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Evaluation of Tooth Movement and Arch Dimension Change in the Mandible Using a New Three-dimensional Indirect Superimposition Method

Hyun-Jun Oh[1], Seung-Hak Baek[2], Il-Hyung Yang[2]

[1]Department of Dentistry, School of Dentistry, Seoul National University, [2]Department of Orthodontics, School of Dentistry, Seoul National University, Dental Research Institute, Seoul National University, Seoul, Korea

Purpose: To analyze the amount and pattern of tooth movement and the changes in arch dimension of mandibular dentition after orthodontic treatment using a new three-dimensional (3D)-indirect superimposition method.

Materials and Methods: The samples consisted of fifteen adult patients with class I bialveolar protrusion and minimal anterior crowding, treated by extraction of four first premolars with conventional sliding mechanics. After superimposition of 3D-virtual maxillary models before and after treatment using best-fit method, 3D-virtual mandibular model at each stage was placed into a common coordinate of superimposition using 3D-bite information, which resulted in 3D-indirect superimposition for mandibular dentition. The changes in mandibular dental and arch dimensional variables were measured with Rapidform 2006 (INUS Technology). Paired t-test was used for statistical analysis.

Result: The anterior teeth moved backward, displaced laterally, and inclined lingually. The posterior teeth showed statistically significant contraction toward midsagittal plane. The amounts of backward movement of anterior teeth and forward movement of posterior teeth showed a ratio of 6 : 1. Although the inter-canine width increased slightly (0.8 mm, $P<0.05$), the inter-second premolar, inter-first molar, and inter-second molar widths decreased significantly with similar amounts (2.2 mm, $P<0.05$; 2.3 mm, $P<0.01$; 2.3 mm, $P<0.001$). The molar depth decreased (6.7 mm, $P<0.001$) but canine depth did not change.

Conclusion: A new 3D-indirect superimposition of the mandibular dentitions using best-fit method and 3D-bite information can present a guideline for virtual treatment planning in terms of tooth position and arch dimension.

Key Words: Dental arch; Three-dimensional imaging; Tooth movement

Corresponding Author: **Il-Hyung Yang**
Department of Orthodontics, School of Dentistry, Seoul National University, Dental Research Institute, Seoul National University, 101 Daehak-ro, Jongno-gu, Seoul 110-749, Korea
TEL : +82-2-2072-3817, FAX : +82-2-2072-3817, E-mail : drortho@snu.ac.kr

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Introduction

Superimposition of the data before and after orthodontic treatment is one of the important analysis tools for not only clinical but also scientific research. However, orthodontists have traditionally relied on superimposition of cephalograms, which can offer two-dimensional (2D) information about skeletal and dental changes. Since the main objects of dental changes acquired from 2D-cephalometric superimposition are usually the central incisors and first molars, it has some limitations to obtain knowledge about dental changes in the other teeth between pre- and post-treatment stages. Recent advance in three-dimensional (3D) virtual model analysis can offer more realistic information of arch dimension and orthodontic tooth movement compared to the conventional 2D-cephalometric analysis[1-3].

Although sophisticated 3D-methodologies have been developed[3-7], reliable 3D-evaluation of individual tooth movement in the mandible has been infeasible unlike the maxilla. The reason that there have been limited researches about 3D-superimposition of the mandibular dentition before and after treatment is due to uniqueness in the dentoalveolar anatomy of the mandible such as no existence of apparent reference areas or stable anatomic landmarks for 3D-superimposition of the mandibular models. Although the apical base is considered not to be influenced by orthodontic tooth movement[8], it cannot be accurately reproduced in mandibular dental cast. Moreover, because the mandible is movable via the temporomandibular joints unlike the maxilla, orthodontic treatment involves not only changes in the mandibular dentition but also skeletal movement. Therefore, it is challenging to accurately estimate the 3D-change of arch dimension and orthodontic tooth movement in the mandibular dentition.

