology, Kharkiv National Medical University, Nauky Avenue 4, Kharkiv, Ukraine, 61022, tel.: +380951405088, e-mail: maryenko.n@gmail.com

ORCID iDs
1. Nataliia Maryenko https://orcid.org/0000-0002-7980-7039
2. Oleksandr Stepanenko https://orcid.org/0000-0002-5686-0857

Abstract

The aim of the study was to determine the values of fractal dimension of the cerebellum in acute cerebellar infarction using the quantitative study of magnetic resonance images of brain. **Materials and methods:** In this study, 11 patients with acute cerebellar infarction and 120 persons without structural changes in the brain (control group) were enrolled. T2-weighted magnetic resonance images of the brain were investigated. Fractal analysis was performed using pixel dilatation method. The values of fractal dimension of the cerebellar tissue as a whole and fractal dimension of the outer contour of the cerebellar tissue were determined. The fractal dimension values were measured in the following areas: cerebellar vermis (superior and inferior cerebellar lobes), foci of cerebellar infarction and areas adjacent to the foci (superior and inferior cerebellar lobes). **Results:** It was established that the values of fractal dimension of cerebellar tissue as a whole and fractal dimension of the outer contour of the cerebellar tissue in the area of cerebellar ischaemic infarction foci were significantly decreased compared to the control group. There was no significant difference between fractal dimension values of the cerebellar vermis, areas adjacent to infarction foci in patients with cerebellar infarction and vermal fractal dimension values in the control group. **Conclusions:** Fractal analysis of cerebellar magnetic resonance images may be used as an additional quantitative method to diagnose acute cerebellar infarction and to assess ischaemic foci to detect the boundaries between damaged and undamaged cerebellar tissue.

Keywords: cerebellum, stroke, cerebellar infarction, magnetic resonance imaging, fractal dimension

Streszczenie

Celem badania było określenie wartości wymiaru fraktalnego móżdżku w diagnostyce ostrego udaru móżdżku na podstawie analizy ilościowej obrazów mózgu uzyskanych w badaniu techniką rezonansu magnetycznego. **Materiał i metody:** Do badania włączono 11 pacjentów z ostrym udarem móżdżku i 120 osób bez zmian strukturalnych w obrębie mózgowia (grupa kontrolna). Analizie poddano obrazy T2-zależne mózgu uzyskane w badaniu metodą rezonansu magnetycznego. Analizę fraktalną przeprowadzono metodą rozszerzania pikseli (*pixel dilatation*). Określono wartości wymiaru fraktalnego tkanki móżdżku jako całości oraz wymiaru fraktalnego jej zewnętrznego obrysu. Pomiaru wartości wymiarów fraktalnych dokonano w następujących obszarach: robak móżdżku (górny i dolny płat móżdżku), ogniska udaru móżdżku oraz obszary sąsiadujące z ogniskami (górny i dolny płat móżdżku). **Wyniki:** Stwierdzono, że wartości wymiaru fraktalnego móżdżku jako całości oraz wymiaru fraktalnego jego zewnętrznego obrysu w okolicy ognisk udaru niedokrwiennego były istotnie niższe w porównaniu z grupą kontrolną. Nie stwierdzono istotnej różnicy między wartościami wymiarów fraktalnych robaka móżdżku, obszarów sąsiadujących z ogniskami udaru a wartościami wymiaru fraktalnego robaka w grupie kontrolnej. **Wnioski:** Analizę fraktalną obrazów móżdżku w badaniu metodą rezonansu magnetycznego można wykorzystać jako dodatkową metodę ilościową w diagnostyce ostrego udaru móżdżku oraz do oceny ognisk niedokrwiennych w celu wykrycia granic między uszkodzoną a nieuszkodzoną tkanką móżdżku.

Słowa kluczowe: móżdżek, udar, udar móżdżku, rezonans magnetyczny, wymiar fraktalny

INTRODUCTION

Acute cerebral stroke is one of the most important medical and social problems. In recent decades, there has been an increasing trend in cerebrovascular morbidity, with an increase in the percentage of young patients, and mortality rates reaching 30% (Kovalchuk and Skoromets, 2006; Vinnychuk, 1999).

Ischaemic cerebellar infarctions account for 5.7% of all cases of cerebral infarction. The average age of patients with cerebellar stroke is about 60 years (from 17 to 80 years). Men suffer from ischaemic stroke 2–2.5 times more often than women (Kovalchuk and Skoromets, 2006).

