FRACTAL ANALYSIS OF MANDIBULAR BONE ARCHITECTURE: A NOVEL CONTOUR SMOOTHING ALGORITHM FOR WHOLE-SLICE QUANTIFICATION

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ABSTRACT

Background. The study of mandibular bone architecture is crucial for understanding remodeling, osteogenesis, and resorption processes under normal and pathological conditions. Traditional morphometric methods often rely on limited regions of interest and do not account for the hierarchical self-organization of bone tissue or the complexity of its surface configuration. There is a need for a modified fractal analysis technique focused on assessing the surface complexity of the entire bone slice rather than just its volume filling.

Aim. To develop an original modification of the contour smoothing method for studying mandibular bone architecture on computed tomography images, enabling the analysis of whole bone slices independent of region of interest selection.

Materials & Methods. The methodological study utilized digital cone-beam computed tomography images of the mandibular bone. The fractal dimension was calculated using a custom "contour smoothing" algorithm across six stages with increasing smoothing radii (2, 4, 8, 16, 32 pixels). Statistical data processing included the calculation of linear regression and the coefficient of determination to assess fractal properties; calculations and graphical visualization were performed using Excel 2016 (Microsoft, USA). The study was conducted as part of the initiative research project "Development of clinical and morphological methods of researching the structures of the human body" (State Registration No.0123U100367, 2023–2025).

Research Ethics. The study was approved by the Ethics and Bioethics Committee of Kharkiv National Medical University.

Results. The analysis revealed that the dependence of variables remained linear during the first four stages (smoothing radii 2–8 pixels). At these stages, the bone trabeculae demonstrated monofractal properties. At stages 5 and 6 (radii 16–32 pixels), linearity was disrupted due to the loss of cortical plate contours, leading to a decrease in the approximation coefficient. Consequently, the optimal scaling range for the mandibular bone was determined to be stages 1–4.

Conclusions. The developed contour smoothing algorithm effectively quantifies the complexity of endosteal surface configurations and internal bone contours. This method offers a robust, resolution-independent approach for evaluating bone remodeling and resorption activity, suitable for diagnosing osteoporosis and assessing implant integration.

Keywords: *theoretical and experimental medicine, mandible, bone architecture, morphometry, computed tomography, fractal dimension.*

Introduction

The investigation of mandibular bone architecture is crucial for understanding the processes of remodeling, osteogenesis, and resorption that occur both in healthy conditions and in pathological states, such as osteoporosis, inflammatory processes, trauma, or following dental interventions. The assessment of bone microstructure on radiographic and Computed Tomography (CT) images allows for the non-invasive investigation of its morphofunctional state, the detection of early signs of remodeling disorders, and the prediction of fracture risks [1–4].

Current methods for studying bone architecture include traditional morphometric approaches,

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specifically the determination of various indices such as bone volume density, bone surface density, trabecular plate number, trabecular thickness, trabecular separation, and the degree of anisotropy [5–7]. However, these methods often present several limitations: they require precise Region Of Interest (ROI) selection, rely on two-dimensional projections of complex three-dimensional structures, and fail to account for the hierarchical self-organization of bone tissue. Furthermore, classical morphometric parameters do not adequately reflect the complexity and irregularity of the bone surface architecture, which is significant for analyzing bone remodeling.

In this context, the application of fractal analysis represents a promising direction for the quantitative assessment of bone tissue morphological organization [8]. Fractal dimension – a parameter determined via fractal analysis – reflects the degree of an object's structural complexity and its space-filling capacity. The more structural elements an object possesses (in the case of bone tissue, bone trabeculae) and the more complex their spatial configuration, the greater the degree of space filling by bone trabeculae, and consequently, the higher the fractal dimension of the trabecular (cancellous) bone as a whole [8–10]. Typically, fractal dimension is used as a complementary morphometric criterion for assessing trabecular bone status, particularly in osteoporosis diagnosis, due to its sensitivity to the reduction in space filling by bone tissue observed in this condition [11; 12]. It has been demonstrated that a decrease in fractal dimension on radiographs or CT images correlates with reduced bone mass and deterioration of trabecular microarchitecture [10; 13].

