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ORIGINAL RESEARCH

Assessment of changes in bone trabeculation after mandibular expansion treatment using fractal dimension analysis

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Abstract

Background: This study evaluated region-specific mandibular trabecular bone changes after expansion using fractal dimension analysis (FDA) on panoramic radiographs and their association with mandibular arch width. **Methods**: In this retrospective controlled longitudinal study, 50 patients (25 per group) aged 8–11 years (mean age: 9.50 ± 0.95) were included. The treatment group comprised patients treated with a mandibular Schwarz appliance, with panoramic radiographs and digital models obtained before (T_0) and after expansion (T_1). The control group included age- and sex-matched untreated subjects with two panoramic radiographs obtained over matched intervals. FDA was performed on five mandibular regions (condyles, angles, and symphysis), and mandibular arch widths were measured on digital models. Group comparisons were analyzed using *t*-tests, and correlations between arch width and FDA changes were assessed using Pearson's coefficient. **Results**: In the treatment group, FDA significantly decreased in the symphysis ($p < 0.001$) and condylar regions ($p < 0.05$) and increased in the angular region ($p < 0.05$), whereas no significant changes were observed in controls ($p > 0.05$). Post-treatment, FDA values differed between groups in all regions ($p < 0.05$), with greater changes in the symphysis and angulus. Mandibular arch widths increased in the treatment group, with mean increases of 2.36 ± 0.31 mm (intercanine), 3.28 ± 0.48 mm (first interdeciduous molar/first interpremolar), 3.46 ± 0.37 mm (second interdeciduous molar), and 2.51 ± 0.64 mm (first intermolar). Intercanine and first interdeciduous molar/first interpremolar changes correlated positively with symphysis FDA changes ($r = 0.202$ and $r = 0.254$, $p < 0.05$), while intermolar changes correlated negatively with angulus FDA ($r = -0.464$, $p < 0.05$). **Conclusions**: Mandibular expansion is associated with region-specific alterations in mandibular trabecular bone microarchitecture. These findings indicate that its effects are not limited to dentoalveolar changes but also involve adaptive responses in the underlying bone.

Keywords

Digital model analysis; Fractal dimension analysis; Mandibular expansion; Panoramic radiographs

1. Introduction

Early orthodontic and orthopedic treatments in pediatric patients play a crucial role in guiding craniofacial growth, reducing the severity of malocclusions, and preventing the need for more complex surgical or orthodontic procedures later in life [1]. In particular, when transverse deficiencies of the dental arches are not treated on time, they may lead to permanent complications, including posterior crossbite, dental crowding, functional shifts, and facial asymmetries [2]. Although transverse deficiencies constitute a decisive factor in extraction decisions because of the space deficiency they create, recent treatment approaches have increasingly shifted towards more conservative methods. In this context, non-extraction treatment alternatives such as interproximal reduction, distalization, and arch expansion are often preferred due to their potential to preserve and increase arch dimensions [1, 3].

The debate on extraction versus non-extraction treatment originated in the history of orthodontics with Edward Angle's opposition to routine tooth extractions [4], has continued to the present day and has become even more complex, particularly with respect to the mandibular arch [3]. The early closure of the mandibular symphysis, which occurs around 6 to 9 months of age, and the inability to achieve skeletal effects comparable to those obtained with rapid maxillary expansion in this region have led to the belief that mandibular expansion is primarily limited to the dentoalveolar level [5]. Therefore, it is generally accepted that its effect is mainly restricted to the buccolingual tipping of the teeth and occurs through alveolar bone adaptation [6]. However, the literature also includes studies that suggest the mandibular arch width can be permanently increased. While some authors argue that mandibular expansion is conceptually unstable, other studies have demonstrated that permanent increases can be achieved in the interpremolar and intermolar widths [7, 8].

The Schwarz appliance is a removable orthodontic device commonly used for mandibular expansion, particularly in growing patients. It consists of an acrylic plate incorporating a midline expansion screw, which is periodically activated to generate transverse forces on the mandibular arch. Biomechanically, activation of the expansion screw produces laterally directed forces that result in transverse displacement of the dentoalveolar structures and may induce adaptive responses in the surrounding bone tissue [9, 10]. Because of its removable design and ease of clinical application, it is widely used in the management of transverse mandibular discrepancies in orthodontic practice.

These clinical debates raise the question of whether mandibular expansion is limited solely to changes in tooth position or whether it also induces biological adaptation in the mandibular bone tissue. Bone is a dynamic tissue that exhibits an adaptive response to mechanical forces, and these responses are reflected through remodeling processes occurring in the trabecular microarchitecture. It is well established that orthodontic and orthopedic forces can lead to structural changes not only in the dental structures but also in the surrounding bone tissue [11]. Therefore, demonstrating the effects of mandibular expansion on bone tissue is importance for understanding the treatment not only at the dentoalveolar level but also from a biological perspective.