Various neuroimaging methods are used to diagnose pathological changes and diseases of the cerebellum, including cerebellar infarction. Magnetic resonance imaging (MRI) is the most commonly used neuroimaging method. Computed tomography (CT) makes it possible to diagnose cerebellar infarction, but some acute cerebellar infarctions may be detected only with MRI (De Cocker et al., 2017; Long and Liang, 1994). For this reason, MRI is a preferable tool to diagnose acute cerebellar infarction. However, cerebellar infarctions are often discovered unexpectedly at autopsy (Amarenco et al., 1989) because of absent, mild, or atypical clinical symptoms, or low sensitivity of neuroimaging tools, including CT (De Cocker et al., 2017; Long and Liang, 1994). Thus, further development of methods for the assessment of cerebellar tissue using MRI is still the goal of modern neuroscience and neuroimaging.

The analysis of MRI brain images takes into account both quantitative morphometric parameters and qualitative characteristics (Hasan et al., 2018; Yousaf et al., 2018; Zhou, 2016). The presence of foci of ischaemic necrosis in different cerebellar areas is the main qualitative criterion for the diagnosis of acute cerebellar infarction (De Cocker et al., 2017; Long and Liang, 1994; Ogawa et al., 2018; Rissardo et al., 2019; Yeh et al., 1993). De Cocker et al. (2017) reported that foci of cerebellar infarction are usually identified as bright areas on diffusion-weighted imaging during the first hours after acute cerebrovascular accident; they become hyperintense on T2-weighted images in the following hours; and may become isointense and therefore invisible on different MRI sequences at around 10 days. Foci of cerebellar infarctions may be found in different areas of the cerebellum: hemispheres, vermis and tonsils (Amarenco et al., 1989; De Cocker et al., 2017; Long and Liang, 1994; Rissardo et al., 2019; Ogawa et al., 2018; Yeh et al., 1993).

Qualitative assessment often fails to provide enough information for the diagnosis, thus, an objective quantitative assessment is required. In recent years, fractal analysis is increasingly used to assess quasi-fractal biological structures, including the cerebellum, whose structure has fractal properties. Fractal analysis allows for quantitative and objective determination of the degree of complexity of spatial organisation.

Studies on fractal analysis of the cerebellum are sparse (Akar et al., 2017, 2015; Liu et al., 2003; Wu et al., 2010). It was established that patients with Chiari malformation type I had significantly reduced fractal dimension (FD) values of the cerebellar white matter (Akar et al., 2017, 2015); another study found that patients with multiple system atrophy of the cerebellar type also had significantly reduced FD values compared to healthy persons (Wu et al., 2010).

Thus, fractal analysis may be used for quantitative assessment of cerebellar MR images as a diagnostic algorithm, possibly including an assessment of infarction foci in acute cerebellar stroke.

In this study, we aimed to determine cerebellar FD values in acute cerebellar infarction using the quantitative study of MR images of the brain.

MATERIALS AND METHODS

The study was conducted in compliance with the basic bioethical provisions of the Council of Europe Convention on Human Rights and Biomedicine (04.04.1997), the Declaration of Helsinki of the World Medical Association on the ethical principles of scientific medical research with human participation (1964–2008), and the order of Ministry of Health of Ukraine №690 dated 23rd September, 2009. The conclusion of the Commission on Ethics and Bioethics of Kharkiv National Medical University confirmed that the study was conducted in compliance with human rights, in accordance with current legislation in Ukraine, met the international ethical requirements and did not violate ethical standards in science and standards of biomedical research (minutes of the meeting of the Commission on Ethics and Bioethics of KhNMU №10 from 07/11/2018).

In this study, 11 patients with acute cerebellar infarction (age range 44–79 years, 6 men and 5 women) were enrolled. MRI of the brain was performed during first three days after clinical manifestation of an acute cerebrovascular accident. Also, 120 persons without structural brain changes (age range 18–86 years, 55 men and 65 women) were enrolled in the study as a control group. All participants provided written informed consent.

T2-weighted MR brain images were investigated. MRI was performed using a 1.5 T MRI scanner (Siemens MAGNETOM Symphony). The image parameters were as follows: TE (echo time) was 122 ms, TR (repetition time) was 4,520 ms; section thickness was 5 mm. Sagittal MRI projection was chosen for the study (Fig. 1).

The 1 × 1-inch (64 × 64-pixels) image fragments containing different cerebellar regions were used for FD measurement. Prior to fractal analysis, the MR images were pre-processed using Adobe Photoshop CS5 software. Segmentation was performed according to the pixels brightness value using the "threshold" tool. Two components of the images were revealed: the analysed structures (black) and the background (white). An empirical brightness threshold value of 100 was used for cerebellar MR images segmentation; it reveals the cerebellar tissue as a whole (Fig. 1 B). The empirical brightness threshold value of 90 was also used for

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*Fig. 1. T2- weighted MR image of the cerebellum. The focus of ischaemic infarction (hyperintense area) is located in the inferior cerebellar lobe (**A**). **B**, **C**. Pre-processing and segmentation of MR images, segmented pixels are coloured black. **B**. Cerebellar tissue as a whole (threshold 100 was used for segmentation). **C**. External contour of the segmented image (the difference between thresholds 90 and 100 was used for segmentation)*

segmentation: the difference between the images, segmented with threshold values of 100 and 90 reveals the outer contour of the segmented image (Fig. 1 C). This contour corresponds to the cerebellar cortex.