Fractal analysis has been employed in numerous studies regarding the mandible, specifically for assessing bone tissue in healthy patients [14] and determining sexual dimorphism [15], evaluating changes in osteoporosis [16; 17], assessing bone status prior to implantation [18] and during healing after orthognathic surgery [19], as well as in renal transplant recipients [20] and patients undergoing systemic glucocorticoid therapy [21].

Nevertheless, existing methodologies for bone fractal analysis have significant limitations. They are typically applied to limited ROI and are sensitive to image resolution, size, and segmentation parameters [14]. Moreover, the derived fractal characteristics primarily reflect the degree of space filling by bone tissue rather than the complexity of its surface configuration [22]. It has been established that with the intensification of resorption and bone remodeling, the micro-relief of trabecular surfaces and the endosteal contour changes, becoming more tortuous and complex [23]. Therefore, the quantitative assessment of bone surface configuration is essential for detecting morphological signs of remodeling, a task that traditional fractal algorithms cannot fully realize.

Given this, a need arises to develop a modified fractal analysis methodology focused on assessing the complexity of the bone tissue surface rather than solely its volumetric filling. In our study, we developed an original algorithm for investigating mandibular bone architecture on CT images based on the contour smoothing method, which we previously developed for the fractal analysis of the pial surface configuration of the cerebral cortex [24].

The **aim** of the study was to develop an original modification of the contour smoothing method for investigating mandibular bone architecture on computed tomography images. The specific objective of this research stage is to calibrate the method and determine the optimal algorithm parameters for fractal analysis, rather than to perform clinical diagnostics on a population.

Material and Methods

To develop and calibrate the fractal analysis methodology, digital cone-beam computed tomography images of the mandible of a healthy volunteer (34 years old, female) were used.

Axial tomographic images were selected (*Fig. 1, A*). The apices of the tooth roots served as anatomical landmarks: the tomographic slices were located immediately below the deepest points of the tooth roots in the mandibular bone. Digital images were selected using the Ez3D2009 software (E-WOO Technology Co., Ltd., Yongin, Republic of Korea).

Further image segmentation and analysis were performed using the Adobe Photoshop CS5 graphics editor (Adobe Systems Inc., San Jose, CA, USA). Selected digital images in DICOM format were transferred to a pre-created "blank" JPEG image with dimensions of 720×720 pixels and a resolution of 72 pixels per inch. The absolute scale was 1 mm = 7.5 pixels.

Next, image segmentation was performed: using the "Threshold" tool, the image was converted to binary format (*Fig. 1, B*). An empirical pixel brightness threshold value of 110 was used: all pixels with a brightness value greater than the threshold were colored white (brightness value 255), and pixels with a brightness value less than the threshold were colored black (brightness value 0).

The threshold value of 110 was selected based on the histogram analysis of the grayscale image, corresponding to the valley between the peaks of soft tissues/marrow and calcified bone tissue. A global threshold was selected for segmentation. As a result of this binarization, bone tissue (including the compact substance of the cortical plate and the cancellous substance inside the mandible) was colored white, while surrounding structures and cavities between bone trabeculae were colored black (*Fig. 1, B*). Following binarization, color inversion was performed, resulting in bone structures becoming black, and the background and cavities within the bone becoming white (*Fig. 1, C*).