However, quantitatively identifying these subtle remodeling processes within the trabecular bone microarchitecture using conventional radiographic evaluations is challenging [12–14]. Fractal dimension analysis (FDA) is a quantitative method used to assess the structural complexity of irregular patterns that do not follow traditional Euclidean geometry, such as trabecular bone. Trabecular bone forms a non-linear, branching network that can be characterized using fractal principles. The FDA provides a numerical value, known as the fractal dimension, which reflects the spatial organization and complexity of the trabecular architecture. Higher values generally indicate a more intricate and interconnected network, whereas lower values may suggest increased porosity [15, 16].

In dental radiology, the FDA has been widely used to evaluate trabecular bone patterns on two-dimensional images, including panoramic radiographs. In this context, it enables quantitative assessment of microstructural changes in trabecular bone in response to mechanical loading [12].

Previous studies have assessed changes in bone structure following maxillary expansion [17], functional orthopedic treatment [18], fixed orthodontic treatment [19], and orthognathic surgery [20] using FDA. However, to the best of our knowledge, no studies have specifically investigated the effects of mandibular expansion treatment on mandibular trabecular bone structure using an FDA approach. Furthermore, the relationship between changes in mandibular arch width and alterations in trabecular bone structure has not yet been systematically evaluated.

Therefore, this study aimed to analyze the effects of mandibular expansion treatment on mandibular bone trabeculation using FDA performed on panoramic radiographs. Furthermore, this study explored the relationship between changes in FDA values and alterations in mandibular arch width measured on digital models.

In this study, the null hypotheses were as follows: (i) Mandibular expansion treatment does not result in significant changes in mandibular trabecular bone structure, as evaluated by the FDA on panoramic radiographs; and (ii) there is no significant relationship between treatment-related changes in mandibular arch widths measured on digital models and changes in FDA values in the mandibular regions.

2. Materials and methods

This study was designed and reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [21].

2.1 Study design and ethics

This study was conducted as a retrospective, controlled, longitudinal investigation using a comparative design. Ethical approval was obtained from the institutional ethics committee (Reference No. 2026/02-32), and the study was conducted in accordance with the principles of the Declaration of Helsinki.

2.2 Patients

Patients were retrospectively selected from our clinic's archived clinical and radiographic records covering the period from January 2023 to December 2024. All patients were children aged between 8 and 11 years.

Sample size estimation was performed using the G*Power 3.1.9.6 software package (Heinrich Heine University Düsseldorf, Düsseldorf, NRW, Germany), based on data reported in a previous study [18]. The calculation assumed a moderate effect size (Cohen's $d = 0.5$), a significance level of $\alpha = 0.05$, and a statistical power of 0.90, using a two-tailed test. The analysis indicated that at least 23 patients per group were required. Therefore, a total of 50 patients (25 per group) were included in the study.

Patients were allocated to groups based on their treatment status. The treatment group consisted of patients with a skeletal Class I relationship who had undergone mandibular expansion treatment using a mandibular Schwarz appliance.

Inclusion criteria for this group were complete availability of clinical records, panoramic radiographs obtained before treatment (T_0) and immediately after completion of the expansion treatment (T_1), and three-dimensional digital models obtained using an intraoral scanner.

The control group comprised age- and sex-matched subjects with skeletal and dental Class I relationships who had not undergone any orthodontic or orthopedic treatment. These subjects were selected based on the availability of two longitudinal panoramic radiographs obtained during routine clinical follow-up, with individually matched time intervals corresponding to the treatment duration of each patient in the treatment group.

Exclusion criteria for both groups comprised craniofacial anomalies or syndromic conditions, mandibular asymmetry (determined based on pre-treatment extraoral photographs and panoramic radiographic evaluation, including assessment of facial asymmetry and differences in condylar lengths), temporomandibular joint pathology, a history of mandibular surgery or facial trauma, systemic diseases or medication use affecting bone metabolism, panoramic radiographs with significant artifacts, positioning errors, or technical distortions that could compromise image quality, as well as digital models with distortions, missing data, or scanning artifacts that could affect measurement accuracy.

2.3 Image analysis procedures

FDA was performed by a single calibrated observer (ŞÇ), while all digital model measurements were obtained by another calibrated observer (MHB), both of whom were experienced in their respective measurement techniques.

2.3.1 Fractal dimension analysis

All panoramic radiographs were obtained using the same device (Veraviewepocs 2D, J. Morita Mfg. Corp., Kyoto, Japan) under standardized exposure parameters (80 kVp, 8 mA, 13 s), in accordance with the manufacturer's instructions. Patient positioning was standardized by aligning the Frankfort horizontal plane parallel to the floor and the sagittal plane with the device's vertical reference line. All panoramic images were saved in tagged image file format (TIFF).

Regions of interest (ROIs) measuring 50 × 50 pixels were selected from five anatomically distinct mandibular regions: the geometric center of the right mandibular condyle (ROI 1), the geometric center of the right mandibular angle (ROI 2), the mandibular symphysis region (ROI 3), the geometric center of the left mandibular angle (ROI 4), and the geometric center of the left mandibular condyle (ROI 5). Care was taken to position all ROIs within trabecular bone, avoiding dental tissue, lamina dura, periodontal ligament, mandibular canal, cortical bone, and other anatomical structures (Fig. 1). These ROIs represent anatomically and functionally distinct mandibular regions that have previously been used in panoramic radiograph-based FDA studies to evaluate trabecular bone structure. They were selected to provide a representative assessment of different functional regions of the mandible [13, 16, 22].

