Original Article

Evaluating the effects of functional orthodontic treatment on mandibular osseous structure using fractal dimension analysis of dental panoramic radiographs

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ABSTRACT

Objective: To evaluate the effects of functional appliance treatment on mandibular trabecular structure using fractal dimension (FD) analysis of dental panoramic radiographs.
Materials and Methods: This study was conducted using digital panoramic radiographs of 45 patients with Class II malocclusion treated with functional appliances (treatment group, mean age: 11.39 $\pm$ 0.97 years; 23 girls, 22 boys) acquired before (T0) and after (T1) treatment and the panoramic radiographs of 45 control subjects who had undergone no orthodontic treatment (control group, mean age: 11.31 $\pm$ 0.87 years; 23 girls, 22 boys). FD values in the condylar process, mandibular corpus, and mandibular angle were analyzed from the panoramic radiographs of both groups.
Results: Analysis of changes in FD between T0 and T1 revealed significant increases in the FD values of the right and left condylar processes and right mandibular corpus in the treatment group ($P < .001$) and in the right condylar process in the control group ($P < .05$). Between-group comparisons demonstrated that the treatment group showed greater changes in the condylar process (right, $P < .001$; left, $P < .05$) and right mandibular corpus ($P < .05$) compared to controls. Correlation analysis between the cephalometric and FD changes in the treatment group showed the right condylar process changes were negatively correlated with GoGn/SN angle ($P < .05$) and positively correlated with Co-Go ($P < .05$), although these correlations were weak.
Conclusions: FD analysis demonstrated significant changes in trabeculation of the condyle and mandibular corpus in the treatment group compared to the control group. Functional appliance treatment may lead to skeletal correction by altering skeletal form and trabeculation of the mandibular bone. (*Angle Orthod.* 2020;90:783–793.)

KEY WORDS: Functional orthodontic appliances; Fractal dimension; Panoramic radiographs

INTRODUCTION

The aim of treatments utilizing functional appliances to correct Class II anomalies due to mandibular underdevelopment is to lengthen the mandible by inducing cell activity in the condylar cartilage.[1–4] In their study investigating the long-term effects of protrusive function, McNamara and Bryan[5] reported that mandibular length increased with remodeling of the posterior and postero-superior surfaces of the condyle. Contrary to these studies, other authors[6–8] reported that functional orthopedic treatment induced little change in the bony elements of the craniofacial system and argued that the effect was limited to the dentoalveolar region. Discrepancies between the findings reported in these studies may be attributable to the variety of measurement methods used, as well as to the fact that most

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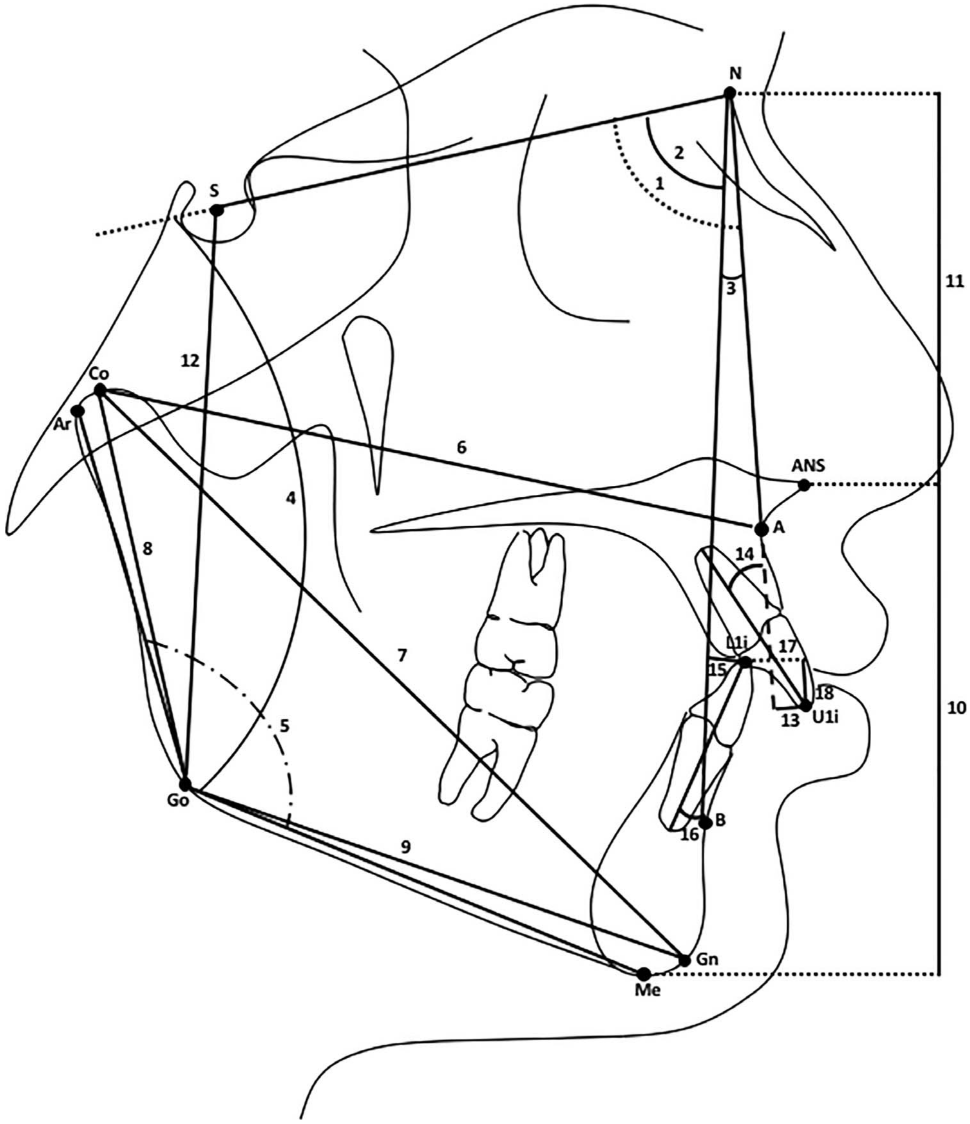

