The use of fractal analysis in medicine: A literature review

Zastosowanie analizy fraktalnej w medycynie – przegląd piśmiennictwa

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Abstract

In many areas of science, there is a need to assess the complexity of the analyzed objects. One instrument used to assess this complexity can be fractal analysis, which provides a quantitative measure in the form of a fractal dimension. A fractal dimension is a quantitative parameter used for measuring the complexity of the examined objects. Fractal analysis is the process of information processing, where the input data is an image. The generated information is stored in the form of numbers, an array of numbers, the decision of the text etc. The implementation of the image processing requires a computer system. In the publications of recent years, there is increasing interest in the potential use of fractal analysis in many fields of science, including medicine. Fractal analysis expands the capabilities of the diagnosis of systemic diseases, facilitating and accelerating their examination. In dentistry, the calculation of the fractal dimension can be a tool for early detection of a periapical lesion on the basic X-rays. Fractal analysis can also be a helpful indicator in predicting the primary stability of an implant. On the basis of the literature and own experience, the authors sum up the use of fractal analysis in accordance with current medical knowledge.

Key words: fractal analysis, fractal dimension, fractals, dentistry

Słowa kluczowe: analiza fraktalna, wymiar fraktalny, fraktale, stomatologia

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Many areas of science require the assessment of the degree of complexity of the analyzed areas. The tools used to assess this complexity include fractal analysis, which provides a quantitative measurement in the form of a fractal dimension.¹ The word *fractus* means “broken” or “partial”. Fractals are objects made of an irregular shape, characterized by self-similarity, which means that they look alike, regardless of the magnification used. A fractal dimension is a quantitative parameter used for measuring the complexity of the examined objects.²

Fractal analysis allows for a comparison between images for the presence of self-similarity.¹ Fractal analysis is the process of information processing, where the input data is in the form of an image. The generated information is stored as numbers, an array of numbers, the decision, the text and the like. The implementation of the image processing requires a computer system.

The quality of the compressed images becomes an important factor, and a considerable compression ratio determines the effective image compression. Compressing an image reduces the amount of redundant data from the image. The objective of quality measures is to reflect the approximate quality of the decoded images. The signal-to-noise ratio is a quality measure which is frequently used to measure the deviation between an original and a coded image.³

The most important feature of the fractal dimension lies in the possibility of being a fractional number. A computer representation of a radiological image is the image matrix, where shades of gray correspond to the elements with coordinates x and y , and create a more or less complex surface whose shape is far from being smooth. In the case of medical images, the values of the fractal dimension are in the range of $2.00 < D < 3.00$.⁴

Image analysis is used in areas such as materials science (evaluation of porosity, grain size), medicine, forensics (comparison of fingerprints), remote sensing (satellite and aerial images), quality control, automatic sorting of correspondence and others.⁵

Cardiological applications

The studies of Lawrence et al. showed the usefulness of fractal analysis in cardiology.⁶ They took advantage of the new marker Gel Point in patients after myocardial infarction and evaluated its therapeutic usefulness. Fractal analysis measured the changes in the microstructure of blood clots. They proved that this method makes it possible to evaluate the effectiveness of therapeutic interventions by measuring changes in the microstructure of the clot.⁶ Beckers et al. analyzed the nonlinear heart rate variability.⁷ They obtained information about the autonomic control of the heart rate. It turned out that the fractal dimension changes reflect physiological and pathophysiological changes taking place in the myocardium.⁷

Recent studies also suggest that fractal analysis describing the nonlinear dynamics of heart rhythm can provide stronger prognostic information than conventional indexes of heart rate variability. In particular, short-term fluctuation analysis can predict the risk of fatal cardiovascular events in different populations.⁸ This is also confirmed by the study by Tapanainen et al.⁹ Their prospective, multi-center study evaluated the prognostic significance of fractal analysis and traditional parameters of variability of the heart rate of patients after acute myocardial infarction. They showed that the fractal analysis of heart rate variability is a strong predictor of mortality among patients who survived acute myocardial infarction.⁹

Oncological applications

A recent study indicates that fractals can be used to diagnose cancerous lesions. This fact is not surprising, because, due to the irregular structure, cancer cells can be interpreted as fractals.

Fractal analysis is widely used in oncology. It enables objective classification of complex patterns of tumor tissue by examining the distribution of nuclei. Changes in fractal dimension are important in a system of classification of tumors. In addition, fractal analysis makes it possible to compare with each other the complexity of increase and intercellular interactions in tumor tissues.¹⁰

Daye et al. investigated the potential of mammographic parenchymal texture as a phenotypic imaging marker of endogenous hormonal exposure.¹¹ They concluded that mammographic texture patterns may reflect the effect of endogenous hormonal exposure on the breast tissue and may capture such effects beyond mammographic density. Differences in texture features between pre- and postmenopausal women are more pronounced in the cancer-affected population, which may be attributed to an increased association to breast cancer risk.¹¹

Zheng et al. have developed a fully automated software pipeline based on a novel lattice-based strategy to extract a range of parenchymal texture features from the entire breast region.¹² They conclude that a lattice-based strategy for mammographic texture analysis makes it possible to characterize the parenchymal pattern over the entire breast. As such, these features provide richer information compared to currently used descriptors and may ultimately improve breast cancer risk assessment.¹²

Heymans et al. examined the differences of micro vessels in malignant melanoma using the fractal method.¹³ They found that it is possible to distinguish the quantitative profile of blood vessels. They have demonstrated the usefulness of the above method as a predictor of disease progression.