FDA values were calculated from panoramic radiographs using the box-counting method originally described by White and Rudolph [12], implemented in ImageJ software (National Institutes of Health, Bethesda, MD, USA). After selecting and cropping each ROI, the images underwent a series of processing steps. Concisely, to eliminate variations in brightness caused by overlapping soft tissues and varying bone thickness, a Gaussian blur filter with a sigma value of 35 pixels was applied. The blurred image was then subtracted from the original ROI, and a grey value of 128 was added to each pixel to normalize the image contrast. Subsequently, the image was binarized using a threshold value of 128 to differentiate trabeculae from marrow spaces. To reduce image noise and improve the continuity of trabecular structures, the image was sequentially eroded and dilated. The image was then inverted and skeletonized to generate a one-pixel-wide representation of the trabecular network. Finally, FDA values were calculated using the box-counting function, in which the skeletonized image was overlaid with a grid of progressively smaller square boxes. The relationship between box size and the number of occupied boxes was used to automatically compute the fractal dimension, which quantitatively represents the complexity of the trabecular bone structure (Fig. 2).

2.3.2 Digital model analysis

All digital models were obtained using the same intraoral scanner (TRIOS 3, 3Shape, Copenhagen, Denmark) under standardized scanning conditions, in accordance with the manufacturer's instructions. Scanning procedures were performed by a single experienced operator to minimize operator-dependent variability. Digital impressions were saved in Standard Tessellation Language (STL) format. Measurements were obtained from archived STL files using the manufacturer's proprietary analysis software, and mandibular arch widths were determined using the software's built-in measurement tools (Fig. 3).

All measurements were performed using predefined anatomical landmarks to ensure high reproducibility. Intercanine width was defined as the linear distance between the cusp tips of the mandibular canines [23, 24]. First interdeciduous molar (or first interpremolar), second interdeciduous molar, and first intermolar widths were measured as the linear distances between the central fossae of the corresponding teeth on the right and left sides [25, 26]. These landmarks were selected as reproducible anatomical reference points for assessing transverse changes on digital models.

Digital model measurements were performed only in the experimental group to evaluate treatment-related changes in mandibular arch width and their relationship with FDA values. No digital model measurements were obtained for the control group, as no treatment was applied.

2.3.3 Reliability analysis

To evaluate intra-observer reliability, 20% of the sample was randomly selected and reanalyzed after a two-week interval. FDA was repeated by the same observer (ŞÇ), and digital model measurements were repeated by the same observer (MHB). The intraclass correlation coefficient (ICC) was calculated for the repeated measurements.

2.4 Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics (version 26.0; IBM Corp., Armonk, NY, USA). Data normality was evaluated using the Shapiro-Wilk test. Descriptive statistics were expressed as mean ± standard deviation (SD). For bilateral anatomical regions, the mean of the right and left measurements was calculated and used in the analyses to derive a single representative value for each region.

Inter-group comparisons of demographic variables were performed using the independent samples *t*-test for continuous variables and Pearson's chi-square test for categorical variables. Intra-group comparisons between the T_0 and T_1

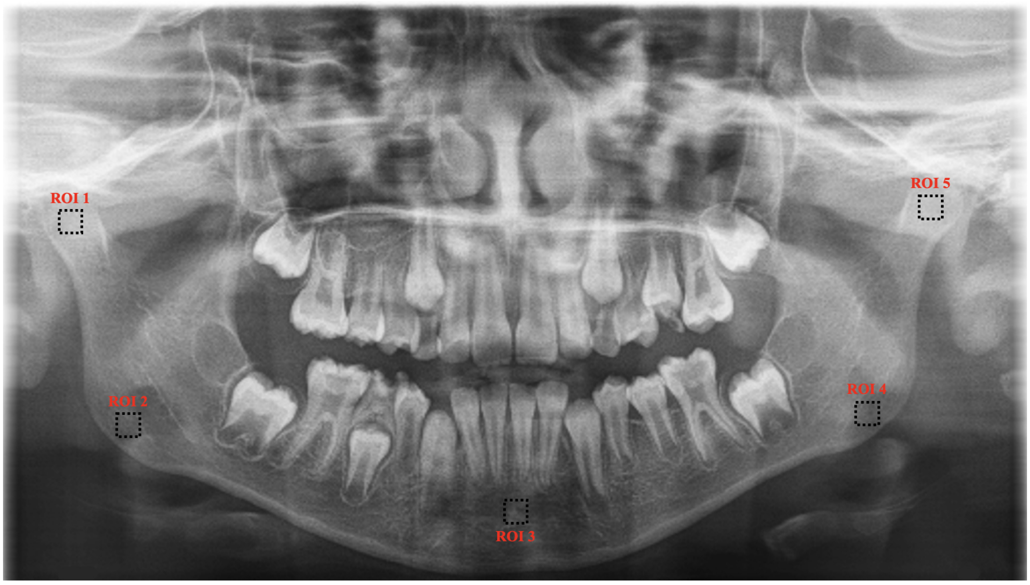

FIGURE 1. Locations of the regions of interest (ROIs) selected in five mandibular regions.