Figure 1. Cephalometric measurements. Skeletal angular measurements (°): (1) SNA; (2) SNB; (3) ANB; (4) GoGn/SN; and (5) Ar-Go-Me. Skeletal linear measurements (mm): (6) Co-A; (7) Co-Gn; (8) Co-Go; (9) Go-Gn; (10) ANS-Me; (11) N-ANS; and (12) S-Go. Dentoalveolar measurements: (13) U1i-NA (mm); (14) U1i-NA (°); (15) L1i-NB (mm); (16) L1i-NB (°); (17) overjet; and (18) overbite.

measurements were based on cephalometric radiographs and could not reflect changes in the osseous structure of the mandibular region.

Dental panoramic radiographs (DPRs) are a cost-effective and routinely used imaging method in dentistry. In addition to demonstrating changes in the dentition, DPRs can also be used to evaluate structural changes in trabecular bone.[9] One of the evaluation methods available is fractal dimension (FD) analysis, a mathematical method used to measure and assess complex structures such as trabecular bone.[10–12] In FD analysis, the trabecular bone pattern is evaluated using a box-counting algorithm that quantifies the bone

Figure 2. Regions of interest (ROIs) from three different areas in the mandible (condylar process, angulus mandibula, corpus mandibula).

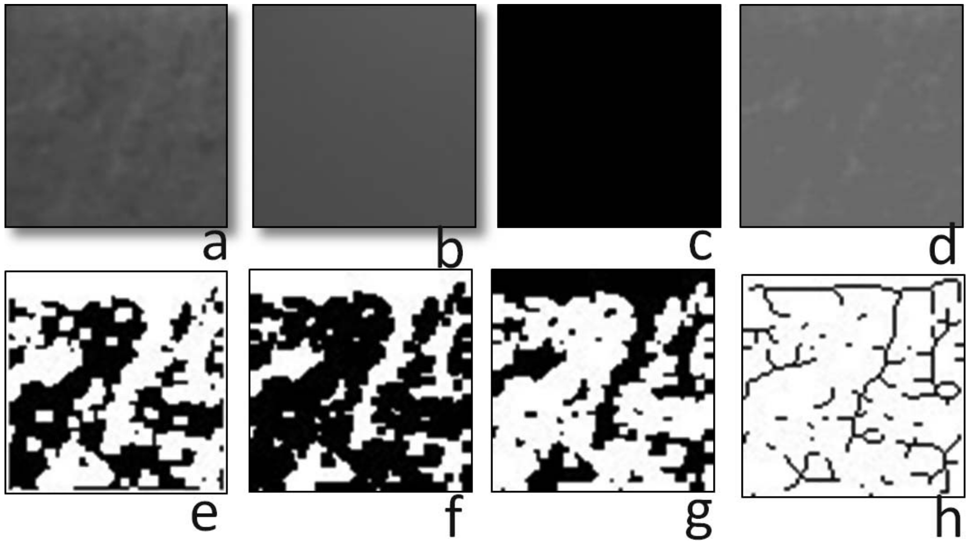

Figure 3. Stages of fractal dimension analysis. (a) Cropped region of interest. (b) Blurred image of duplicated region of interest. (c) The blurred image was then subtracted from the original image. (d) Addition of a gray value of 128 to each pixel location. (e) Erode. (f) Dilate. (g) Invert. (h) Skeletonize.

marrow and trabecular bone interface. A higher FD value indicates a more complex bone structure.[13,14]

Considering the lack of consensus, despite the many studies that have investigated the effects of functional treatment, as well as the possibility that FD analyses applied to panoramic radiographs may offer a new perspective on this issue, the present study was conducted to evaluate the effects of functional orthodontic treatment on mandibular trabecular structure by FD analysis of DPR.

MATERIALS AND METHODS

This retrospective study was conducted using data obtained from patients from Istanbul Medipol University and Ankara University, Faculty of Dentistry. The study was approved by the Istanbul Medipol University Ethics Committee (approval number 544).

Subject Selection

GPower 3.1.0 software package (Universität Düsseldorf, Germany) was used to determine the number of individuals to include in the study, and power analysis was performed. Sample size calculation was based on the ability to detect significant differences at $\alpha = .05$ error probability (critical t: 2.0085591; noncentrality parameter: 2.8844410). According to the power analysis, a sample size of 26 patients for each group would give more than 80% power (actual power: 0.8074866) with an allocation ratio (N2/N1) = 1. Therefore, the analysis included the radiographs of 90 individuals: 45 patients with Class II malocclusion treated with functional orthopedic appliances (twin block/monoblock) (mean age: 11.39 $\pm$ 0.97 years; 23 girls, 22 boys) and 45 control subjects (mean age: 11.31 $\pm$ 0.87 years; 23 girls, 22 boys).

