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The Role of Fractal Analysis in Evaluating Bone Structure in Pediatric Dentistry

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ABSTRACT: Fractal analysis (FA) is an emerging quantitative method used to assess mandibular trabecular architecture in pediatric dentistry. While bone mineral density (BMD) measurements such as DEXA provide limited information about bone quality, fractal dimension (FD) analysis offers additional insight into microstructural complexity using routine dental radiographs.

Current evidence shows that FD values reflect developmental, metabolic, and functional changes in children. Studies report preserved mandibular FD in Familial Mediterranean Fever and MIH, age-related increases in FD during normal growth, reduced FD in newly diagnosed celiac disease with improvement after a gluten-free diet, altered trabecular patterns in amelogenesis imperfecta, and region-specific FD increases in pediatric bruxism due to mechanical loading. Children with previous chemotherapy generally exhibit stable FD values.

Overall, FA represents a non-invasive, accessible, and cost-effective adjunct for evaluating pediatric mandibular bone microarchitecture. Despite methodological limitations, standardized protocols and longitudinal research are needed to optimize its clinical utility.

KEYWORDS: Bone mineral density, Fractal analysis, Pediatric Dentistry

1. ASSESSMENT OF BONE MINERAL DENSITY (BMD) IN CHILDREN AND ADOLESCENTS

Bone is an energetically dynamic connective tissue responsible for providing structural integrity, facilitating movement, and shielding essential organs. Architecturally, it is categorized into two main subtypes. Cortical bone constitutes approximately 80% of the body's total bone mass and exhibits significantly greater tensile strength than its trabecular counterpart. It offers robust resistance against bending, twisting, and compressive forces, possessing a higher density with a minimal role in metabolism.

Conversely, trabecular bone makes up only 20% of the total bone but presents a surface-to-volume ratio ten times greater than that of cortical bone. This feature allows it to respond to shifts in load up to eight times faster, rendering it considerably more metabolically active. Bone undergoes continuous remodeling in direct response to both applied stress and systemic hormonal regulation. Under conditions where stress is diminished, the process of bone resorption accelerates, consequently resulting in net bone loss. (Cowan et al. 2024)Kemiklerin yapısal bütünlüğüne birçok faktör katkıda bulunur: toplam kemik kütlesi, kemik geometrisi ve onu oluşturan dokunun özellikleri. Kemik yapısal bütünlüğüne katkıda bulunan faktörlerin çokluğuna rağmen, altın standart, kemik kalitesi ve mimarisi hakkında herhangi bir bilgi olmaksızın yalnızca kantitatif kemik parametreleri sağlayan çift enerjili X-ışını absorpsiyometri (DEXA) kullanılarak yapılan "Kemik Mineral Yoğunluğu(KMY)" ölçümüdür.(Martineau ve Leslie 2017) Bu yöntem, çocuklar için güvenli ve etkili bir ölçüm tekniğidir.(Christofaro ve ark. 2022)

Bone development is a highly dynamic continuum that commences at birth and persists until the completion of adolescence. Throughout this period, there is a progressive increase in both the length and the density of the skeletal structure. The successful acquisition of adequate bone mass during the childhood and adolescent years is a crucial factor in mitigating the lifetime risk of developing osteoporosis.

In pediatric assessments, Bone Mineral Density (BMD) measurements are evaluated by comparison with reference values specifically established for the patient's age and gender. A BMD result that falls below the age-appropriate normal limits is diagnosed as low bone density or osteopenia, which can be an important predictor of future osteoporosis vulnerability. (Crabtree et al. 2017)

Table 1 presents a classification of the methodologies utilized to evaluate bone mineral density, grouping them into three principal categories. (Emer et al. 2016)

Table 1. Methodologies Employed for the Assessment of Bone Mineral Density

Radiological Methods	Photon Absorptiometry Techniques	Other Methods
Standard conventional radiography Bone radiometry Radiologic photodensitometry Digital image processing (DIP) Quantitative computed tomography (QCT)	Single photon absorptiometry (SPA) Dual photon absorptiometry (DPA) Single-energy X-ray absorptiometry Dual-energy X-ray absorptiometry (DEXA / DXA)	• Quantitative ultrasonography (QUS) • Neutron activation analysis • Magnetic resonance imaging (MRI) • Lateral scanning radiography • Bone biopsy