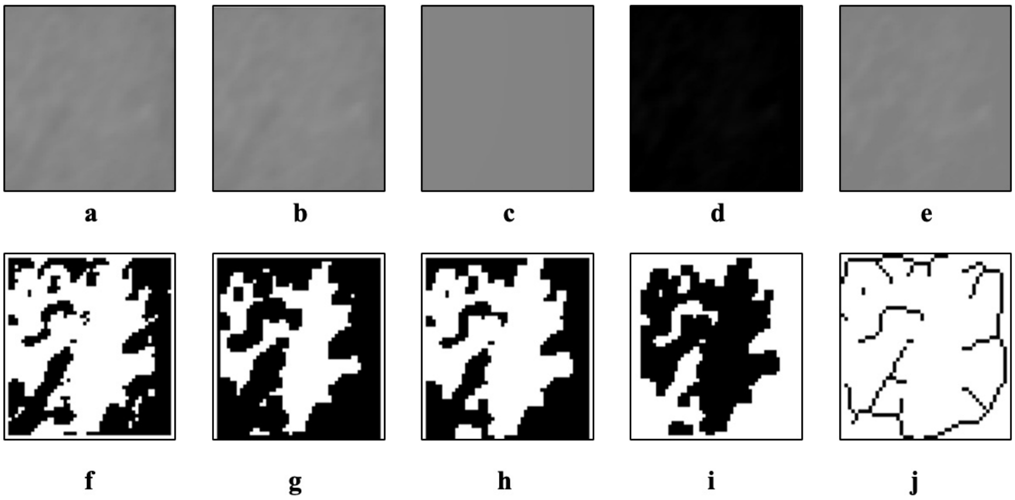

FIGURE 2. Fractal dimension analysis (FDA) procedure. (a) cropping of the region of interest; (b) duplication; (c) Gaussian-blurred image of the duplicated ROI; (d) subtraction of the blurred image from the original image; (e) addition of 128 gray values; (f) binarization; (g) erosion; (h) dilation; (i) inversion; (j) skeletonization.

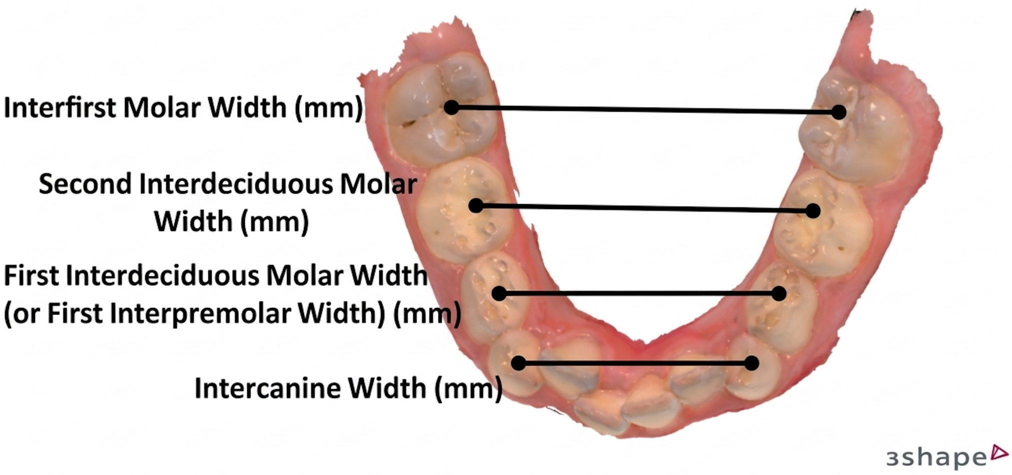

FIGURE 3. Locations of mandibular arch width measurements on the digital model.

time points were performed using the paired samples *t*-test. Inter-group comparisons of FDA values obtained at T_0 and T_1, as well as comparisons of the amount of change ($\Delta = T_1 - T_0$) between the treatment and control groups, were carried out using the independent samples *t*-test. Changes in mandibular arch widths were calculated for the digital model data, and their associations with changes in FDA values were assessed using Pearson's correlation coefficient.

The intra-observer reliability of both the FDA and digital model measurements was evaluated using the ICC based on a two-way mixed-effects model with absolute agreement. All statistical tests were two-tailed, and $p < 0.05$ was considered statistically significant.

3. Results

The intra-observer reliability was high, with ICC values of 0.944 for FDA measurements and 0.878 for digital model measurements.

3.1 Patient characteristics

The patient characteristics are presented in Table 1. There were no statistically significant differences between the treatment and control groups in terms of gender distribution ($p = 0.899$). Similarly, no significant difference was observed between the groups regarding chronological age ($p = 0.794$). The mean chronological age was 9.45 ± 0.94 years in the control group and 9.54 ± 0.96 years in the treatment group. The mean treatment/follow-up duration was 1.01 ± 0.19 years for the control group and 0.84 ± 0.11 years for the treatment group, with no statistically significant difference between the groups ($p = 0.405$).