FD values were measured in segmented images. Fractal analysis was performed using two-dimensional pixel dilatation method in the author's modification (described for the first time in Maryenko and Stepanenko, 2019). The pixel dilatation method was chosen due to its simplicity and accessibility: special fractal analysis software is not required to determine the FD. Adobe Photoshop CS5 software was used for fractal analysis in this study; other graphic editors with similar or better technical characteristics can be used for pixel dilatation method in the present modification.

The modified pixel dilatation method of fractal analysis included 6 stages (iterations) (Fig. 2).

At stage 1 of fractal analysis image size was not changed (it was 64 × 64 pixels), image resolution was 64 pixels per inch. The number of pixels, corresponding to the studied structure (black, or non-white pixels) was counted using "histogram" tool of Adobe Photoshop CS5 software.

At stage 2, the image resolution was halved (from 64 to 32 pixels per inch), image size was 32 × 32 pixels. Thus, the image pixels were enlarged and the absolute area of the image corresponding to one pixel was quadrupled. As a result, some pixels, corresponding to the investigated structure, became grey as an average shade of 4 pre-existing pixels. All background pixels remained white (average shade of 4 pre-existing white background pixels). The number of pixels, corresponding to the studied structure (non-white pixels), was counted again.

At stages 3 and 6, the image resolution was iteratively halved (it was 16 pixels per inch at stage 3, 8 pixels per inch at stage 4, 4 pixels per inch at stage 5, and 2 pixels per inch at stage 6), and the image size was changed accordingly (16 × 16 pixels at stage 3, 8 × 8 pixels at stage 4, 4 × 4 pixels at stage 5, 2 × 2 pixels at stage 6). The number of pixels, corresponding to the studied structure, was counted at each stage of fractal analysis.

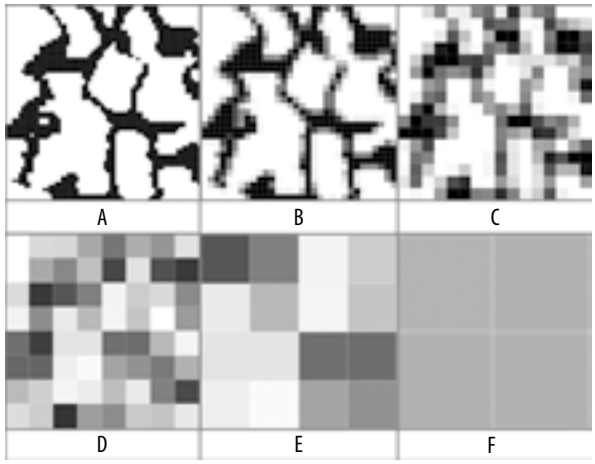

*Fig. 2. Modified pixel dilatation method of fractal analysis. This method includes 6 stages (iterations) (**A–F**). **A**. Stage 1 of fractal analysis: the image is binary (segmented during pre-processing), the pixels corresponding to the investigated structure are black; image resolution is 64 pixels per inch, image size is 64 × 64 pixels. **B**. Stage 2 of fractal analysis: image resolution is 32 pixels per inch, image size is 32 × 32 pixels; at this and following stages the pixels corresponding to the studied structure are black or grey (non-white) because of pixel dilatation. **C**. Stage 3: image resolution is 16 pixels per inch, image size is 16 × 16 pixels. **D**. Stage 4: image resolution is 8 pixels per inch, image size is 8 × 8 pixels. **E**. Stage 5: image resolution is 4 pixels per inch, image size is 4 × 4 pixels. **F**. Stage 6: image resolution is 2 pixels per inch, image size is 2 × 2 pixels. The number of pixels, corresponding to the investigated structure (non-white), is counted on each stage of fractal analysis. FD is determined by formula given in the text*

The FD values were counted by the formula:

$$FD = \frac{\sum_{i=1}^{6}(Ln_{(R_i)} - \overline{Ln_{(R)}})(Ln_{(N_i)} - \overline{Ln_{(N)}})}{\sum(Ln_{(R_i)} - \overline{Ln_{(R)}})^2}$$

Where: FD – fractal dimension, R – image resolution, N – number of pixels, corresponding to the studied structure, *i* – iteration (stage of fractal analysis).