When selecting patients for the treatment group (group 1), pre- and posttreatment radiographs were evaluated, and those who met the following criteria were included: Skeletal and dental Class II malocclusion due to mandibular underdevelopment before treatment, use of only monoblock or twin block appliances to stimulate mandibular development, and Class I occlusion after treatment. The control group (group 2) was created by selecting individuals who were age- and sex-matched to those in group 1 from among those who presented for routine dental procedures, had no history of orthodontic treatment, and exhibited no systemic disease and/or deformity associated with the craniofacial area.

Cephalometric and digital panoramic radiographs of patients in group 1 were taken before (T0) and after (T1) treatment. The mean treatment duration was 1.31 $\pm$ 0.46 years. With the twin block appliance routinely used in the clinic where the patients were treated, the upper and lower acrylic plates interlocked at a 70° angle.[15] Group 2 included individuals with two DPRs taken for routine dental procedures at two different time points in order to analyze normal changes in the mandibular trabecular structures due to growth for comparison to group 1. Control subjects were matched to the treatment group not only in terms of age at T0 but also in terms of the time elapsed between panoramic radiographs; the mean interval between T0 and T1 panoramic radiographs in group 2 was 1.23 $\pm$ 0.65 years.

Cephalometric radiographs of individuals included in group 2 were not taken or evaluated because they

Table 1. Descriptive Statistics of Cephalometric Parameters and Comparison of the Cephalometric Changes Occurred During Post- (T1) and Preobservation (T0) Periods for Group 1[a]

	Pretreatment (T0)				Posttreatment (T1)				T1-T0 Paired-Samples Test	
n = 45	Mean	± SD	Min.	Max.	Mean	± SD	Min.	Max.	Mean ± SD	*P*-Value
Skeletal angular measurements, °										
SNA	80.4	3.8	72.0	92.0	80.2	3.7	73.0	90.0	−−.191 ± 1.23	.304
SNB	74.2	3.5	65.0	83.0	76.0	3.6	70.0	85.0	1.8156 ± 1.32	.000***
ANB	6.2	2.2	2.0	10.0	4.1	2.1	0.0	9.0	−2.071 ± 1.33	.000***
GoGn/SN	32.3	5.5	16.0	46.0	32.12	5.67	16.00	46.00	−.196 ± 1.85	.482
Ar-Go-Me	126.8	5.4	115.1	139.0	127.9	5.9	114.3	141.0	1.180 ± 3.2	.018*
Skeletal linear measurements, °										
Co-A	79.23	3.74	71.69	88.20	79.81	12.69	.01	89.59	.574 ± 12.16	.753
Co-Gn	98.07	4.45	89.86	111.97	104.20	4.67	97.00	118.58	6.127 ± 3.24	.000***
Co-Go	48.34	4.28	40.00	58.75	51.98	3.78	43.50	60.07	3.637 ± 3.02	.000***
Go-Gn	66.13	4.00	60.43	74.20	69.50	5.89	56.71	95.66	3.369 ± 5.09	.000***
ANS-Me	57.53	5.18	46.73	68.98	60.58	5.34	49.50	72.56	3.045 ± 2.74	.000***
N-ANS	48.51	2.85	43.10	55.00	50.17	2.79	44.60	56.10	1.665 ± 1.59	.000***
S-Go	67.75	4.24	60.73	84.02	72.22	4.94	63.71	85.57	4.471 ± 2.96	.000***
Dentoalveolar measurements										
U1i-NA, mm	4.52	2.46	−2.08	8.38	3.66	2.56	−.48	13.07	−.860 ± 2.18	.011*
U1i-NA, °	25.8	8.2	8.0	46.0	22.6	6.7	8.0	37.0	−3.224 ± 6.15	.001***
L1i-NB, mm	4.47	2.80	−.72	12.08	6.09	2.97	−.62	11.74	1.618 ± 1.86	.000***
L1i-NB, °	25.9	8.1	6.0	47.0	30.5	9.0	3.0	46.0	4.573 ± 7.50	.000***
Overjet, mm	7.62	2.97	2.57	14.06	2.99	1.79	−1.11	7.99	−4.622 ± 2.37	.000***
Overbite, mm	5.16	2.68	.40	15.95	2.44	1.87	−.50	7.97	−2.713 ± 2.41	.000***

[a] SD indicates standard deviation; min, minimum value; and max, maximum value.
Paired *t*-test: * $P \leq .05$; *** $P \leq .001$.

Table 2. Comparison of the Cephalometric Parameters Between Preobservation (T0) and Postobservation (T1) Periods for Different Genders in Group 1[a]