Although Heiser et al.[9] investigated the 3D-change in the mandibular arch dimension after orthodontic treatment, evaluation of orthodontic tooth movement in each tooth using superimposition was not performed. Chen et al.[10] investigated 3D tooth movement and arch dimension change in cases with obstructive sleep apnea with an oral appliance treatment with a contact-type 3D-digitizer. However, they have several limitations as follows: First, they superimposed the maxillary and mandibular models using the three occlusal contact points, not the whole 3D-bite information. Second, they did not evaluate the change between pre- and post-treatment. And third, only linear variables were measured. Therefore, the purpose of this study was to analyze the amount and pattern of orthodontic tooth movement and the changes in arch dimension in the mandibular dentition in class I bialveolar protrusion cases treated by first premolar extraction and moderate anchorage using a new 3D indirect superimposition method.

Materials and Methods

The sample consisted of 15 young adult patients with class I malocclusion and bialveolar protrusion (1 male and 14 females; Table 1). Since

Table 1. Descriptive analysis of the samples

Measurement	Value
Age (yr)	24.3±5.5
Treatment period (mo)	22.5±4.7
Cephalometric measurement	
SNA (°)	80.93±3.95
SNB (°)	77.67±3.06
ANB (°)	3.26±2.65
U1-SN (°)	111.03±5.91
FMA (°)	30.81±3.89
IMPA (°)	97.95±8.95
Upper lip to E-line (mm)	2.05±3.23
Lower lip to E-line (mm)	5.72±3.03
Amount of crowding	
Crowding (upper) (mm)	1.73±0.97
Crowding (lower) (mm)	1.6±0.97

Values are presented as mean±standard deviation.

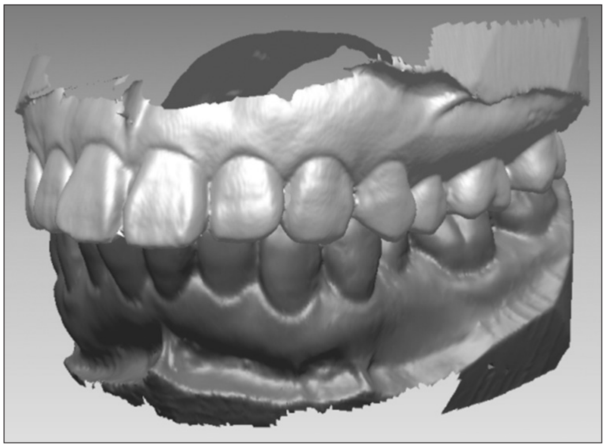

Fig. 1. Combination of three-dimensional virtual maxillary (3D-VMX) and 3D virtual mandibular (3D-VMN) models according to the 3D-bite information, which were constructed by a 3D-laser scanner and 3Txer program (Orapix).

dentoalveolar change by orthodontic treatment can vary according to the pre-treatment condition, strict selection criteria were applied. The inclusion criteria were as follow: Young adult patient with a full permanent dentition; skeletal class I malocclusion, bialveolar protrusion, and normodivergent pattern; less than 4 mm of crowding in each arch, ovoid and symmetric dental arch form; orthodontic treatment with extraction of the maxillary and mandibular first premolars, sliding mechanics without any anchorage enhancement or any usage of intermaxillary elastics; usage of preadjusted appliance (0.022×0.028 inch slot, MBT set-up; 3M-Unitek, Monrovia, CA, USA); and good treatment outcome with class I canine and molar relationships, and normal overbite and overjet. The exclusion criteria were cleft lip and