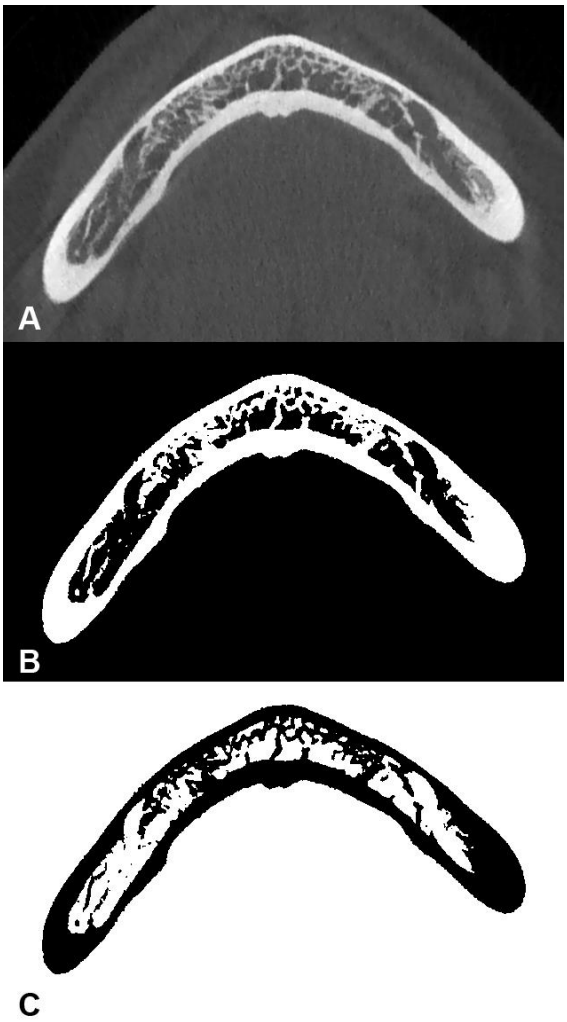

Fig. 1. Computed tomography image of the mandible and its segmentation:
A – original CT image,
B – segmentation (binarization) using the "Threshold" tool,
C – inversion of the binary image.

Subsequently, the actual fractal analysis was performed using the contour smoothing method. Since this technique was previously employed by the authors to investigate the external surfaces of anatomical structures, it was modified for the study of bone (and internal surfaces – contours of cavities within it). To outline the external and internal surfaces of the mandibular bone tissue, the "Selection" tool of the graphics editor was used; all black pixels were automatically selected, creating a closed selection area corresponding to the silhouette of the bone tissue in the image. The contour of the selected area corresponded to the external and internal surfaces of the bone (*Fig. 2, A*).

To develop the methodology for bone tissue investigation, six stages of Fractal Analysis (FA) were initially used, consistent with the original methodology. At the *first FA stage*, no contour smoothing was performed. After outlining the contour, its length (perimeter, P1) was determined. Starting from the *second FA stage*, the contour smoothing procedure was performed: at the second stage, the contour smoothing radius (R2) was 2 pixels; at the third (R3) – 4 pixels; fourth (R4) – 8 pixels; fifth (R5) – 16 pixels; and sixth (R6) – 32 pixels. Considering that no smoothing was performed at the first stage, the smoothing radius for the first FA stage (R1) was taken as unity (1) for further calculations.

The smoothing procedure stepwise removes protrusions or invaginations from the contour with a radius of curvature smaller than the smoothing radius. Thus, at the initial stages, the contours of small bone trabeculae and small protrusions on them are removed; subsequently, the contours of larger bone trabeculae are removed (*Fig. 2, A–C*). As a result, at the *fourth FA stage*, the contours of the cortical plates remain, while the contours of cancellous bone trabeculae are mostly absent, persisting only in areas of their dense arrangement (*Fig. 2, D*). At the *fifth FA stage*, smoothing led to partial removal of cortical plate contours (since their thickness was less than the set smoothing radius – 16 pixels) (*Fig. 2, E*), and at the sixth FA stage, the contour was represented by only a few areas where the bone as a whole had a thickness slightly greater than the set smoothing radius – 32 pixels (*Fig. 2, F*).

At each FA stage, the contour length P (P1–P6) was measured, and the data were recorded (*Table 1*). Mathematical modeling and statistical processing were performed using Excel 2016 (Microsoft Corp., Redmond, WA, USA). For the analysis, two values were calculated: the natural logarithm