Factors Influencing Bone Mineral Density in Children (Kalkwarf et al. 2007, Weaver et al. 2016)

The development of optimal Bone Mineral Density (BMD) in the pediatric age group is multifactorial, shaped by the interaction of several key elements:

1. Genetic Predisposition : BMD levels are significantly determined by an individual's genetic background. Children who have a family history of osteoporosis are deemed to be at an elevated risk for reduced bone mineral density.
2. Nutritional Status : Crucially, Calcium and Vitamin D intake plays a pivotal role in fostering healthy skeletal development. Insufficient dietary calcium and a deficiency in Vitamin D are documented causes that can precipitate lower-than-normal BMD readings.
3. Physical Loading :Consistent engagement in physical exercise encourages the strengthening of bones through the application of mechanical loading. Specifically, weight-bearing activities have proven effective in augmenting overall bone mass.
4. Hormonal Regulation: Skeletal growth is tightly regulated by various hormones, including growth hormone, thyroid hormones, and sex hormones (notably estrogen and testosterone). Imbalances within this hormonal system can detrimentally affect bone health and development.
5. Chronic Illnesses and Pharmacotherapy : A number of chronic health conditions and the long-term use of specific medications (such as corticosteroids) have been linked to a reduction in bone mineral density.

2. BONE QUALITY AND QUANTITY ASSESSMENT TECHNIQUES IN DENTISTRY

Table 2 provides a summary of the fundamental imaging and analytical techniques utilized for evaluating the structural characteristics and mineral density of the jawbones. These methodologies encompass a range from elementary radiological measurements to sophisticated tomographic and ultrasonographic procedures, thereby revealing diverse facets of bone quality (Emer et al. 2016).

Table 2. Methods Used For Bone Mineral Density Measurement

Methods Used in the Radiological Evaluation of the Jaw Bones	
Mandibular Indices	Micro-Computed Tomography (micro-CT / µCT)
Fractal Dimension Analysis	
Quantitative Computed Tomography (QCT)	Densitometric Analysis (DA)
Computed Tomography (CT)	Dual-Energy X-Ray Absorptiometry (DEXA / DXA)
Cone-Beam Computed Tomography (CBCT)	Quantitative Ultrasonography (QUS)
	High-Resolution Magnetic Resonance Imaging (HR-MRI)

3. FRACTAL ANALYSIS: FRACTAL DIMENSION AND ITS APPLICATION IN DENTISTRY

Fractal Analysis (FA) is recognized as a mathematical approach capable of quantifying irregular and complex structures found within biological systems. The resultant quantitative output of this technique is defined as the Fractal Dimension (FD) (Güngör et al. 2016). Interest in the potential applications of fractal analysis has been progressively expanding across numerous scientific disciplines in recent years, including the field of medicine. FA has found widespread adoption, specifically due to its broad applicability in the analysis of various imaging examinations (Leszczyński and Sokalski 2017).

Researchers in the field of dentistry, aiming to investigate the Bone Mineral Density (BMD) of the jawbones using dental radiographs, have leveraged this Fractal Analysis (FA) methodology for the quantitative assessment of trabecular bone. (Çoban Büyükbayraktar and Eninanç 2024).

The Role of Fractal Analysis in Evaluating Bone Structure in Pediatric Dentistry

In the literature, there are numerous fractal analysis studies, particularly concerning osteodystrophic diseases that affect bone metabolism, such as Paget's disease, hyperparathyroidism, hypoparathyroidism, osteomalacia, renal osteodystrophy, diabetes, rheumatoid arthritis, ankylosing spondylitis, osteogenesis imperfecta, and osteoporosis (Bulut et al. 2023, Czajkowska et al. 2023, Gulec et al. 2023, Altunok et al. 2024, Dedeoğlu et al. 2024, Ozturk and Artas 2024).