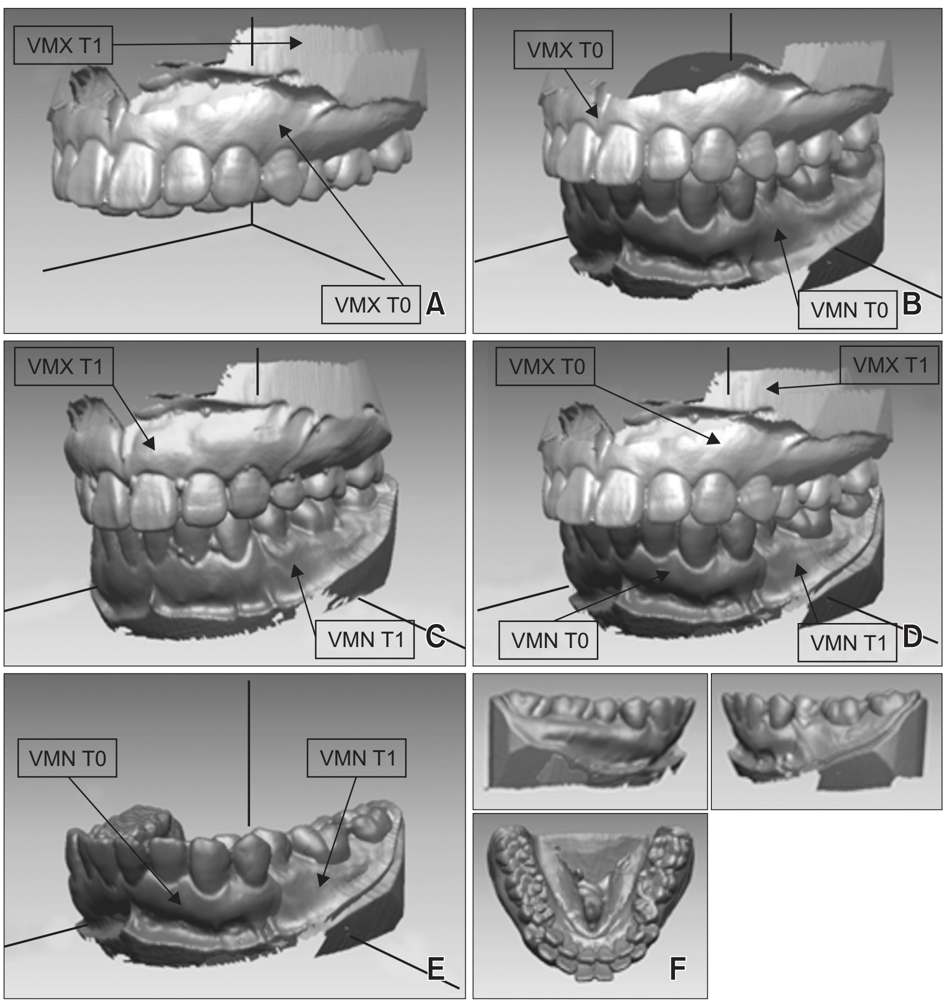

Fig. 2. Three-dimensional (3D)-indirect superimposition procedure of the 3D virtual mandibular (3D-VMN) models pre-orthodontic treatment (T0) and post-orthodontic treatment (T1). (A) Step 1. Superimposition of the 3D virtual maxillary (3D-VMX) models between T0 and T1 using best-fit method, establishing a common 3D-coordinates. (B~D) Step 2. Combination of 3D-VMX models and 3D-VMN models using 3D-bite information at T0 and T1 on a common 3D-coordinates, respectively. (E) Step 3. After removing 3D-VMX models at T0 and T1, 3D-VMN models at T0 and T1 remained. (F) Step 4. Final result of 3D-indirect superimposition of 3D-VMN models: right-side, occlusal, and left-side views.