3.2 Image analysis results

3.2.1 Fractal dimension analysis

The inter-group comparisons revealed no statistically significant differences between the treatment and control groups at baseline in the symphysis ($p = 0.067$), angulus ($p = 0.346$), or condylar regions ($p = 0.088$). The intra-group comparisons of FDA values are presented in Table 2. In the treatment group, intra-group comparisons revealed statistically significant decreases in the symphysis ($p < 0.001$) and condylar ($p = 0.027$) regions, while the angulus region showed a statistically significant increase ($p = 0.011$). In contrast, no statistically significant differences were observed between the two time points in any of the evaluated regions in the control group ($p > 0.05$).

The inter-group comparison of changes in FDA values during the treatment/follow-up period in the different mandibular regions is presented in Table 3. Statistically significant differences were observed between the groups in the symphysis ($p < 0.001$) and angulus ($p = 0.006$) regions. However, no statistically significant difference was found between the groups in the condylar region with respect to changes in FDA values ($p = 0.704$).

3.2.2 Digital model analysis

In the treatment group, mandibular arch widths increased in all measured regions following expansion treatment. The mean increase was 2.36 ± 0.31 mm in intercanine width, 3.28 ± 0.48 mm in the first interdeciduous molar (or first interpremolar) width, 3.46 ± 0.37 mm in the second interdeciduous molar width, and 2.51 ± 0.64 mm in the first intermolar width.

3.2.3 Correlation analysis

The correlations between changes in mandibular arch widths and changes in FDA values in different mandibular regions are presented in Table 4. A statistically significant positive correlation was observed between changes in intercanine width and changes in FDA values in the symphysis region ($r = 0.202$, $p = 0.023$). Furthermore, a statistically significant positive correlation was observed between the change in the first interdeciduous molar (or first interpremolar) width and the change in FDA values in the same region ($r = 0.254$, $p = 0.035$).

In addition, a statistically significant negative correlation was detected between changes in the first intermolar width and changes in FDA values in the angular region ($r = -0.464$, $p = 0.044$). No statistically significant correlations were found between changes in arch widths and FDA values in the condylar region.

4. Discussion

The present study aimed to evaluate the effects of mandibular expansion treatment on mandibular trabecular bone structure using the FDA and to investigate its relationship with changes in mandibular arch width. The findings demonstrated that mandibular expansion resulted in region-specific alterations in trabecular bone microarchitecture, with significant decreases in FDA values in the symphysis and condylar regions and an increase in the angular region, whereas no significant changes were observed in the control group. Furthermore, significant correlations were identified between changes in mandibular arch widths and FDA values in specific regions. These findings

TABLE 1. Patient characteristics.

	Gender		Age (yr) Mean ± SD	Treatment/Follow-up Period (yr) Mean ± SD
	Male	Female		
Control group	13	12	9.45 ± 0.94	1.01 ± 0.19
Treatment group	13	12	9.54 ± 0.96	0.84 ± 0.11
p	0.899[a]		0.794[b]	0.405[b]

[a]: *Pearson's chi-square test;* [b]: *Independent samples t-test; SD: Standard deviation.*

TABLE 2. The intra-group comparisons of fractal dimension analysis values.

	Symphysis Mean ± SD			Angulus Mean ± SD			Condyle Mean ± SD		
	T_0	T_1	p^c	T_0	T_1	p^c	T_0	T_1	p^c
Control group	1.6081 ± 0.0361	1.6079 ± 0.0358	0.103	1.608 ± 0.033	1.608 ± 0.036	0.606	1.607 ± 0.035	1.607 ± 0.034	0.799
Treatment group	1.6120 ± 0.0190	1.6041 ± 0.0356	<0.001	1.609 ± 0.025	1.611± 0.018	0.011	1.611 ± 0.018	1.610 ± 0.022	0.027

c: Paired samples t-test; SD: Standard deviation; T_0: Baseline; T_1: Treatment/follow-up period.

TABLE 3. Inter-group comparison of the changes in fractal dimension analysis values during treatment/follow-up period.

	Symphysis Mean ± SD	Angulus Mean ± SD	Condyle Mean ± SD
Control group	−0.0002 ± 0.0031	−0.0006 ± 0.0033	−0.0005 ± 0.0012
Treatment group	−0.0079 ± 0.0083	0.002 ± 0.007	−0.001 ± 0.004
p^b	<0.001	0.006	0.704

b: Independent samples t-test; SD: Standard deviation.

TABLE 4. The correlations between the changes in mandibular arch widths and the changes in fractal dimension analysis values.

Mandibular Arch Width	Fractal Dimension Analysis Values					
	Symphysis		Angulus		Condyle	
	r	*p*	*r*	*p*	*r*	*p*
Intercanine width	0.202	0.023	−0.012	0.915	0.084	0.458
First interdeciduous molar/First interpremolar width	0.254	0.035	−0.040	0.725	0.009	0.938
Second interdeciduous molar width	0.334	0.447	−0.072	0.526	0.007	0.952
First intermolar width	0.301	0.331	−0.464	0.044	0.236	0.144

r: Pearson's correlation coefficient.

provide novel evidence supporting the presence of adaptive biological responses in mandibular trabecular bone following expansion treatment and contribute to the growing body of literature on bone microarchitectural adaptation.