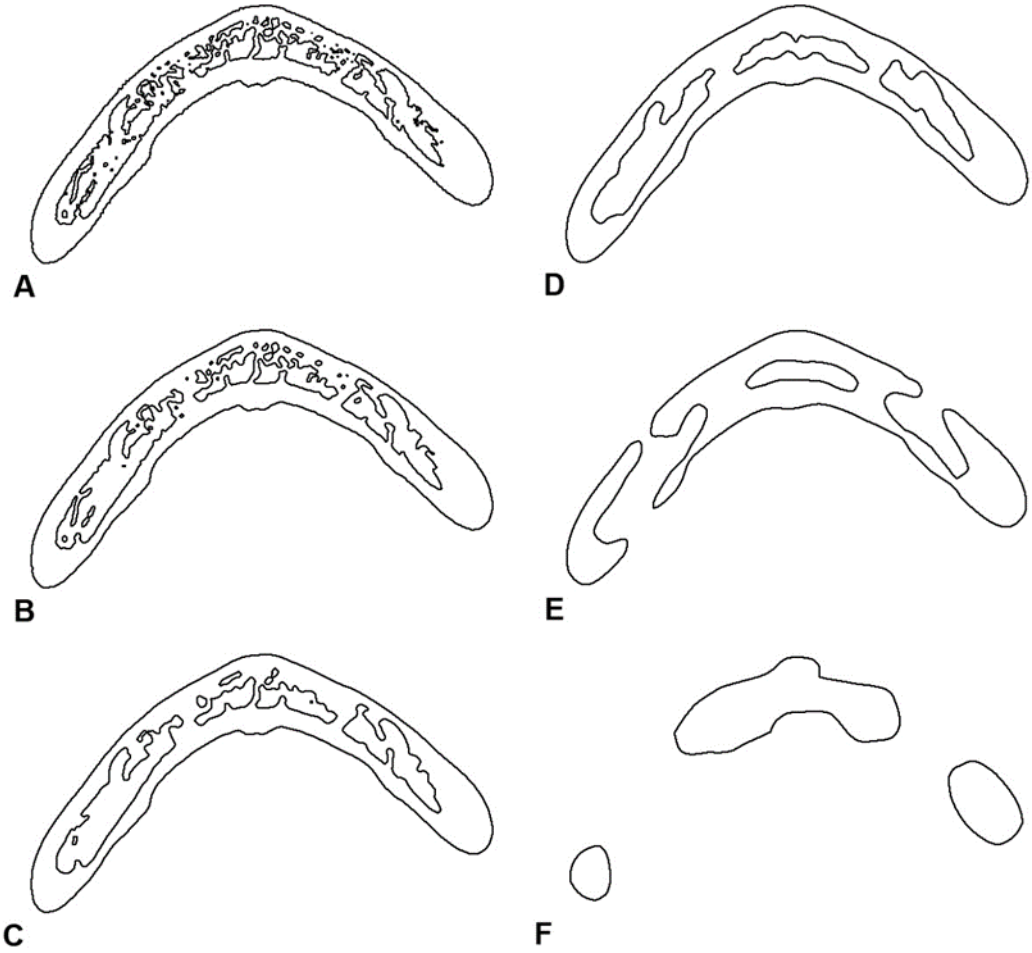

Fig. 2. Fractal analysis (FA) of mandibular bone tissue contours using the contour smoothing method; the contour is outlined in black for clarity.

A – 1st FA stage, contour without smoothing;
B – 2nd FA stage, contour smoothing with a radius of 2 pixels;
C – 3rd FA stage, contour smoothing with a radius of 4 pixels;
D – 4th FA stage, contour smoothing with a radius of 8 pixels;
E – 5th FA stage, contour smoothing with a radius of 16 pixels;
F – 6th FA stage, contour smoothing with a radius of 32 pixels

of the reciprocal of the smoothing radius, *ln(1/R)*, and *ln(P/R)*. Based on these values, linear regression analysis was performed using the least squares method to derive the equation $y = bx + a$. In this equation, the independent variable x corresponds to *ln(1/R)*, the dependent variable y corresponds to *ln(P/R)*, a is the intercept coefficient, and b is the slope coefficient (*Fig. 3*). The fractal dimension of the investigated structure is defined as the slope coefficient b.

The quality of the linear model fit was evaluated using the coefficient of determination (R2). The linearity of the relationship was considered sufficient at R2 values close to 1.0 (R2 > 0.99), which served as the criterion for selecting the optimal range of smoothing scales demonstrating monofractal properties.