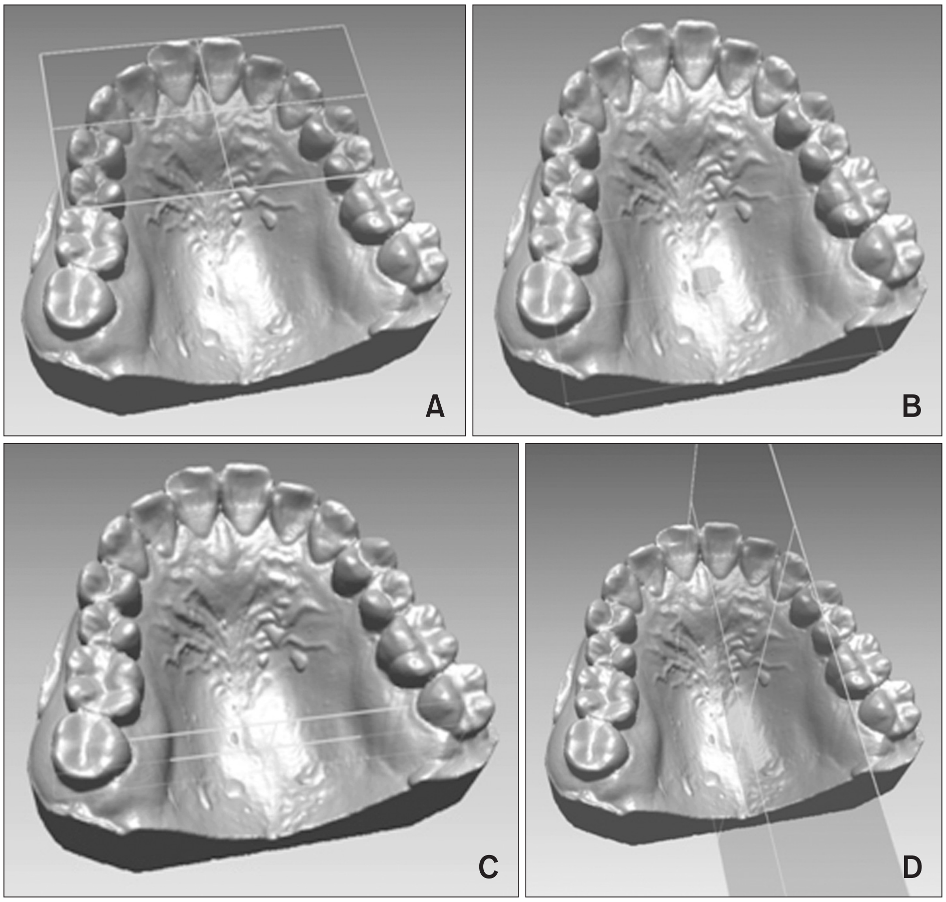

Fig. 3. Definitions of the reference planes. (A) The maxillary occlusal plane was established using the midpoint between the midpoints of the maxillary right and left central incisor edges, and the mesiobuccal cusp tip of the maxillary right (#16) and left first molars (#26). (B) The horizontal plane was set to be parallel to the maxillary occlusal plane containing the uppermost region in the midpalatal area. (C) The coronal plane was set to be perpendicular to the horizontal plane connecting the facial axis points of upper right (#17) and left second molars (#27) at the pre-orthodontic treatment (T0) stage. (D) The midsagittal plane was set to be perpendicular to the horizontal and coronal planes passing through a midpoint between the maxillary right and left central incisor edges; the origin was set at the intersection of horizontal, coronal, and midsagittal planes.

palate or any syndromes, severe facial asymmetry, temporomandibular joint disorder, and more than two dental prostheses.

The 3D virtual maxillary and mandibular models at the pre-orthodontic treatment (T0) and post-orthodontic treatment (T1) stages were obtained with a 3D laser scanner (Orapix, Seoul, Korea) and 3Txer software (Orapix) (Fig. 1). The 3D laser scanner built virtual models from dental casts with accuracy of ±0.02 mm/10 mm and resolution of 1,024×768 pixels. Afterward the digital files for virtual models were transported to 3Txer software and transformed into the specific file type for

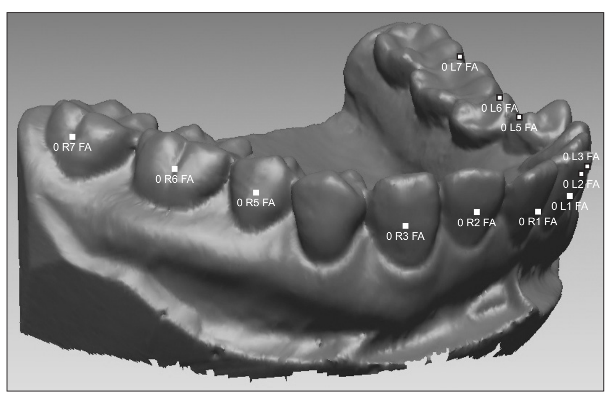

Fig. 4. The facial axis (FA) points in each tooth as reference points for measurement.

further measurement using Rapidform 2006 (INUS Technology, Seoul, Korea).