FDA and related radiomic and radiographic texture-based approaches have been widely utilized as quantitative imaging biomarkers to evaluate mandibular bone microarchitecture in various clinical contexts [15]. Previous studies using panoramic radiographs have demonstrated the utility of these methods in assessing trabecular bone alterations associated with systemic conditions, such as diabetes mellitus and osteoporosis [12, 27, 28], as well as in dental and functional conditions, including hypodontia [13], sleep bruxism [16], and various orthodontic treatments [18].

Within this broader context of radiographic texture analysis, the present study contributes to the literature by specifically analyzing regional trabecular adaptations following mandibular expansion and correlating these findings with clinically measurable arch-width changes. This integrated radiographic and digital model-based approach provides additional insight into the biomechanical relationship between dentoalveolar expansion and trabecular bone remodeling.

Expansion treatment is frequently preferred in clinical practice for the management of transverse discrepancies. Removable appliances such as the Schwarz appliance are widely used due to their ability to produce controlled transverse changes in the mandibular arch, making them suitable for evaluating potential trabecular bone adaptations associated with expansion. For this reason, the Schwarz appliance represents an appropriate clinical model for investigating trabecular bone adaptation following mandibular expansion. However, there remains ongoing debate about whether its effects occur at the skeletal level or are primarily limited to the dentoalveolar level [29, 30]. Most studies in the literature have focused on the millimetric increases in dental arch widths following mandibular expansion. However, limited research has evaluated the biological response of the internal bone structure, especially the trabecular bone microarchitecture, to applied mechanical forces [6, 30].

Although bone mineral density measurement is considered the gold standard, the routine use of dual-energy X-ray absorptiometry in orthodontic patients is limited by practical issues such as accessibility, cost, and additional imaging requirements [31]. Similarly, although cone-beam computed tomography (CBCT) provides detailed three-dimensional information, its routine use for longitudinal evaluation is not always justified because of increased radiation exposure [32, 33].

In this context, the FDA offers a practical alternative because it enables quantitative assessment of trabecular structural complexity using routinely acquired panoramic radiographs [15]. Despite the limitations associated with panoramic radiography, including its two-dimensional nature and the risk of anatomical superimposition, the standardized analysis protocol described by White and Rudolph [12] allows reliable and reproducible evaluation of trabecular bone structure [34]. Previous studies have reported that FDA has been widely applied to dental radiographs, with panoramic radiographs being among the most frequently used imaging modalities [15]. Because such radiographs are routinely obtained in clinical practice, they provide a low-cost and low-radiation method for monitoring bone structural changes longitudinally [27].

Accordingly, panoramic radiographs were selected in the present study due to their frequent use in orthodontic practice and their availability for both pre- and post-treatment evaluation. This enabled standardized longitudinal comparison without additional radiation exposure [35]. These characteristics make panoramic radiographs well-suited for evaluating treatment-related changes in trabecular bone structure in a clinical setting. Furthermore, their use is consistent with current radiation protection principles, particularly in pediatric populations [36].

The selection of the ROIs (symphysis, mandibular angle, and condyle) was based on their distinct anatomical and biomechanical roles within the mandible, as well as their previous use in FDA studies assessing mandibular trabecular bone on panoramic radiographs [13, 16, 22]. The symphysis represents the anterior part of the mandibular arch and is likely influenced by transverse expansion forces. The mandibular angle represents a major muscle attachment site, particularly for the masseter and medial pterygoid muscles, and reflects functional loading conditions that play a key role in shaping mandibular bone structure [37, 38]. The condyle represents an adaptive growth site exposed to both mechanical loading and developmental influences [39, 40]. In the context of mandibular expansion, evaluating these distinct regions allows for a comprehensive assessment of regional trabecular responses to transverse expansion forces.

The size of the ROI may influence FDA measurements. Previous studies have demonstrated that FDA values are sensitive to ROI size and that variations in ROI selection can significantly affect the results [15]. In particular, smaller ROIs may increase variability and susceptibility to noise due to limited structural representation, whereas sufficiently large ROIs provide a more representative sampling of trabecular architecture and improve measurement stability [41]. In the present study, a fixed ROI size of 50×50 pixels was used to ensure consistency across all measurements and to provide a sufficiently large and representative sampling area of trabecular bone while avoiding cortical bone and surrounding anatomical structures. This approach was applied in accordance with standardized methodologies in panoramic radiograph-based FDA [34, 42].

For an accurate interpretation of the results, study groups must be demographically comparable. In the present study, no significant differences were found between the treatment and control groups in terms of gender, age, and treatment/follow-up duration, indicating baseline comparability. However, because the sample consisted of patients aged 8–11 years, corresponding to a period of active craniofacial growth, the contribution of physiological growth to the observed structural changes cannot be completely excluded.