An analysis of fractal dimensions is ancillary used in setting a definitive diagnosis. It helps to distinguish the normal structure images of histological tissue from the tissue with characteristics of malignancy.¹⁴

Use in ophthalmology

Available publications indicate the particular utility of fractal analysis in the examination of the surface of the retina. The research of Frydkjaer-Oslen et al. has shown the relationship between early vascular changes and neurogenic changes in patients with type 2 diabetes.¹⁵ They considered retinal fractal analysis an effective method for early identification of neurodegenerative disorders.¹⁵ Fractal analysis is also used in studies of macular vessels. It allows for reliable, accurate analysis of the structure of the retina in macular degenerations – diabetic maculopathy.¹⁶

A Talu study confirmed the multifractal nature of the network of tiny blood vessels in the retina.¹⁷ Their analysis allows for a non-invasive way to measure various aspects of the topography of the blood vessels. He showed that image analysis can be used as a potential marker for early detection of diseases of the retina.

Pathological lesions in the microcirculation of the retina may reflect microvascular processes in the brain. Quantitative analysis of the small blood vessels on the capillary level opens a new era of microcirculation research in small cerebrovascular diseases.¹⁸

Use in radiology

The mathematical nature of fractal analysis is widely used in radiology. There are two types of image compression: 'Lossless' compression and Lossy compression. 'Lossy' compression always produces an image which is not an exact copy of the original data. It removes redundancy and creates an approximation of the original. Lossy compression are required to apply on those data where reproduction of original data is not required.

The following diagrams show the processing of radiological images for the purpose of fractal analysis proposed by White.¹⁹ Processing of radiological images deliver a binary image.

A fractal dimension using e.g. the method of box-counting can be calculated from a binary image.

These studies suggest that the bone tissue is of a fractal construction. Bone strength depends on the mass and structure of bone tissue. Research by Sindeaux et al. confirmed that the fractal dimension values of cortical bone are lower in women with osteoporosis.²⁰ They proved that fractal analysis can be considered a pre-test to measure bone density, normally used in the diagnosis of osteoporosis.²⁰ The study by Bianciardi et al. shows that the results obtained from the analysis of the fractal images of X-rays of bones directly correlate with the results obtained with ultrasound methods in patients suffering from osteoporosis.²¹ Attempts have been made to develop an automatic testing system of trabecular bone using fractal analysis. Selected areas were tested in tension and compression condition. Preliminary results show that the above method may have significant clinical application.²²

Luo et al. transformed 3D images of bones obtained through CT to flat, 2-dimensional X-ray images. Using a fractal analysis of the obtained radiographs, they showed that using this method can evaluate the architecture of bone tissue.²³ They proved that the fractal dimension increases as bone density decreases. Fractal analysis of conventional radiographs may become an alternative to costly and specialized imaging tests.^{23,24}

The use in dentistry

Currently, the literature provides relatively few reports on the use of fractal analysis in dentistry. Its use is based on the finding that bone tissue has a fractal construction. Thus the calculation of the fractal dimension can be a tool for the early detection of periapical lesion on basic X-rays. This hypothesis was confirmed using artificial, chemically-generated lesions.²⁵ Fractal analysis can also be used to evaluate the periapical area after endodontic treatment.²⁶

Sobolewska-Siemieniuk et al. assessed the quantitative changes in the bone tissue regions of reincluded teeth.⁴

Fig. 1. Processing radiological images using the S.C. White method¹⁹

They found that, in the case of reincluded teeth, bone tissue of the alveolar part exhibits a high degree of irregularity, and fractal analysis expands the evaluation of radiological images.⁴ Studies also suggest that comparing the fractal dimension is a promising tool for detecting changes in the bone tissue associated with the patients receiving bisphosphonates.²⁷

Kąkolewska's research aimed to determine whether there is a relationship between the dimension of implant stability and a fractal dimension of radiological images of bone tissue.²⁸ She obtained a correlation between the implants primary stability and the fractal dimension, making it possible to draw the conclusion that the smaller the fractal dimension of the bone, the higher the primary stability obtained can be. The results of this study show that the fractal dimension can be a helpful indicator in predicting the primary stability of an implant.²⁸

Kozakiewicz et al. analyzed how different implanted materials affected the healing of alveolar defects using fractal dimension computation taken from radiographs.²⁹ Studies suggest that a fractal dimension varied with different biomaterials throughout the time of observation and reflected the individual character of bone remodeling. Visible changes in the structure emerge earlier in places of implantation of bovine bone mineral and beta-tricalcium phosphate in comparison to the group of biomaterials constituting more stable patterns of radiotexture: algae derived hydroxyapatite, biological active glass, synthetic hydroxyapatite. The authors conclude that fractal techniques can be a descriptor of bone substitutes.²⁹

However, an examination of the fractal dimension is not a suitable method to be used in each case. In order to obtain reliable data, the image resolution and the exposure time must be appropriately chosen.³⁰

Summary

The publications of recent years show increasing interest in the potential use of fractal analysis in many fields of science, including medicine. Fractal analysis expands the diagnostic capabilities regarding systemic diseases by facilitating and accelerating their diagnosis. However, fractal analysis also has its drawbacks as it is sensitive to image processing and the phenomenon of noise. This suggests the desirability of undertaking further research into the use of fractal analysis to be used in medicine.

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