Since stable anatomic landmarks or areas have not been reported in the dentoalveolar area of the mandible, the 3D-vrtual maxillary model and 3D-bite information were used as references for placement of the 3D virtual mandibular model. 3D-bite was obtained by the 3D-laser scanning of upper and lower models in their maximum intercuspation position as one piece, from which each of upper and lower models was removed to remain digital bite information. The 3D-superimposition procedure for the 3D virtual mandibular models was as follows (Fig. 2): step 1, the 3D virtual maxillary models of T0 and T1 stages were superimposed by best-fit method using stable reference areas such as the third and fourth palatal rugae in the anterior part of the hard palate and the midpalate between the maxillary first and second molars in the posterior part of the hard palate[3]; step 2, the 3D-virtual mandibular models of T0 and T1 stages were superimposed with the 3D-virtual maxillary models of T0 and T1 stages using each 3D-bite information from registered wax bite, respectively; step 3, the 3D-virtual maxillary models of T0 and T1 stages were removed; and step

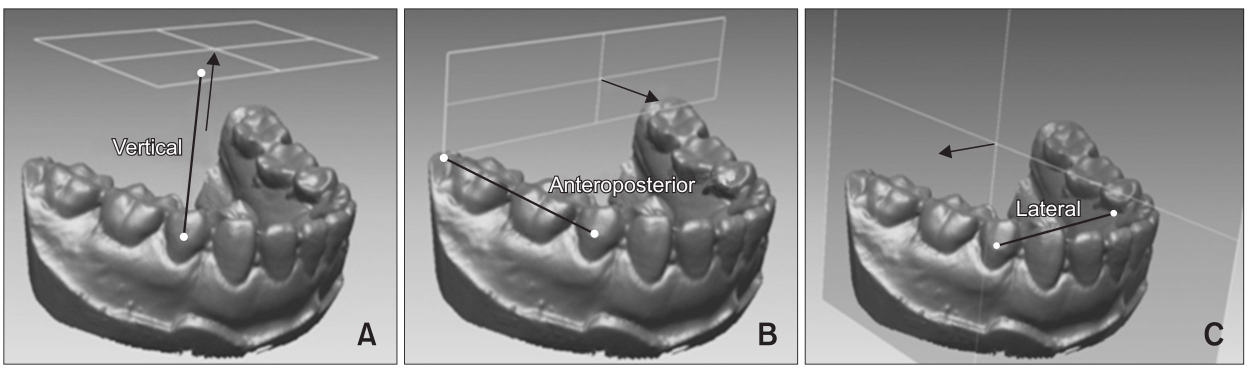

Fig. 5. Definitions of the linear variables. (A) Vertical displacement (mm): distance between facial axis (FA) point and the horizontal plane. For the difference between pre-orthodontic treatment (T0) and post-orthodontic treatment (T1) (T0~T1), positive means intrusion and negative means extrusion. (B) Anteroposterior displacement (mm): distance between FA point and the coronal plane. For T0~T1, positive means posterior movement and negative means anterior movement. (C) Lateral displacement (mm): distance between FA point and the midsagittal plane. For T0~T1, positive means contraction; negative means distraction. The direction of each arrow denotes negative values for the measurements.

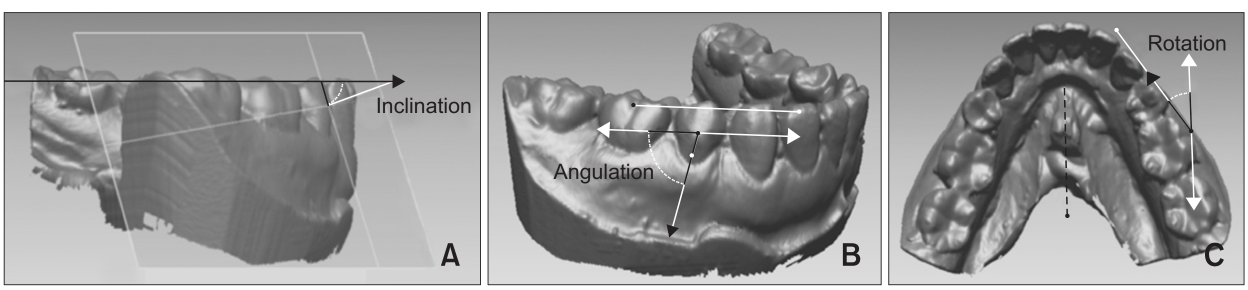

Fig. 6. Definitions of the angular variables. A tangential plane (A) on facial axis (FA) point was established for each tooth. (A) Inclination (°): the labiolingual or buccolingual slope of the clinical crown to the mandibular occlusal plane. For the difference between pre-orthodontic treatment (T0) and post-orthodontic treatment (T1) (T0~T1), positive means labioversion/buccoversion and negative means linguoversion. (B) Angulation (°): the mesiodistal slope of the clinical crown to the mandibular occlusal plane. For T0~T1, positive means distal tipping and negative means mesial tipping. (C) Rotation (°): the angle made with the tangential plane on the FA point and the mandibular midsagittal plane on the occlusal plane. For T0~T1, positive means mesial-inward rotation and negative means distal-inward rotation.