Within this controlled framework, mandibular expansion treatment produced region-specific changes in FDA values, characterized by decreases in the symphysis and condylar regions and an increase in the angular region, whereas no significant changes were observed in the control group. These findings indicate distinct biomechanical responses among different mandibular regions, leading to the rejection of the first null hypothesis [28, 43].

The mandibular symphysis is considered particularly susceptible to biological adaptation because of its anterior location in the arch and its direct exposure to transverse expansion forces [44]. In the present study, the significant decrease in FDA values observed in this region suggests trabecular reorganization associated with active bone remodeling. The applied lateral forces may have increased mechanical stress within the trabecular network, resulting in widening of intertrabecular spaces and reduced structural complexity [40]. Because lower FDA values indicate a more porous trabecular configuration, this finding may reflect temporary reductions in mineralization or increased bone turnover during the early stages of remodeling [45].

By contrast, the increased FDA values observed in the angular region indicate a different biomechanical response pattern. The angular region represents the attachment site of the pterygomasseteric sling, formed by the masseter and medial pterygoid muscles [37, 38]. The functional loads generated by these muscles play a decisive role in the trabecular organization of the mandibular bone [16, 22]. Mandibular expansion treatment not only increases transverse dimensions but may also influence occlusal relationships and muscle function due to buccal tipping of the teeth. According to Wolff's law, bone remodels in response to the functional loads applied to it [39]. During treatment, possible increases in masticatory muscle activity or changes in force vectors resulting from occlusal alterations may have led to adaptive strengthening of the trabecular structure and an increase in its complexity in the angular region, which is reflected by the observed increase in FDA values [22].

The smaller decrease observed in the condylar region compared with the symphysis may be related to the condylar region's biological and functional characteristics. The condyle is a structure with high adaptive capacity, primarily shaped by functional loading and growth patterns. This finding may be explained by the more indirect effect of the forces applied during mandibular expansion on the condyle [44]. However, the condylar changes should be interpreted with caution, as the mandibular condyle is a major growth site that undergoes continuous remodeling during development, particularly in growing individuals [46]. Therefore, the observed alterations may reflect a combined effect of natural growth and the mechanical stress induced by expansion treatment, rather than being solely attributed to the Schwarz appliance. The inclusion of an age-matched control group in the present study provides a comparative framework to help distinguish treatment-related effects from physiological development. The significant differences observed between the experimental and control groups suggest that expansion treatment may contribute to measurable microstructural adaptations. Nevertheless, the potential influence of inherent growth patterns cannot be entirely excluded [9, 46]. Taken together, these findings suggest that although natural growth likely contributes to the observed condylar changes, expansion treatment may also play a role in modulating these adaptations.

Intergroup comparisons further support the regional sensitivity of mandibular expansion. The absence of significant differences between the groups in any region at baseline (T_0) strengthens the reliability of the comparisons. The significantly greater changes observed in the symphysis and angular regions compared with the control group suggest that these areas are biologically more sensitive to expansion forces. In contrast, a decrease was detected within the condylar region. However, the absence of a significant difference in the magnitude of change compared with the control group indicates that the condylar bone response to expansion treatment may be more limited or more variable than that of the symphysis and angular regions.

The interpretation of these findings is supported by the existing literature. FDA has been used to evaluate changes in bone structure following various orthodontic treatments [47]. However, the results have been reported to vary depending on the selected ROI, the type of treatment, and the timing of evaluation [48]. For example, Tai *et al.* [29] and O'Grady *et al.* [49] reported that the effects of mandibular expansion treatment are largely dentoalveolar, with a limited skeletal contribution. The findings of the present study, which demonstrate changes in bone microarchitecture, do not contradict this view. Rather, they suggest that the basal bone may respond to dentoalveolar tooth movement through a stress-induced remodeling process. In addition, the findings of Kolcakoglu *et al.* [16] and Gulec *et al.* [22], which demonstrated that parafunctional forces can alter mandibular trabeculation, support our observation of adaptive bone response to mechanical loading.

The results of the correlation analysis indicate that the effect of the applied expansion forces on bone is closely related to anatomical proximity and muscle function. A positive correlation was observed between transverse expansion in the intercanine and first interdeciduous molar/first interpremolar regions and the change in FDA values in the symphysis region. This finding is biomechanically expected and consistent with the observed force distribution. The symphysis, located in the anterior segment of the mandibular arch, represents one of the bending points of the arch and is anatomically close to the expansion screw. It is therefore among the areas where forces are transmitted most directly [50, 51]. Accordingly, each millimetric increase in transverse width in the anterior region results in increased stress transmission to the trabecular structure of the symphysis, leading to a measurable adaptive response in bone microarchitecture [52]. This correlation observed in the symphysis region demonstrates a mechanical link between dental movement and the biological response of bone trabeculation. Accordingly, the second null hypothesis is rejected, given the significant correlations between arch-width changes and FDA alterations in specific regions.