Two FD values were determined: FD(100) and FD(100–90). FD(100) corresponds to the cerebellar tissue as a whole and FD(100–90) corresponds to the outer contour of the segmented image. The values of FD(100) and FD(100–90) were measured in different cerebellar regions.

Superior and inferior lobes of the cerebellar vermis (midsagittal plane) were studied in both groups (patients with cerebellar infarctions and control group). Vermal FD(100) and FD(100–90) values were measured in the superior lobe of cerebellar vermis (lobules I–V) and the inferior lobe of cerebellar vermis (lobules VI–X); their average value (average vermal FD) was calculated. In patients with cerebellar infarctions, involving the vermis, areas without visible structural changes were selected for FD measurement.

In patients with cerebellar infarctions, fragments of MR images containing foci of ischaemic infarction were investigated.

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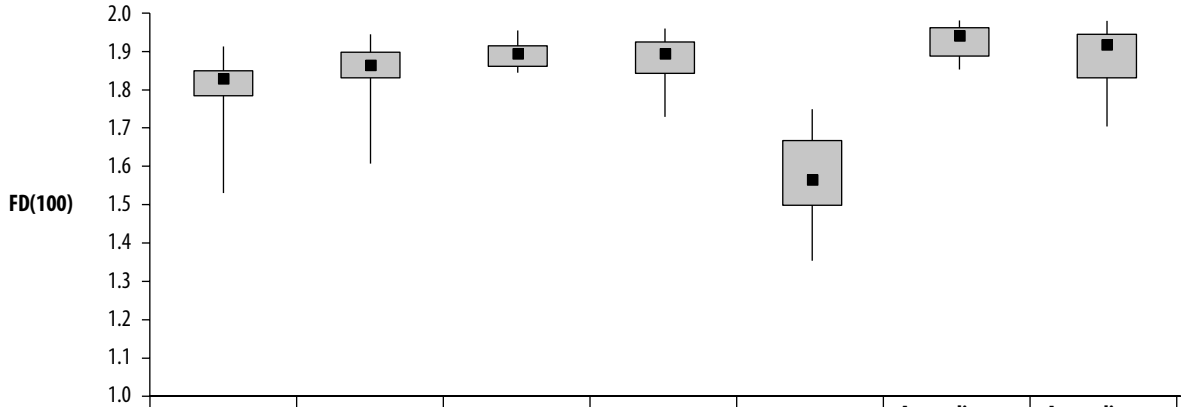


	Vermis – superior lobe Control group	Vermis – inferior lobe Control group	Vermis – superior lobe Cerebellar infarction	Vermis – inferior lobe Cerebellar infarction	Infarction focus Cerebellar infarction	Area adjacent to the focus (superior lobe) Cerebellar infarction	Area adjacent to the focus (inferior lobe) Cerebellar infarction
Percentile 75	1.850	1.898	1.915	1.924	1.668	1.962	1.944
Max	1.912	1.945	1.955	1.960	1.750	1.981	1.980
■ *Me*	1.829	1.863	1.894	1.893	1.565	1.941	1.917
Min	1.530	1.607	1.844	1.730	1.354	1.853	1.705
Percentile 25	1.784	1.831	1.861	1.842	1.498	1.887	1.832

Fig. 3. The distribution of the FD(100) values (FD of cerebellar tissue as a whole) in the control group vs. patients with acute cerebellar infarction. The FD(100) values of the superior, inferior vermal lobes, average vermal FD(100) and the FD(100) value of the areas adjacent to infarction foci in patients with acute cerebellar infarction were not significantly different from corresponding vermal FD values in the control group (p > 0.05). The mean FD(100) value of the cerebellar infarction areas was significantly decreased compared to value of average vermal FD(100) of control group (p < 0.01)

Areas adjacent to the foci of ischaemic infarction (areas of superior and inferior cerebellar lobes without visible structural changes, surrounding the focus of ischaemic infarction) were also assessed. FD(100) and FD(100–90) were measured in both areas – infarction foci and areas adjacent to the foci (on the same MR image).

Vermal FD values of patients with cerebellar infarction were compared with the corresponding vermal FD values of control group (superior and inferior lobes, respectively). FD values of cerebellar infarction foci were compared with the average vermal FD values in the control group. FD values of the areas adjacent to the foci were compared with the vermal FD values in the control group (superior and inferior lobes, respectively).