	Girls (n = 23)				Boys (n = 22)			
			T1-T0				T1-T0	
	T0	T1	Paired *t*-Test		T0	T1	Paired *t*-Test	
	Mean ± SD	Mean ± SD	Mean ± SD	*P*-Value	Mean ± SD	Mean ± SD	Mean ± SD	*P*-Value
Skeletal angular measurements, °								
SNA	80.4 ± 3.9	80.1 ± 3.8	−.313 ± 1.04	.166	80.3 ± 3.9	80.3 ± 3.6	−.063 ± 1.41	.835
SNB	74.6 ± 4.0	76.2 ± 4.1	1.656 ± 1.30	.000***	73.9 ± 3.1	75.9 ± 3.0	1.981 ± 1.36	.000***
ANB	5.9 ± 2.2	3.9 ± 2.0	−2.095 ± 1.47	.000***	6.5 ± 2.2	4.4 ± 2.1	−2.045 ± 1.19	.000***
GoGn/SN	31.4 ± 6.4	31.61 ± 6.74	.177 ± 1.48	.572	33.3 ± 4.3	32.66 ± 4.37	−.586 ± 2.14	.213
Ar-Go-Me	126.1 ± 6.0	127.3 ± 6.3	1.16 ± 2.49	.036*	127.4 ± 4.8	128.6 ± 5.4	1.20 ± 3.87	.161
Skeletal linear measurements, mm								
Co-A	79.18 ± 3.32	77.39 ± 17.18	−1.797 ± 16.69	.611	79.29 ± 4.21	82.34 ± 3.89	3.055 ± 2.33	.000***
Co-Gn	97.67 ± 2.64	102.56 ± 3.09	4.893 ± 2.75	.000***	98.49 ± 5.82	105.91 ± 5.45	7.416 ± 3.27	.000***
Co-Go	48.47 ± 4.10	51.15 ± 3.99	2.678 ± 2.09	.000***	48.20 ± 4.55	52.84 ± 3.44	4.64 ± 3.53	.000***
Go-Gn	66.53 ± 4.04	69.12 ± 4.71	2.594 ± 3.07	.001***	65.71 ± 4.01	69.89 ± 7.02	4.18 ± 6.56	.007**
ANS-Me	56.89 ± 5.41	59.89 ± 5.51	3.003 ± 2.31	.000***	58.21 ± 4.96	61.30 ± 5.18	3.089 ± 3.18	.000***
N-ANS	48.10 ± 2.92	49.68 ± 2.59	1.577 ± 1.42	.000***	48.93 ± 2.78	50.69 ± 2.95	1.756 ± 1.77	.000***
S-Go	67.23 ± 3.69	71.27 ± 4.78	4.033 ± 2.58	.000***	68.29 ± 4.77	73.22 ± 5.01	4.929 ± 3.31	.000***
Dentoalveolar measurements								
U1i-NA, mm	4.06 ± 2.37	2.92 ± 2.10	−1.14 ± 1.64	.003**	5.00 ± 2.51	4.43 ± 2.81	−.567 ± 2.63	.324
U1i-NA, °	25.0 ± 8.1	20.9 ± 7.1	−4.1 ± 6.11	.004**	26.6 ± 8.4	24.3 ± 6.0	−2.309 ± 6.20	.096
L1i-NB, mm	4.23 ± 2.32	6.10 ± 2.26	1.875 ± 1.65	.000***	4.73 ± 3.27	6.08 ± 3.62	1.349 ± 2.06	.006**
L1i-NB, °	26.5 ± 6.6	32.7 ± 5.9	6.247 ± 4.86	.000***	25.4 ± 9.4	28.2 ± 11.1	2.822 ± 9.33	.171
Overjet, mm	7.18 ± 2.87	2.71 ± 1.59	−4.466 ± 2.33	.000***	8.07 ± 3.07	3.29 ± 1.98	−4.786 ± 2.45	.000***
Overbite, mm	5.27 ± 2.69	2.09 ± 1.21	−3.184 ± 2.53	.000***	5.04 ± 2.73	2.82 ± 2.35	−2.22 ± 2.22	.000***

[a] SD indicates standard deviation.
Paired *t*-test: * $P \leq .05$; ** $P \leq .01$; *** $P \leq .001$.

Table 3. Comparison of the Mean Values of the Chronological Ages and Fractal Dimension (FD) Parameters at the Beginning of the Observation Period (T0) Between Groups 1 and 2[a]

	Group 1 T0 (n = 45)		Group 2 T0 (n =45)		Group 1–Group 2				
					Independent-Samples Test			95% Confidence Interval of the Differences	
	Mean	± SD	Mean	± SD	*t*	*P*-Value	Mean Difference	Lower	Upper
Age, y	11.39	.97	11.31	.87	.432	.667	.08400	−.30264	.47064
Proc. condylaris (right)	1.29	0.14	1.30	0.10	−.434	.665	−.0111	−.0619	.0397
Angulus mandibula (right)	1.31	0.15	1.26	0.15	1.534	.129	.0498	−.0147	.1143
Corpus mandibula (right)	1.22	0.12	1.34	0.09	−5.709	.000***	−.1257	−.1694	−.0819
Proc. condylaris (left)	1.33	0.12	1.27	0.13	2.231	.028*	.0594	.0065	.1123
Angulus mandibula (left)	1.27	0.15	1.26	0.14	.213	.832	.0063	−.0529	.0655
Corpus mandibula (left)	1.21	0.13	1.31	0.13	−3.677	.000***	−.1002	−.1544	−.0460

[a] SD indicates Standard deviation.
Independent *t*-test; * $P \leq .05$; *** $P \leq .001$.