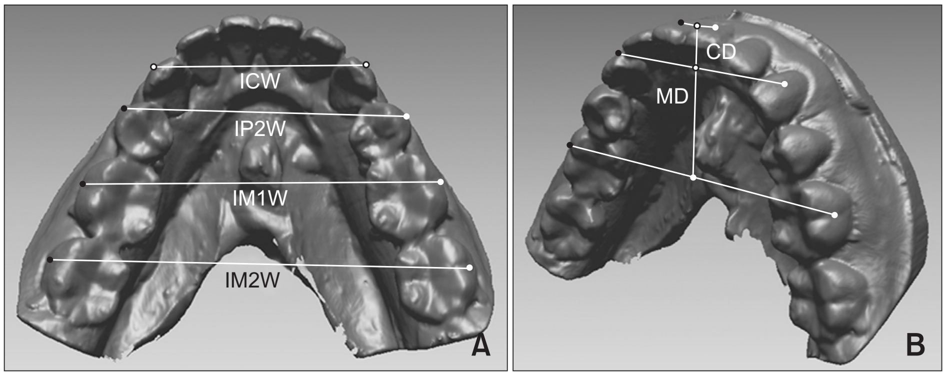

Fig. 7. Definitions of the arch dimension variables. (A) Arch width: inter-canine width (ICW), the distance between the facial axis (FA) points of right and left mandibular canines; inter-second premolar width (IP2W), the distance between the FA points of right and left mandibular second premolars; inter-first molar width (IM1W), the distance between the FA points of right and left mandibular first molars; inter-second molar width (IM2W), the distance between the FA points of right and left mandibular second molars. (B) Arch depth: canine depth (CD), the shortest distance from the midpoint between the FA points of right and left mandibular canines to the midpoint between the FA points of right and left mandibular central incisors; molar depth (MD), the shortest distance from the midpoint between the FA points of right and left mandibular first molars to the midpoint between the FA points of right and left mandibular central incisors.

4, 3D superimposition of the 3D-virtual mandibular models of T0 and T1 stages was achieved.

Definitions of the reference planes and landmarks are illustrated in Figs. 3, 4. The horizontal, coronal, and midsagittal planes of the 3D-virtual maxillary model were used as reference planes and the facial axis (FA) points by Andrews[11] of the mandibular teeth were used as a reference point for measurement of tooth movement in the mandibular dentition, respectively. The definitions of linear variables (vertical, anteroposterior, and lateral displacement), angular variables (inclination, angulation, and rotation), and arch dimension are illustrated in Figs. 5~7, respectively. The linear and angular variables and the arch dimension of the mandibular dentition were measured with Rapidform 2006.

The sample size determination was performed by a power analysis using the Sample Size Determination Program version 2.0.1 (Seoul National University Dental Hospital, Seoul, Korea). Since there was no significant difference in the values of left and right sides at T0 and T1 stages (Table 2), the mean values of both sides for each tooth were used. To analyze the test-retest reliability of the measurements, all samples were measured twice with 4 months interval by one examiner (H.J.O.). Intraclass correlation coefficient of the linear and angular variables and the arch dimension showed excellent results (Tables 3, 4). Since the measurements in this study showed normality and homoscedasticity, pared t-test was used for statistical analysis (IBM SPSS Statistics version 21.0; IBM Co., Armonk, NY, USA).

Result

1. Comparison of the Amount of Change in Each Tooth between T0 and T1 Stages (Tables 5, 6)

Mandibular central incisor (L1) moved backward (6.3 mm, $P<0.001$), displaced laterally (0.3 mm, $P<0.001$), inclined lingually (11.4°, $P<0.001$), tilted mesially (1.8°, $P<0.05$), and rotated distally (7.1°, $P<0.01$). However, there was no significant change in vertical displacement in L1 between T0 and T1 stages, respectively.