In our previous studies, we determined FD values for different cerebellar areas using fractal analysis of serial MR sections of the cerebellum of persons without structural brain changes (Maryenko and Stepanenko, 2020) and serial anatomical sections of cadaveric cerebella (Stepanenko and Maryenko, 2017). We have found that FD values determined in the vermis (midsagittal section) and parasagittal sections of the cerebellar hemispheres were not significantly different. Thus, we concluded that FD values should be equal or very close in all areas, including the vermis, in a cerebellum with no structural changes. To simplify the analysis, we decided to use one area as a checkpoint to compare FD values. Our reason to choose vermis as an area of study was the anatomical variability of cerebellum. The cerebellum width can be quite different, and therefore the MR sections located at the same distance from the midline may show different regions of the cerebellar hemispheres. Because of this, tomographic sections of the cerebellar hemispheres of different people are difficult to compare with each other. The midsagittal tomographic section visualizes the cerebellar vermis in all persons with typical brain anatomy (without cerebellar malformations or surgical removal of the cerebellum, etc.). Thus, we submitted a proposition to use cerebellar vermis as a checkpoint in the fractal analysis of the cerebellum: vermis area is simple and uniform in the identification; FD values determined in different regions of cerebellum (including foci of infarctions) may be compared to FD values determined in the vermis area.

Statistical data processing was performed using Excel 2010. The following values were calculated: the sample mean (M) and the standard error of the mean (m), the median with interquartile ranges including the median value (Me, percentile 50), the values of percentiles 25 and 75, the minimum (min) and the maximum (max) values. The normality of distribution was verified using the Shapiro–Wilk W test. The significance of statistical differences between the FD values of cerebella of patients with cerebellar infarction and cerebella of persons enrolled in the control group was assessed using the Mann–Whitney U test. The significance level for all results was set at $p < 0.05$.

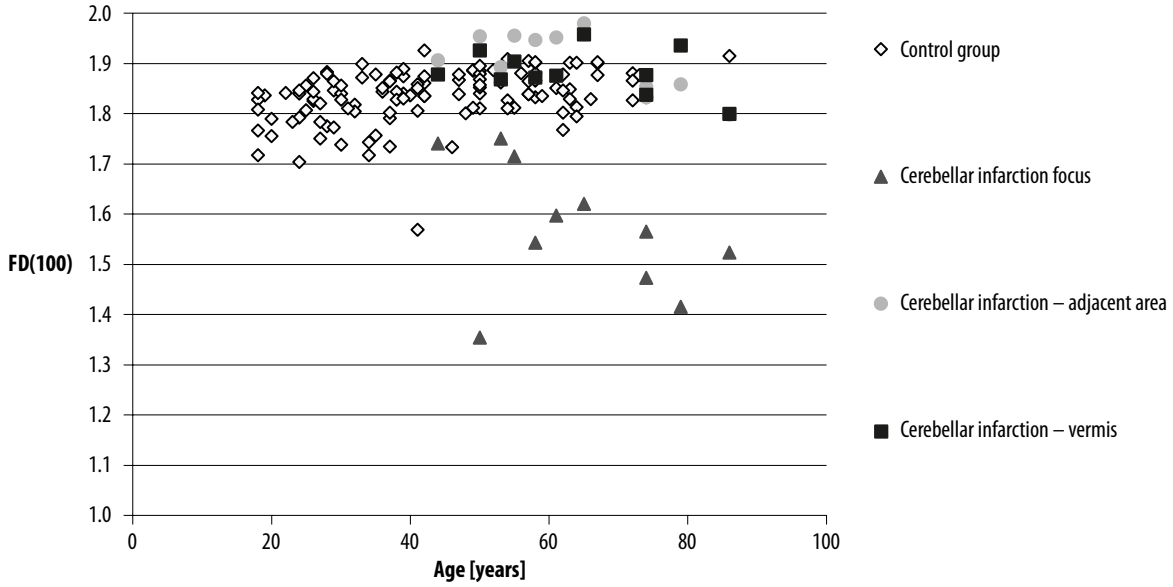


Fig. 4. The distribution of the average (superior and inferior lobes) FD(100) values (FD of cerebellar tissue as a whole) of the control group and patients with acute cerebellar infarction. The FD(100) values of the cerebellar infarction areas were lower than the FD(100) values of cerebellar vermis of control group (compared to persons with compatible age). The FD(100) values of cerebellar vermis and the areas adjacent to infarction foci in patients with acute cerebellar infarction were distributed close to FD(100) values in the control group

RESULTS

The foci of ischaemic infarction were found in different regions of cerebellum. The foci were isolated in the cerebellar hemispheres in 2 cases (of 11, or 18.2%), isolated in the paravermal area in 1 case (9.1%), in the hemispheres and paravermal area in 5 cases (45.5%), in the hemispheres, paravermal area and vermis in 3 cases (27.3%). The right-side location was found in 8 cases (72.7%), and the left-side location was found in 3 cases (27.3%).