Table 4. Fractal Dimension (FD) Changes and Comparison of the Changes Occurring During Post- (T1) and Preobservation (T0) Periods for Groups 1 and 2 by Paired *t*-Test

	Group 1 (n = 45)				Group 2 (n = 45)			
	T0	T1	T1-T0		T0	T1	T1-T0	
	Mean ± SD	Mean ± SD	Mean Difference ± SD	*P*-Value	Mean ± SD	Mean ± SD	Mean Difference ± SD	*P*-Value
Age	11.39 ± .97	12.71 ± 1.02	1.311 ± .460	.000***	11.31 ± .87	12.54 ± .90	1.234 ± .655	.000***
Proc. condylaris (right)	1.29 ± 0.14	1.41 ± 0.11	.113 ± .132	.000***	1.30 ± 0.10	1.34 ± 0.09	.033 ± .097	.028*
Angulus mandibula (right)	1.31 ± 0.15	1.33 ± 0.14	.016 ± .191	.556	1.26 ± 0.15	1.30 ± 0.13	.037 ± .161	.125
Corpus mandibula (right)	1.22 ± 0.12	1.30 ± 0.13	.081 ± .133	.000***	1.34 ± 0.09	1.36 ± 0.09	.02 ± .112	.240
Proc. condylaris (left)	1.33 ± 0.12	1.40 ± 0.11	.067 ± .114	.000***	1.27 ± 0.13	1.30 ± 0.11	.022 ± .116	.211
Angulus mandibula (left)	1.27 ± 0.15	1.31 ± 0.15	.035 ± .205	.251	1.26 ± 0.14	1.29 ± 0.09	.029 ± .151	.202
Corpus mandibula (left)	1.21 ± 0.13	1.26 ± 0.13	.045 ± .156	.056	1.31 ± 0.13	1.33 ± 0.13	.019 ± .121	.279

* $P \leq .05$; *** $P \leq .001$; SD indicates standard deviation.

Table 5. Comparison of the Postobservation (T1)–Preobservation (T0) Differences Between Groups 1 and 2 by Independent *t*-Test

	Group 1–Group 2					
					95% Confidence Interval of the Differences	
	t	*P*-Value	Mean Difference	± SD	Lower	Upper
Age, y	.646	.520	.077	.119	.3144	.1602
Proc. condylaris (right)	3.474	.001***	.093	.026	.1467	.0399
Angulus mandibula (right)	−.235	.815	−.008	.037	.0663	−.0841
Corpus mandibula (right)	2.204	.030*	.062	.028	.1183	.0061
Proc. condylaris (left)	2.133	.036*	.053	.025	.1030	.0036
Angulus mandibula (left)	.114	.910	.004	.039	.0821	.0732
Corpus mandibula (left)	.745	.458	.022	.029	.0815	.0370

* $P \leq .05$; *** $P \leq .001$; SD indicates standard deviation.

Table 6. Comparison of the Intragroup Pre- (T0) and Postobservation (T1) Fractal Dimension (FD) Parameters Between Genders for Groups 1 and 2 by Independent *t*-Test

	Group 1 (n)							
	T0				T1			
	Girls (23) A	Boys (22) B	A-B		Girls (23) A	Boys (22) B	A-B	
	Mean ± SD	Mean ± SD	*P*	Test	Mean ± SD	Mean ± SD	*P*	Test
Age, y	11.45 ± 1.04	11.34 ± 0.92	.704		12.54 ± 1.12	12.88 ± 0.90	.283	
Proc. condylaris (right)	1.34 ± 0.12	1.25 ± 0.15	.031	*	1.41 ± 0.11	1.40 ± 0.11	.917	
Angulus mandibula (right)	1.29 ± 0.16	1.33 ± 0.15	.384		1.32 ± 0.14	1.34 ± 0.15	.514	
Corpus mandibula (right)	1.24 ± 0.14	1.20 ± 0.08	.279		1.30 ± 0.15	1.30 ± 0.09	.936	
Proc. condylaris (left)	1.36 ± 0.14	1.31 ± 0.11	.178		1.37 ± 0.12	1.43 ± 0.10	.069	
Angulus mandibula (left)	1.29 ± 0.13	1.25 ± 0.16	.315		1.28 ± 0.15	1.34 ± 0.13	.161	
Corpus mandibula (left)	1.24 ± 0.13	1.19 ± 0.13	.185		1.25 ± 0.15	1.27 ± 0.12	.738	

* $P \leq .05$; ** $P \leq .01$; *** $P \leq .001$. SD indicates standard deviation.

presented for routine dental procedures, not orthodontic treatment. As a result of ethical concerns, cephalometric radiographs are not acquired at different time points for patients who are not receiving orthodontic treatment.

Cephalometric Measurements

Lateral radiographs of all patients were obtained with Sirona Orthophos XG 5 DS/Ceph X-ray device, and AutoCAD®2016 (Autodesk, San Rafael, Calif) software was used to make measurements. Five skeletal angular measurements, seven skeletal linear measurements, and six dentoalveolar measurements were made on the cephalometric radiographs (Figure 1).

FD Analysis of Panoramic Radiographs

All DPRs were obtained using the Sirona Orthophos XG 5 device, with a resolution of 0.027-mm pixel size at 64 kVp, 8 mA, and 8.0 seconds. The dose area product (DAP) values were measured as 39 mGycm^2, according to the dose information provided by the manufacturer.

DPRs were measured using Image J® version 1.3 software (National Institutes of Health, Bethesda, Md). ImageJ is a Java-based image-processing program, and it was preferred to use ImageJ to process DPRs. FD analysis was conducted using customized software designed by White and Rudolph[16] by means of the box-counting method.