Data suggesting that bone metabolism may be affected in FMF is linked to the disease's recurrent inflammatory attacks and periods of subclinical inflammation. Some studies have reported that systemic bone mineral density in individuals with FMF may be lower compared to healthy peers; this has been suggested to be particularly associated with the increased inflammatory burden and alterations in OPG levels. However, studies evaluating the mandibular bone structure are quite limited.A recent study conducted on panoramic radiographs found that mandibular indices and fractal analysis results in children with FMF were similar to those of healthy controls, with only the mandibular cortical index (MCI) values reported to be slightly higher (Altunok Ünlü et al. 2023). This situation suggests that FMF does not cause a significant negative effect on the jawbone microarchitecture and that regular colchicine treatment may support bone metabolism in a protective manner. The literature also indicates that colchicine treatment brings systemic bone values closer to normal limits, implying that a similar protective effect might be present at the mandibular level as well.

The assessment of the mandibular trabecular structure using Fractal Dimension (FD) analysis, alongside established dental age estimation methods (Willems and London Atlas), is notable because it reveals the reflection of chronological age on bone trabeculation (Okumuş et al. 2025). Fractal analysis was performed on digital panoramic radiographs, and the resulting FD values were shown to increase concurrently with both chronological age and dental age calculated using WDA/LADA. The finding of significantly lower FD values in the 6–7 age groups and significantly higher FD values in the 13–14 age groups supports the notion that mandibular trabecular complexity increases parallel to growth and development. The lack of a significant difference in FD between genders in the study suggests that age-related changes in the trabecular structure during the pediatric period may be gender-independent. Nevertheless, the fact that measurements were performed on two-dimensional panoramic radiographs using fixed and small ROI (Region of Interest) areas, coupled with potential artifacts due to superposition, limits the use of FD as a single determining criterion for age estimation. Still, the study is important because it demonstrates that the use of mandibular fractal analysis, combined with dental age methods, can be considered a complementary tool in forensic age estimation and growth and development assessment. In a fractal analysis assessment conducted on pediatric patients with MIH (Molar Incisor Hypomineralization), no significant difference was observed in the fractal dimension values when compared to the control group ($p>0.05$) (Önsüren et al. 2025). The finding of similar FD values across all ROIs suggests that although hypomineralization leads to significant structural changes in the enamel tissue, it does not affect the micro-architecture of the trabecular bone.The stability of the FD suggests that the mandibular trabecular system in the growing age group may be more resistant to systemic and local stresses, or that the effect of MIH manifests primarily in the cortical structures. Overall, the findings indicate that trabecular bone complexity is preserved in MIH, thereby not supporting the use of fractal analysis as a standalone discriminatory biomarker. However, they suggest that FD can be interpreted more meaningfully when evaluated in conjunction with radiomorphometric indices.

The evaluation of the condylar trabecular structure using fractal analysis in pediatric celiac patients yields notable results, as it reveals the effects of systemic malabsorption on mandibular micro-architecture. The finding that FD values are lower in newly diagnosed children and significantly higher in children who have adhered to a gluten-free diet for at least 6 months suggests that bone structure can rapidly recover with dietary intervention (Bulut et al. 2023).Although blood biochemical parameters (Ca, ALP, Vitamin D) were within the reference ranges in all groups in the study, it is noted that the higher FD values in the previously diagnosed group may be associated with villus recovery, normalization of calcium absorption, and the regulation of bone turnover following the gluten-free diet. Overall, the findings suggest that the mandibular trabecular structure can be preserved through early recognition of celiac disease and adherence to the diet in early childhood; fractal analysis, therefore, shows potential as a meaningful, non-invasive, low-cost, and accessible tool for monitoring microstructural bone improvement in these patients.