The foci of the ischaemic infarction were present in different cerebellar lobules. An isolated damage of the upper paleocerebellar lobules (lobules I–V) was observed in 1 case (9.1%), an isolated damage of the neocerebellar lobules (lobules VI–VII) was found in 2 cases (18.2%), an isolated damage of the lower paleocerebellar lobules and archicerebellar lobules (lobules VIII–X) was detected in 1 case (9.2%). In some cases, combined damage of 2 and more cerebellar regions was found. Damage of the upper paleocerebellar and neocerebellar lobules (lobules I–VII) was found in 1 case (9.2%). Combined damage of the neocerebellar, lower paleocerebellar and archicerebellar lobules was found in 5 cases (45.5%). The subtotal damage of all lobules, including the upper paleocerebellar, neocerebellar, lower paleocerebellar and archicerebellar lobules (lobules I–X), was found in 1 case (9.2%).

The distribution of the FD(100) values in the control group and patients with acute cerebellar infarction is shown in Figs. 3 and 4.

The normality of FD(100) value distribution was verified using the Shapiro–Wilk *W* test. It was shown that vermal FD(100) values in the control group (FD(100) values for superior, inferior vermal lobes and their average value) were not normally distributed ($p < 0.05$); values were distributed with left skew and long left tale. But all FD(100) values of patients with cerebellar infarction were distributed normally ($p > 0.05$). Thus, the sample mean and the standard error of the mean values ($M \pm m$) were calculated in addition to the median with interquartile ranges, which are shown in Fig. 3.

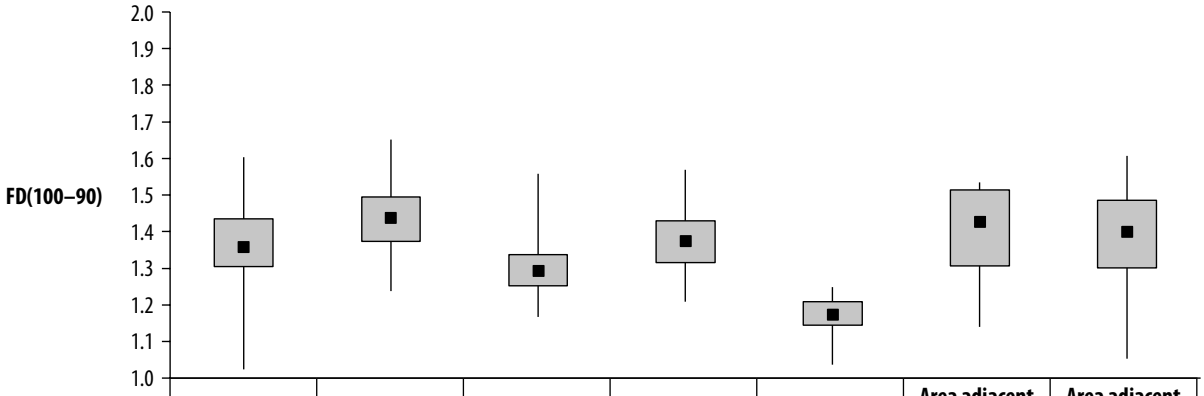
The mean vermal FD(100) value in the control group was 1.82 ± 0.004 for the superior lobe, 1.82 ± 0.002 for the inferior lobe, with the mean value of the average vermal FD(100) estimated at 1.83 ± 0.003.

The mean vermal FD(100) value in patients with acute cerebellar infarction was 1.89 ± 0.01 for the superior lobe, 1.88 ± 0.02 for the inferior lobe, with the mean value of the average vermal FD(100) estimated at 1.88 ± 0.01. The differences in these values with corresponding vermal FD values in the control group were not significant ($p > 0.05$).

The mean FD(100) value of the cerebellar infarction areas was 1.57 ± 0.04. This value was significantly decreased compared to the average vermal FD(100) in the control group ($p < 0.01$).

The mean FD(100) value in patients with acute cerebellar infarction was 1.92 ± 0.01 for the areas adjacent to infarction foci in the superior cerebellar lobe, 1.88 ± 0.02 for the inferior cerebellar lobe, with the mean value of the average FD(100) estimated at 1.90 ± 0.02. The differences between these values and corresponding vermal FD(100) values in the control group (FD(100) values of the superior, inferior lobes and the average vermal FD(100) value) were not significant ($p > 0.05$).

The distribution of FD(100–90) values in the control group and patients with acute cerebellar infarction is shown in Figs. 5 and 6.