Research Ethics

The research protocol was approved by the Ethics and Bioethics Committee of Kharkiv National Medical University (Protocol No.5 dated February 01, 2023). The study was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later

Table 1. Fractal analysis using the contour smoothing method: data for fractal dimension calculation

FA stage	Smoothing radius, R	1/R	ln(1/R)	The contour length (perimeter, P)	P/R	ln(P/R)
1	1*	1.0000	0.000	1981	1981.0	7.591
2	2	0.5000	–0.693	1747	873.5	6.773
3	4	0.2500	–1.386	1606	401.5	5.995
4	8	0.1250	–2.079	1564	195.5	5.276
5	16	0.0625	–2.773	2167	135.4	4.909
6	32	0.0313	–3.466	1184	37.0	3.611

Note: * – since no contour smoothing is performed at the first stage, the value of R1 is taken as unity for calculations.

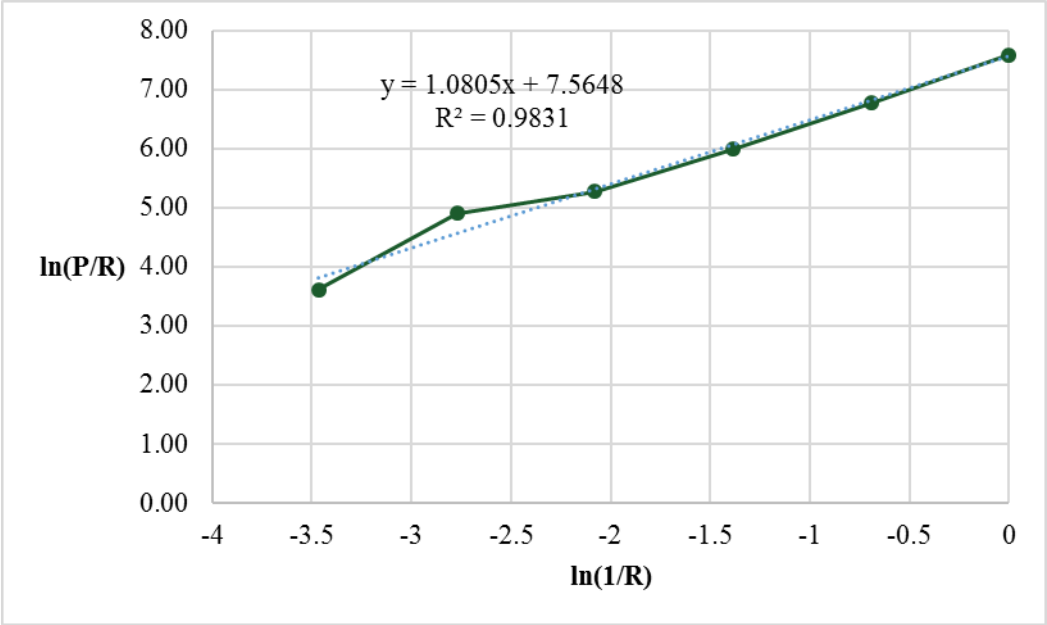

Fig. 3. Calculation of the linear regression equation characterizing the dependence of ln(P/R) on ln(1/R): six FA stages

amendments. Written informed consent was obtained from the patient for the use of their medical data (computed tomography images) for scientific purposes. All data were anonymized prior to analysis to ensure confidentiality.

Results

A critical step in FA is selecting the range of scales used to calculate the fractal dimension. It is necessary to determine the range where the investigated object exhibits fractal properties, which manifests as a linear dependence between the scaling coefficient (in this case, *ln(1/R)*) and the quantitative parameter characterizing the structure's size at different FA stages (*ln(P/R)*).

As shown in the graph in *Fig. 3*, from the first to the fourth stage of fractal analysis, the dependence of *ln(P/R)* on *ln(1/R)* is linear. This indicates the invariance of the bone structural organization across different scales and a consistent change in the configuration of bone trabeculae during contour smoothing. Such a property is characteristic of monofractal structures; precisely within this

range of FA stages, the bone trabeculae demonstrate fractal properties.

However, at the 5th and 6th FA stages, the linearity of the relationship between the two variables is disrupted. Furthermore, the smoothing process at these stages leads to the disappearance of cortical plate contours (*5th FA stage, Fig. 2, E*) and entire fragments of the mandible (*Fig. 2, F*).