A dentomaxillofacial radiologist with 10 years of experience (SB) determined the region of interest (ROI) selection. ROIs were in 60 × 63-pixel size range and were chosen from three different areas of the mandible (both right and left sides), as follows:

- Region 1: Condylar process; subcortical area of the condyle;

Table 7. Comparison of the Fractal Dimension (FD) Parameters Between Post- (T1) and Pretreatment (T0) Periods for Different Genders in Groups 1 and 2 by Paired *t*-test

		Group 1			
		T0	T1	T1-T0 (Paired-Samples Test)	
		Mean ± SD	Mean ± SD	Mean Difference ± SD	*P*-Value
Girls (n = 23)	Age, y	11.45 ± 1.04	12.54 ± 1.12	1.094 ± .31	.000***
	Proc. condylaris (right)	1.34 ± 0.12	1.41 ± 0.11	.07 ± .093	.002**
	Angulus mandibula (right)	1.29 ± 0.16	1.32 ± 0.14	.023 ± .153	.476
	Corpus mandibula (right)	1.24 ± 0.14	1.30 ± 0.15	.064 ± .172	.089
	Proc. condylaris (left)	1.36 ± 0.14	1.37 ± 0.12	.013 ± .08	.444
	Angulus mandibula (left)	1.29 ± 0.13	1.28 ± 0.15	−.015 ± .185	.689
	Corpus mandibula (left)	1.24 ± 0.13	1.25 ± 0.15	.014 ± .172	.697
Boys (n = 22)	Age, y	11.34 ± 0.92	12.88 ± 0.90	1.537 ± .488	.000***
	Proc. condylaris (right)	1.25 ± 0.15	1.40 ± 0.11	.157 ± .152	.000***
	Angulus mandibula (right)	1.33 ± 0.15	1.34 ± 0.15	.01 ± .228	.833
	Corpus mandibula (right)	1.20 ± 0.08	1.30 ± 0.09	.098 ± .075	.000***
	Proc. condylaris (left)	1.31 ± 0.11	1.43 ± 0.10	.124 ± .118	.000***
	Angulus mandibula (left)	1.25 ± 0.16	1.34 ± 0.13	.089 ± .216	.066
	Corpus mandibula (left)	1.19 ± 0.13	1.27 ± 0.12	.079 ± .134	.012*

* $P \leq .05$; ** $P \leq .01$; *** $P \leq .001$; SD indicates standard deviation.

Table 6. Extended

Group 2 (n)							
T0				T1			
Girls (23) A	Boys (22) B	A-B		Girls (23) A	Boys (22) B	A-B	
Mean ± SD	Mean ± SD	*P*	Test	Mean ± SD	Mean ± SD	*P*	Test
11.40 ± 0.94	11.22 ± 0.81	.501		12.52 ± 0.96	11.22 ± 0.81	.881	
1.29 ± 0.08	1.32 ± 0.11	.205		1.34 ± 0.06	1.32 ± 0.11	.979	
1.31 ± 0.14	1.21 ± 0.16	.035	*	1.31 ± 0.12	1.21 ± 0.16	.793	
1.33 ± 0.08	1.36 ± 0.10	.179		1.39 ± 0.09	1.36 ± 0.10	.076	
1.24 ± 0.14	1.32 ± 0.11	.038	*	1.27 ± 0.11	1.32 ± 0.11	.089	
1.27 ± 0.12	1.26 ± 0.16	.805		1.29 ± 0.15	1.26 ± 0.16	.988	
1.2 ± 0.15	1.34 ± 0.10	.653		1.32 ± 0.13	1.34 ± 0.10	.653	

- Region 2: Angulus mandibular; above the supracortical area of the mandibular angle; and
- Region 3: Corpus mandibula; above the mandibular canal, distal of the second premolar (Figure 2).

DPRs of the patients in the groups were converted to tagged image file formats (TIFFs) because of their high resolution. Gaussian blur was used to distract brightness differences due to overlying soft tissues and varying thicknesses of bone. The resulting image was then subtracted from the original image. Bone marrow spaces and trabeculae were distinguished with the addition of a 128 gray value to each pixel location. After applying binary, erode, dilate, invert, and skeletonizing processes, FD values were calculated (Figure 3).

Statistical Analysis

Data obtained in the study were analyzed using SPSS 21 package software. Because the data showed a normal distribution, independent-samples and paired-samples *t*-tests were used. Relationships between variables were evaluated using correlation analysis. A *P*-value of less than .05 was considered statistically significant.

Table 7. Extended

Group 2			
T0	T1	T1-T0 (Paired-Samples Test)	
Mean ± SD	Mean ± SD	Mean Difference ± SD	*P*-Value
11.40 ± 0.94	12.52 ± 0.96	1.126 ± .804	.000***
1.29 ± 0.08	1.34 ± 0.06	.051 ± .098	.020*
1.31 ± 0.14	1.31 ± 0.12	−.0043 ± .157	.898
1.33 ± 0.08	1.39 ± 0.09	.062 ± .104	.009**
1.24 ± 0.14	1.27 ± 0.11	.033 ± .132	.241
1.27 ± 0.12	1.29 ± 0.15	.024 ± .156	.469
1.2 ± 0.15	1.32 ± 0.13	.039 ± .129	.156
11.22 ± 0.81	12.57 ± 0.87	1.345 ± .442	.000***
1.32 ± 0.11	1.34 ± 0.11	.014 ± .096	.485
1.21 ± 0.16	1.30 ± 0.13	.081 ± .157	.024*
1.36 ± 0.10	1.34 ± 0.09	−.024 ± .105	.299
1.32 ± 0.11	1.33 ± 0.10	.01 ± .097	.632
1.26 ± 0.16	1.29 ± 0.11	.034 ± .149	.289
1.34 ± 0.10	1.34 ± 0.13	−.0007 ± .112	.976

RESULTS

Cephalometric measurements were repeated by the same orthodontist 4 weeks after the initial measurements to determine intraobserver reliability. Fractal measurements were also repeated by the same maxillofacial radiologist approximately 4 weeks after the initial measurements to permit calculations of the intraclass correlation coefficient (ICC), with a confidence interval of 95%. The ICC calculations for cephalometric and fractal measurements indicated good reliability ($P = .05$).