	Vermis – superior lobe Control group	Vermis – inferior lobe Control group	Vermis – superior lobe Cerebellar infarction	Vermis – inferior lobe Cerebellar infarction	Infarction focus Cerebellar infarction	Area adjacent to the focus (superior lobe) Cerebellar infarction	Area adjacent to the focus (inferior lobe) Cerebellar infarction
Percentile 75	1.436	1.495	1.337	1.429	1.209	1.514	1.486
Max	1.603	1.651	1.557	1.569	1.249	1.535	1.607
■ *Me*	1.357	1.438	1.294	1.374	1.174	1.427	1.399
Min	1.024	1.238	1.168	1.208	1.036	1.140	1.053
Percentile 25	1.304	1.373	1.252	1.315	1.145	1.306	1.301

Fig. 5. The distribution of the FD(100–90) values (FD of outer linear contour) in the control group and patients with acute cerebellar infarction. The FD(100–90) values of the superior, inferior vermal lobes, average vermal FD(100–90) and the FD(100–90) value of the areas adjacent to infarction foci in patients with acute cerebellar infarction were not significantly different from corresponding vermal FD values in the control group (p > *0.05). The mean FD(100–90) value of the cerebellar infarction areas was significantly decreased compared to value of average vermal FD(100–90) in the control group* (p < *0.01)*

The normality of FD(100–90) values distribution was verified using the Shapiro–Wilk *W* test. It was shown that all FD(100–90) values in the control group and patients with cerebellar infarction were distributed normally ($p > 0.05$). Thus, the sample mean and the standard error of the mean values ($M \pm m$) were also calculated.

The mean vermal FD(100–90) value in the control group was 1.39 ± 0.013 for the superior lobe, 1.46 ± 0.008 for the inferior lobe, with the mean value of the average vermal FD(100–90) estimated at 1.42 ± 0.01.

The mean vermal FD(100–90) value in patients with acute cerebellar infarction was 1.31 ± 0.03 for the superior lobe, and 1.38 ± 0.03 for inferior lobe, with the mean value of the average vermal FD(100–90) estimated at 1.35 ± 0.03. The difference between these values and corresponding vermal FD values in the control group was not significant ($p > 0.05$).

The mean FD(100–90) value for the cerebellar infarction areas was 1.17 ± 0.02. This value was significantly decreased compared to the average vermal FD(100–90) in the control group ($p < 0.01$).

The mean FD(100–90) value in patients with acute cerebellar infarction was 1.39 ± 0.04 for the areas adjacent to infarction foci in the superior cerebellar lobe, and 1.39 ± 0.05 for the inferior cerebellar lobe, with the mean value of the average FD(100–90) estimated at 1.39 ± 0.04. The differences between these values and corresponding vermal FD(100–90) values in the control group [FD(100–90) values of the superior, inferior lobes and the average vermal FD(100–90) value] were not significant ($p > 0.05$).

DISCUSSION

Fractal analysis used in this study as the main method revealed statistically significant changes in the FD in the area of ischaemic cerebellar infarction. But is FD an appropriate indicator for quantifying the cerebellar structure?

FD allows to quantify the qualitative characteristics: degree of space filling and the degree of spatial complexity of structures analysed. The cerebellum has the most complex spatial configuration among all brain structures and it may be useful to provide quantitative assessment of the degree of cerebellar spatial complexity. Various pathological changes, including cerebellar infarctions, lead to the destruction of cerebellar tissue, which in turn alters the spatial configuration of cerebellar structures and possibly can be reflected in quantitative FD changes.

Studies involving fractal analysis of MR images of the cerebellum are scarce. Different modifications of fractal analysis methods were applied (two-dimensional, or 2D, and three-dimensional, or 3D). Different modifications of fractal analysis determine different values of FD: FD values determined by 2D modifications vary from 1 to 2, FD values determined by 3D modifications usually vary from 2 to 3.