To evaluate how well the calculated linear regression equation fits the graph characterizing the dependence of the two variables *ln(P/R)* and *ln(1/R)*, the coefficient of determination (R2) was used. When using all six FA stages, the R2 value is 0.9831 (*Fig. 3*), which is lowered due to the violation of linearity at the 5th and 6th stages. Consequently, it is advisable to exclude these stages when studying the mandibular bone and to retain only those stages where the structures demonstrate a monofractal character of organization. This corresponds to the linearity of the relationship between the variables – specifically, the first four stages of FA (*Fig. 4*).

When using data from the first four FA stages for calculations (*Fig. 4*), the R2 value is 0.9992, indicating a practically functional linear relationship between the two investigated variables, *ln(P/R)* and *ln(1/R)*.

Thus, the range of FA stages to be used for determining the fractal dimension includes the first through fourth stages. These stages utilize small smoothing radius values (2–8 pixels), which allows for the stepwise removal of bone trabeculae contours without removing the contours of cortical plates and the bone as a whole, as occurs at the 5th and 6th FA stages when using large smoothing radii (16 and 32 pixels). This range covers the stages where the surface configuration of the mandibular bone exhibits a monofractal character; these precise stages allow for the accurate determination of the fractal dimension of the investigated structure. The linear regression equation in *Fig. 4*, calculated based on the results of four FA stages, is *y = 1.1144x + 7.5674*. Therefore, the fractal dimension of the mandibular bone surface contours (Hausdorff dimension) in this example equals 1.1144.

Discussion

When performing fractal analysis of bone tissue and other natural structures, various FA methods can be employed, determining different types of fractal dimensions. The most common method used in morphological studies is the box-counting method [25] and its variants, such as the tile-counting method, which is used for investigating bone trabeculae [14; 19]. This method determines the Minkowski dimension, which primarily characterizes the capacitive properties and the degree of space filling by the investigated object.

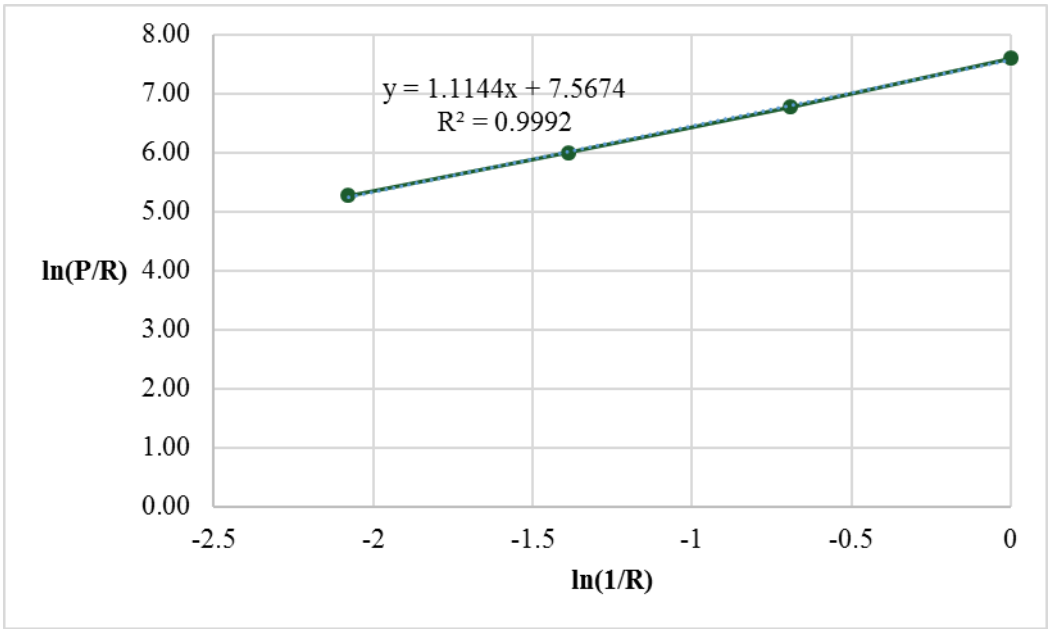

Fig. 4. Calculation of the linear regression equation characterizing the dependence of ln(P/R) on ln(1/R): four FA stages.
The fractal dimension equals 1.1144.

In histomorphometric studies of bone trabeculae, methods such as box-counting (used to determine the Kolmogorov dimension), dilation (for the Minkowski-Bouligand dimension), and sandbox (for the "mass-radius" dimension) have been utilized [22]. In their classical variations, these techniques predominantly characterize the space filling by trabeculae rather than surface characteristics.