Cephalometric Measurements

Analysis of the changes in cephalometric measurements from T0 to T1 in group 1 revealed an increase in SNB ($P < .001$) and decreases in ANB angles ($P < .001$) and Ar-Go-Me ($P < .05$). Significant increases were also detected in Co-Gn, Co-Go, Go-Gn, ANS-Me, N-ANS, and S-Go distances ($P < .001$). For dentoalveolar measurements, there was retrusion ($P < .05$) and retroclination ($P = .001$) of the upper incisors and marked protrusion and proclination of the lower incisors ($P < .001$). There were decreases of both overjet and overbite after treatment ($P < .001$) (Table 1).

Changes in SNB and ANB angles were significant in both sexes ($P < .001$), while the Ar-Go-Me angle decreased significantly only in girls ($P < .05$). The Co-Gn, Co-Go, Go-Gn, ANS-Me, N-ANS, and S-Go parameters increased significantly in both sexes, whereas the Co-A distance increased significantly only in boys ($P < .001$). Changes were significant for all of the dentoalveolar measurements in girls, but only the increases in L1i-NB distance ($P < .01$) and overjet and overbite ($P < .001$) were found to be significant in boys (Table 2).

Fractal Dimension Analysis

There was no difference between groups 1 and 2 in patient age at T0. FD analysis showed that at T0, group 1 had higher FD values in the right and left mandibular corpus ($P < .001$) and left condylar process ($P < .05$) compared to group 2 (Table 3). Analysis of changes in FD values between T0 and T1 revealed significant increases in the FD values of the right and left condylar processes and right mandibular corpus in group 1 ($P < .001$), whereas only the FD of the right condylar process increased significantly in group 2 ($P < .05$) (Table 4). When these changes were compared between the groups, group 1 showed greater changes in the FD values of the condylar process (right, $P = .001$; left, $P < .05$) and right mandibular corpus ($P < .05$) (Table 5).

When pre- (T0) and posttreatment (T1) FD values were compared between sexes for groups 1 and 2, pretreatment proc. condylaris (right) for group 1 and angulus mandibularis (right) for group 2 were significantly higher for girls ($P < .05$). Pretreatment proc. condylaris (left) was higher for boys in group 2. There was no difference between posttreatment FD values between girls and boys ($P > .05$) (Table 6). When changes in FD were compared according to sex, in group 1 only the increase in FD of the right condylar process was significant in girls ($P < .01$), whereas boys had significant changes in FD for the right and left condylar processes ($P < .001$) and right mandibular corpus ($P < .001$). In group 2, girls showed significant increases in FD of the right condylar process ($P < .05$) and right mandibular corpus ($P < .01$), while the only significant change in boys was FD of the right mandibular angle ($P < .05$) (Table 7).

Correlation Analysis

In correlation analysis between the cephalometric and FD changes in group 1, the right condylar process change was negatively correlated with GoGn/SN ($P <$ .05) and positively correlated with Co-Go ($P < .05$), although these correlations were weak (Table 8).

DISCUSSION

FD analysis, a mathematical method used for the measurement of complex structures such as trabecular bone, has long been used in the evaluation of changes in bone structures in various systemic diseases and can be applied to DPR.[10–14,17] No previous studies used FD analysis to investigate the changes in trabecular bone patterns resulting from orthodontic treatment. Despite ample research together with recent reports indicating that FD analysis successfully demonstrates changes in trabeculae, the continuing lack of consensus on the effects of functional appliance treatment prompted this study of a new method with which to investigate the changes in mandibular trabecular structures resulting from functional appliance treatment.

A study[18] comparing the effects of monoblock and twin block appliances showed that mandibular growth was activated at similar rates in both study groups. Because the main aim of the current study was to analyze changes in the mandibular area only, patients treated with monoblock or twin block appliances were not analyzed as separate groups. In addition, patients who underwent gradual activation were not included in the study. However, skeletal and dental developmental stages were considered when choosing patients for the treatment group; all patients were selected from among individuals in, or just entering, the peak pubertal growth stage.[1]

This study consisted primarily of separate FD analyses conducted in the treatment and control groups, which demonstrated that changes in FD values in the right and left condylar processes were greater in the treatment group. The differences in these areas were not very striking when considered alongside the cephalometric findings of the study. It is notable that analysis of the cephalometric radiographs of the patients in the treatment group demonstrated mandibular advancement (SNB) and significant changes in all parameters of mandibular size (Co-Gn, Co-Go, Go-Me) after treatment. With functional appliance treatment, the direction of condylar growth changes and mandibular form is altered as a result of the remodeling that occurs in certain areas of the mandible.[19,20]

The change in mandibular length induced by treatment was previously shown[5,21,22] to be closely associated with the increase in condylar growth. In the current study, when the correlations between FD and cephalometric measurements were evaluated, a positive correlation between FD of the right condylar process and ramus (Co-Go) was found. This suggested that functional orthopedic devices can indeed cause changes in the osseous structures of the condyle, and this may be associated with mandibular growth.