Studies investigating the mandibular bone structure using fractal analysis in children with Amelogenesis Imperfecta (AI) demonstrate that the genetic mutations affecting enamel development can also alter the trabecular bone microarchitecture (Taşdemir and Taşsöker 2025). Assessments performed specifically reported that the fractal dimension (FD) values were significantly lower on the right side, particularly in the condylar, gonial, and interdental regions, indicating a reduction in mandibular trabecular complexity and a more porous bone structure. Furthermore, although Mandibular Cortical Index (MCI) scores were not statistically different, cortical thinning at the C2 level was more frequently observed in children with AI, emphasizing that the genetic mechanisms accompanying the enamel defect might also affect alveolar bone mineralization. The asymmetric FD distribution is suggested to be related to functional factors such as differences in occlusal loading, chewing habits, or accompanying dental hypersensitivity. These findings highlight the need to move beyond a diagnostic approach focused solely on enamel defects and underscore the importance of monitoring the mandibular bone structure in this patient group using sensitive methods like fractal analysis.

The assessment of mandibular trabecular structure using fractal analysis in individuals with a history of chemotherapy during the pediatric period is important for revealing potential microarchitectural disturbances related to the treatment. In the measurements performed, no significant difference was found between the fractal dimension (FD) values of three different ROIs (Region of Interests) representing the condyle, angle, and corpus regions and the values of the healthy control group (Kış et al.).The fact that the average FD values were similar in both groups suggests that despite the known mineralization loss in the skeletal system due to chemotherapy, the mandibular trabecular complexity may not have been significantly affected. However, in a comparison based on cancer type, the finding of a higher FD in the trabecular bone region distal to the premolars in the mandibular corpus of individuals who had received treatment for hematological malignancies indicates that the trabecular architecture may exhibit varying degrees of sensitivity to chemotherapy protocols or medications affecting bone metabolism. Overall, the findings suggest that childhood chemotherapy does not cause a significant decrease in mandibular trabecular complexity, but that the Klemetti index, which assesses the cortical structure, may be more sensitive to changes.

The assessment of the mandibular trabecular structure using fractal analysis in pediatric bruxism demonstrates that non-functional muscle activities can regionally affect bone microarchitecture. Studies conducted specifically report that fractal dimension (FD) values were significantly increased particularly in the angle and condyle regions, indicating an increase in trabecular density and a more complex bone structure due to recurrent muscle activity (Kolçakoğlu et al. 2022). Similarly, a larger-sample study found that FD values were significantly higher compared to the control group in all trabecular areas of the ramus, angle, and anterior to the molars, supporting the notion that bruxism creates a widespread mechanical loading that affects bone architecture in different regions of the mandible (Önsüren et al. 2025). This increase observed at the insertion sites of the masticatory muscles on the mandible is explained, in accordance with Wolff's Law, by the recurrent muscle forces increasing osteoblastic activity and making the trabecular network more complex. Conversely, the fact that the FD did not change in the corpus/periradicular regions suggests that the effect of bruxism is more pronounced in areas with high muscle attachments. When all findings are evaluated together, fractal analysis is seen as a valuable non-invasive method that reveals the functional adaptations of bruxism on the mandibular bone structure.

Fractal analysis methods applied in the pediatric population present an important tool for elucidating the effects of systemic diseases, developmental disorders, dental anomalies, and functional habits on the mandibular trabecular structure. The regional increases or decreases in FD values observed in various clinical conditions, such as MIH, hypodontia, amelogenesis imperfecta, celiac disease, history of chemotherapy, and bruxism, demonstrate that the mandible is a dynamic bone structure sensitive to functional loading, mineralization balance, and developmental processes. However, the two-dimensional limitations of panoramic radiographs, variations in ROI (Region of Interest) selection, age-related trabecular variability, and sample heterogeneity make it difficult to compare results across studies. Nevertheless, the existing evidence shows that fractal analysis can support both the diagnostic approach and guide treatment planning by providing non-invasive, accessible, and cost-effective information about bone microarchitecture in children during the growth and development period. Therefore, supporting pediatric mandibular fractal analysis studies with standardized protocols, larger sample sizes, and long-term follow-up data will strengthen the clinical applicability of the findings.

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