To characterize the surface properties of bone trabeculae, modifications of the box-counting method with specific image preprocessing have been previously used. For instance, a modification of the tile-counting method additionally employed contour outlining, allowing for the determination of its Minkowski dimension [14]. The box-counting method with contour outlining has also been used to assess implant surface roughness to predict osseointegration [26]. However, the use of the Minkowski dimension determined via box-counting (and its variants) with pre-outlined structure contours has limitations: such algorithms are dependent on image resolution and size, the thickness of the outline used, and the segmentation algorithm [27].

In view of this, the Hausdorff dimension, determined via the contour smoothing method, is a more appropriate parameter for assessing surface contour configuration. In our previous research, we established that this dimension is independent of image scale, size, resolution, and contour thickness [27]. Therefore, the use of the contour smoothing method for investigating bone tissue surfaces may be more informative and technically robust compared to existing methods. We previously used this FA method to assess the configuration of external contours of anatomical structures and artificial fractals [24; 27]. In the present work, this method demonstrated its capability to determine the fractal dimension of internal structure contours – specifically, the contours of the endosteum lining the bone cavities. We hypothesize that in healthy bone, the trabecular network is dense and complex, resulting in a higher fractal dimension. In osteoporosis, the loss of trabeculae simplifies the contour, likely leading to a decrease in the Hausdorff dimension.

Another challenge in bone fractal analysis is the selection of ROI. Typically, small square areas corresponding to the cancellous bone are analyzed rather than the bone as a whole. Fractal dimension values can vary depending on both the size of the digital image area used for analysis and its localization [14; 21]. Performing fractal analysis on the entire mandibular tomographic slice, as implemented in our algorithm, allows for the assessment of the whole bone state and mitigates errors caused by ROI selection bias.

The main limitations of the proposed methodology include the ability to investigate only closed contours, which may restrict the use of this algorithm when studying cropped image fragments of bone tissue. Another important factor is the selection of the FA stage range (the range of smoothing radii where the *ln(P/R)* vs. *ln(1/R)* dependence is strictly linear) when using CT images with different scales and resolutions. Future studies should address the influence of metal artifacts on contour extraction.

The proposed algorithm for fractal analysis of mandibular bone architecture using the modified contour smoothing method can be used to assess bone remodeling and resorption activity during healing after implant placement, fracture healing, or following mandibular surgery. Additionally, this technique can be employed to evaluate the complexity of bone architecture for assessing changes in osteoporosis and predicting implant integration into the mandible.

Conclusions

1. The original fractal analysis algorithm using the contour smoothing method, described in this study, allows for the quantitative assessment of the configuration complexity of internal endosteal surface contours within the mandibular bone.

2. The surface contours of the mandibular bone tissue demonstrate monofractal properties within a smoothing radius range of 2 to 8 pixels; consequently, the fractal analysis algorithm was modified and restricted to four stages with small smoothing radius values.

3. The advantages of the proposed algorithm include the ability to analyze mandibular bone slices in their entirety, independence from the size and location of a selected ROI, and independence from image size and resolution.

4. The proposed fractal analysis algorithm can be used for diagnostic purposes to assess the activity of remodeling and resorption of mandibular bone tissue on computed tomography images.

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Authors' Contributions

Contribution / Authors	A	B	C	D	E	F
Stepanenko O.Yu.	+	+		+	+	+
Maryenko N.I.	+	+	+		+	+

Notes: A – concept; B – design; C – data collection; D – statistical processing and interpretation of data;
E – writing or critical editing of the article;
F – approval of the final version for publication and agreement to be responsible for all aspects of the work.

Declarations

Conflict of interest is absent.

All authors have given their consent to the publication of the article, to the processing and publication of their personal data.

The authors of the manuscript state that in the process of conducting research, preparing, and editing this manuscript, they did not use any generative AI tools or services to perform any of the tasks listed in the Generative AI Delegation Taxonomy (GAIDeT, 2025). All stages of work (from the development of the research concept to the final editing) were carried out without the involvement of generative artificial intelligence, exclusively by the authors.

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