The results of FD analyses in this study demonstrated significant increases not only in the condylar area but also in the right mandibular body in individuals receiving treatment compared with those in the control group. Comparisons of changes in FD values between premolars in the mandible corpus according to sex showed a significant increase in both the right and left sides among boys. These changes may be associated with the increase in total length of mandibular

Table 8. Correlations Between Cephalometric Changes and Fractal Dimension (FD) Changes Between Post- (T1) and Pretreatment (T0) Periods for Group 1

		Proc. condylaris (right)	Angulus mandibula (right)	Corpus mandibula (right)	Proc. condylaris (left)	Angulus mandibula (left)	Corpus mandibula (left)
Skeletal angular measurements, °							
SNA	*r*	.127	.129	.067	−.143	.239	.107
	P	.406	.397	.663	.347	.114	.485
	N	45	45	45	45	45	45
SNB	*r*	.136	.109	−.032	.041	.123	.171
	P	.372	.476	.834	.791	.419	.262
	N	45	45	45	45	45	45
ANB	*r*	.025	−.056	.088	−.143	.108	−.058
	P	.871	.715	.565	.350	.481	.705
	N	45	45	45	45	45	45
GoGn/SN	*r*	−.350	−.153	−.024	.038	−.191	−.099
	P	.018*	.317	.877	.802	.209	.519
	N	45	45	45	45	45	45
Ar-Go-Me	*r*	−.147	−.236	−.092	.168	−.137	.023
	P	.334	.118	.550	.270	.370	.881
	N	45	45	45	45	45	45
Skeletal linear measurements, mm							
Co-A	*r*	−.007	.084	−.183	−.047	.077	−.108
	P	.965	.585	.228	.759	.615	.478
	N	45	45	45	45	45	45
Co-Gn	*r*	.023	−.103	.178	.005	.152	.180
	P	.879	.501	.241	.975	.318	.238
	N	45	45	45	45	45	45
Co-Go	*r*	.299	.055	.114	.113	.086	−.067
	P	.019*	.721	.455	.459	.572	.662
	N	45	45	45	45	45	45
Go-Gn	*r*	.152	.125	.164	−.027	.065	.149
	P	.320	.411	.282	.861	.670	.330
	N	45	45	45	45	45	45
ANS-Me	*r*	−.096	−.036	.002	−.219	.023	.018
	P	.530	.813	.991	.149	.879	.905
	N	45	45	45	45	45	45
N-ANS	*r*	−.064	−.005	.094	−.142	−.087	.010
	P	.678	.972	.541	.353	.572	.947
	N	45	45	45	45	45	45
S-Go	*r*	−.041	−.024	−.154	−.274	.037	−.051
	P	.787	.876	.311	.068	.807	.740
	N	45	45	45	45	45	45
Dentoalveolar measurements							
Overjet	*r*	−.029	.068	.144	−.268	.051	−.017
	P	.848	.658	.347	.075	.738	.910
	N	45	45	45	45	45	45
Overbite	*r*	−.005	−.038	.289	.059	.016	.157
	P	.973	.802	.054	.699	.917	.304
	N	45	45	45	45	45	45

* $P \leq .05$; ** $P \leq .01$; *** $P \leq .001$.

dimensions with treatment. In fact, treatment of mandibular deficiency does not consist only of condylar elongation. During growth, the whole mandible is repositioned posteriorly through apposition and resorption.[21]

Another important point that must be considered is that the acrylic extending over the posterior teeth of the appliance—in the belief that it may contribute to correction of the occlusal relationship—could be ground down to allow for the eruption of mandibular posterior teeth. Therefore, changes emerging in the mandibular corpus especially might not originate solely from skeletal change. This was supported by observations of an overall increase in posterior and anterior height despite no significant change in the GoGn/SN angle. The results of the correlation analysis between FD and cephalometric changes also revealed a negative correlation between GoGN/SN and FD value of the right condylar process. Pancherz[23] stated that skeletal and dental structures contributed equally to the improvements that resulted from using an activator, whereas Cozza et al.[24] reported that while both effects played a role in correcting anomalies, the skeletal effect was dominant (70%). In the current study, the positive changes in overjet and overbite did not originate from the changes in these parameters alone, and retrusion/retroclination of the upper incisors and protrusion/proclination of the lower incisors was observed, which was more significant in girls. According to researchers,[25] the movement of incisors is an undesirable, but difficult-to-eliminate, adverse effect of functional orthopedic treatment. However, it could be considered that as long as incisor positions remain within acceptable limits, this should not be regarded as unwanted movement, because the philosophy of functional jaw orthopedics is to correct malfunction and restore normal development.[21]

Limitations

The use of the FD analysis method has been shown to be suitable for assessing bone on panoramic radiographs, in the diagnosis of systemic diseases such as thalassemia and diabetes, and in many sensitive conditions, such as the postoperative evaluation of bone healing.[11–14] Although previous studies have reported high reliability of this analysis, it may be beneficial to conduct future studies using three-dimensional images.

CONCLUSIONS

- Patients treated with functional orthopedic appliances exhibited significant improvements according to clinical and cephalometric analyses.
- FD analysis of changes in the trabecular structure of the mandible demonstrated significant changes in the treatment group compared to the control group, especially in the condyle and mandibular body.
- This indicates that functional orthopedic treatments lead not only to dentoalveolar changes but also to skeletal correction by inducing mandibular bone remodeling and altering its form.

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