By contrast, the significant negative correlation observed in the posterior region, particularly between changes in the first intermolar width and FDA values in the angular region, can be biomechanically explained by the influence of the pterygomasseteric sling mechanism acting on the angular region [37, 38]. Buccal expansion and tipping of the molar teeth alter the functional length, tension, and force vectors of these muscles. This, in turn, modifies the nature of the mechanical loads transmitted to the angular region and leads to trabecular reorganization [38]. The presence of a relationship between molar expansion and changes in FDA values in the angular region suggests that mandibular expansion exerts an indirect biomechanical effect on bone not only through the teeth but also via the masticatory muscles. This finding supports the concept that the posterior mandible exhibits an adaptive bone response shaped by muscle function.

In the condylar region, the absence of a significant correlation between changes in dental arch width and alterations in FDA is biomechanically consistent with the principle of force dissipation. As the expansion force is transmitted from the teeth to the alveolar bone and along the mandibular body, its magnitude progressively decreases and is partially dissipated by the surrounding tissues. As a result, the load reaching the temporomandibular joint complex becomes more diffuse and attenuated rather than direct and concentrated [53, 54]. Therefore, the condyle is one of the structures most indirectly influenced by the applied expansion forces.

Recent three-dimensional imaging studies have shown that orthodontic treatment-related changes in the condylar region are generally manifested not as linear bone deformation, but as adaptive and rotational modifications in condylar position, morphology, and its relationship with the glenoid fossa [55]. Therefore, the absence of a direct and linear relationship between the millimetric increases in dental arch width and changes in the condylar trabecular structure is an expected finding. The lack of a significant correlation in the condylar region in the present study indicates that the effects of mandibular expansion forces on the condyle are likely limited and indirect. This result is consistent with the current biomechanical literature.

Several limitations should be considered when interpreting the results of this study. First, the two-dimensional nature of the panoramic radiographs used for FDA constitutes an inherent limitation in the assessment of bone microarchitecture, particularly due to the risk of anatomical superimposition and geometric distortion, especially in the anterior region. Although all radiographs in the present study were obtained using the same device and standardized protocols, and although all paired analyses were performed to evaluate intra-individual changes to minimize this effect, volumetric and three-dimensional alterations in bone structure could be assessed more comprehensively using methods such as CBCT. The second limitation of this study is that masticatory muscle activity was not directly assessed by electromyography, as the retrospective design did not allow prospective functional measurements. Although our interpretation that the increase in FDA in the angular region is related to muscle function is based on biomechanical principles described in the literature, this relationship could not be directly confirmed in the present study. Therefore, prospective studies using objective assessments of muscle activity are needed to further demonstrate this association. A third limitation is the timing of the T_1 evaluation. Bone remodeling is a time-dependent biological process, and the follow-up period may not fully reflect long-term structural adaptations of trabecular bone [56]. The observed changes are therefore likely to represent early-stage remodeling responses to mechanical loading rather than fully stabilized bone architecture. Consequently, the findings should be interpreted with caution, and future longitudinal studies with longer follow-up periods are required to better understand the long-term effects of mandibular expansion on trabecular bone structure.

Despite these limitations, the use of homogeneous patient groups, the inclusion of a control group, and the application of standardized imaging and analysis protocols allowed for a reliable and focused evaluation of the effects of mandibular expansion on bone microarchitecture. Moreover, the combined assessment of radiographic FDA and dental arch width measurements obtained from digital models represents a major strength of this study. This approach provides a comprehensive view of the relationship between bone microstructural adaptation and dentoalveolar changes. Therefore, this study provides quantitative evidence that biological bone adaptation occurs alongside measurable transverse changes in dental arch width within the same patient sample in pediatric patients treated with the Schwarz appliance. However, the findings are limited to pediatric patients treated with the Schwarz appliance who had no systemic or local pathology and were evaluated over a short-term follow-up period. Therefore, generalization to other age groups, expansion protocols, or patients with more severe skeletal discrepancies should be made with caution. Future prospective studies with longer follow-up periods, supported by three-dimensional imaging and, where possible, histological and biomechanical data, are needed to better clarify the temporal pattern and underlying biological mechanisms of bone response to mandibular expansion treatment.

5. Conclusions

Mandibular expansion treatment resulted in significant, region-specific changes in mandibular trabecular bone structure, indicating that dentoalveolar movement is accompanied by biological adaptation of the underlying bone. The significant associations between changes in mandibular arch widths and FDA values further demonstrate a biomechanical link between dentoalveolar changes and trabecular bone remodeling. From a clinical perspective, these findings suggest that mandibular expansion is associated with measurable microstructural adaptation in mandibular bone and is not limited to dentoalveolar changes alone. However, further research is required to determine the clinical significance of these biological changes and their potential influence on long-term treatment outcomes.

AVAILABILITY OF DATA AND MATERIALS

The datasets used and/or analyzed during the current study are available from the corresponding author.

AUTHOR CONTRIBUTIONS

ŞÇ and MHB—contributed to the conceptualization and methodology; collected the data. ŞÇ—wrote the original draft. MHB—performed the statistical analysis. Both authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This retrospective study was approved by the local ethics committee (2026/02-32, Kütahya Health Sciences University Ethics Committee, Kütahya, Türkiye) in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from the parents or legal guardians of all participants at the time of routine clinical examination and treatment, which included permission for the use of anonymized clinical and radiographic data for scientific research purposes.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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