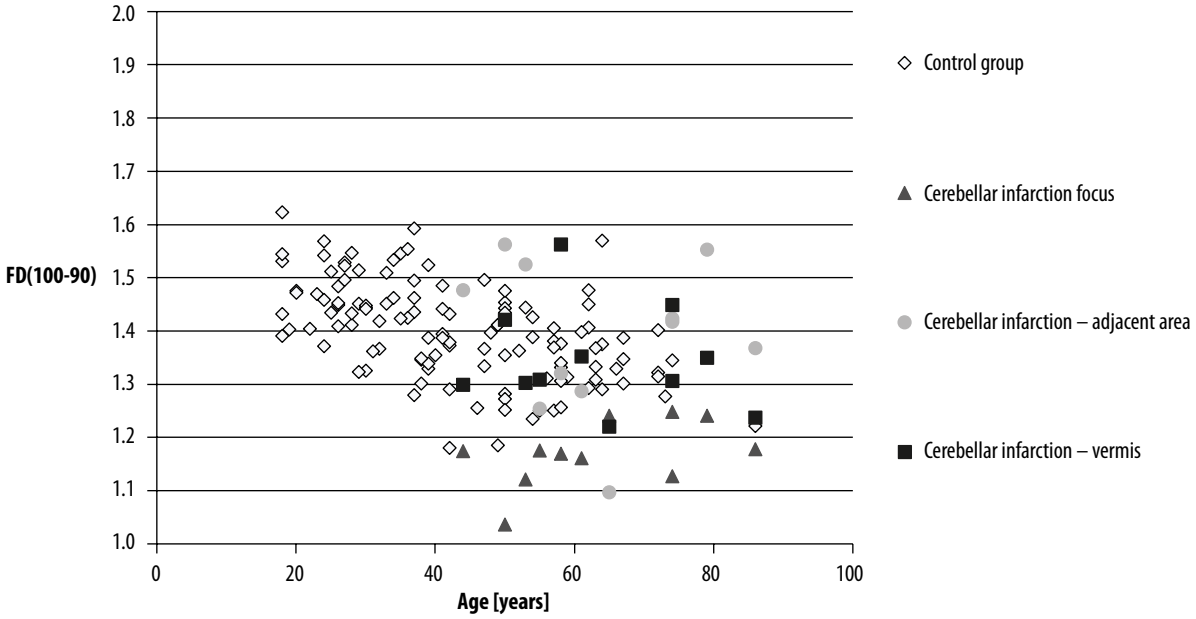


Fig. 6. The distribution of the average (superior and inferior lobes) FD(100–90) values (FD of outer linear contour) of the control group and the patients with acute cerebellar infarction. The FD(100–90) values of the cerebellar infarction areas were lower than the FD(100–90) values of cerebellar vermis in control group (compared to persons with compatible age). Most of the FD(100–90) values of cerebellar vermis and the areas adjacent to infarction foci in patients with acute cerebellar infarction were distributed close to FD(100–90) values in the control group

This feature explains differences in values obtained in the different studies.

2D modification of box counting method was used for the fractal analysis of cerebellar MR images in the studies of Akar et al. (2017, 2015). The mean FD value of the cerebellar white matter of healthy persons was 1.49 ± 0.06. These studies revealed significant changes of FD values in patients with Chiari malformation type I.

Pseudo-3D fractal analysis was applied by Liu et al. (2003), who described their method as a box counting. The mean FD value of the skeletonised images was 2.57 ± 0.01.

3D modification of the box counting method was used for the fractal analysis by Wu et al. (2010); the mean FD value was 2.2746 ± 0.0446 for the white matter and 2.5267 ± 0.0228 for the grey matter (Wu et al., 2010). This study revealed significant changes of FD values in patients with multiple system atrophy of the cerebellar type.

Therefore, fractal analysis and FD revealed some changes in cerebellar diseases and may be useful for quantitative studies of the cerebellum in other diseases.

However, cerebellar FD in acute cerebellar infarction has not been determined before. Thus, the FD values obtained in the present study may be taken into account during the assessment of cerebellar MRI for acute cerebellar infarction diagnosis. But what is the usefulness of the obtained FD values?

It was established that FD values for cerebellar tissue as a whole and FD of the outer contour of the cerebellar tissue in the area of cerebellar ischaemic infarction foci were significantly decreased compared to the control group. As it was noticed earlier, the foci of cerebellar ischaemic infarction may be isointense and therefore invisible (De Cocker et al., 2017); thus, additional methods of quantitative assessment may be useful for comprehensive studies of cerebellum for accurate diagnosis.

Identification of the borders between foci of infarction and adjacent areas is a valuable goal during diagnosis of cerebellar infarctions. In some cases, it is difficult to distinguish damaged and intact cerebellar tissue due to the high heterogeneity of cerebellar MR images (compared to the tissue of cerebral hemispheres and brainstem). We have found that there was no significant difference between FD values of cerebellar vermis, areas adjacent to infarction foci in patients with cerebellar infarction and corresponding vermal FD values in the control group. But the FD values of infarction areas were significantly different from all other FD values. Based on this fact, it is possible to identify the boundary between intact areas and foci of ischaemic cerebellar infarction using quantitative MRI assessment.

CONCLUSIONS

Fractal analysis of cerebellar MR images may be used as an additional quantitative tool to diagnose acute cerebellar infarction and to assess ischaemic foci to detect the boundaries between damaged and undamaged cerebellar tissue. Cerebellar FD values in acute cerebellar infarction, determined in the present study using pixel dilation method, may be used as diagnostic criteria in MRI.

Conflict of interest

The authors do not declare any financial or personal links with other persons or organisations that might adversely affect the content of the publication or claim any right to the publication.

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