Mandibular lateral incisor (L2) and mandibular canine (L3) moved backward (6.3 mm and 6.4 mm, all $P<0.001$), displaced laterally (0.4 mm, $P<0.05$; 0.4 mm, $P<0.01$, respectively), and inclined lingually

Table 2. Comparison of the values between the right and left sides

Variable	T0			T1		
	Right side	Left side	P-value	Right side	Left side	P-value
Vertical displacement (mm)						
L1	22.81±2.70	22.81±2.64	0.978	23.30±3.11	23.23±3.00	0.451
L2	22.97±2.46	22.67±2.63	0.064	23.26±3.03	23.12±2.96	0.452
L3	23.07±1.94	23.10±2.28	0.823	23.57±2.93	23.03±2.51	0.648
L5	21.68±2.12	21.71±1.94	0.894	22.20±2.29	21.86±2.46	0.293
L6	21.46±1.88	21.55±2.02	0.438	21.85±1.86	21.18±2.34	0.086
L7	20.05±2.10	20.36±2.24	0.175	20.49±1.76	19.92±2.61	0.160
Anteroposterior displacement (mm)						
L1	40.77±2.91	40.72±2.66	0.796	34.43±2.04	34.39±2.11	0.515
L2	39.06±2.24	38.85±2.32	0.237	32.72±1.76	32.57±2.05	0.502
L3	35.47±1.99	35.39±1.85	0.702	29.08±1.44	28.90±1.80	0.601
L5	21.32±1.84	21.59±1.40	0.376	22.36±1.44	22.31±1.86	0.911
L6	12.80±1.57	13.16±1.57	0.091	13.69±1.52	13.36±1.87	0.550
L7	1.49±0.93	2.14±1.01	0.218	2.26±1.19	2.75±1.48	0.270
Lateral displacement (mm)						
L1	2.84±0.76	2.71±0.74	0.706	3.03±1.48	3.12±1.45	0.905
L2	8.90±1.05	8.72±0.95	0.655	9.16±1.53	9.32±1.38	0.829
L3	15.08±1.01	14.99±0.85	0.816	15.40±1.30	15.45±1.39	0.940
L5	21.92±1.39	21.69±1.60	0.611	20.75±1.10	20.60±1.65	0.793
L6	25.59±1.36	25.53±1.65	0.774	24.43±1.14	24.32±1.38	0.783
L7	28.68±1.47	28.53±1.28	0.516	27.56±1.58	27.35±0.97	0.522
Inclination (mm)						
L1	80.95±7.72	80.07±6.83	0.522	91.39±6.95	92.47±6.53	0.104
L2	82.39±6.69	84.05±6.33	0.200	93.43±6.94	94.30±7.52	0.441
L3	89.94±6.62	91.13±7.84	0.497	99.74±7.02	102.43±6.39	0.431
L5	115.64±7.55	114.18±7.58	0.177	112.90±6.06	112.68±9.31	0.915
L6	121.22±7.39	123.94±5.83	0.145	121.03±5.65	124.06±8.24	0.209
L7	124.42±6.58	122.25±9.11	0.206	126.80±9.51	126.39±7.56	0.861
Angulation (mm)						
L1	88.65±4.54	88.16±3.91	0.756	88.75±3.65	91.73±2.68	0.055
L2	90.39±5.77	91.35±4.71	0.541	88.59±4.26	92.07±4.48	0.321
L3	91.93±6.19	93.33±7.31	0.438	91.35±4.83	92.68±5.51	0.384
L5	97.69±8.39	104.15±9.30	0.220	95.30±8.04	99.33±5.56	0.159
L6	96.18±9.35	96.13±8.85	0.983	90.25±6.67	93.07±8.59	0.292
L7	98.99±13.03	101.99±13.12	0.344	96.31±12.29	97.75±10.23	0.618
Rotation (mm)						
L1	90.75±10.45	88.77±7.38	0.274	97.03±2.07	96.78±3.00	0.797
L2	116.85±15.63	114.80±11.18	0.505	113.87±4.50	115.55±4.50	0.088
L3	138.10±9.26	137.33±12.49	0.783	132.77±7.42	132.88±6.23	0.924
L5	155.33±10.90	149.27±17.32	0.116	152.04±7.18	148.35±11.23	0.170
L6	157.51±16.41	157.65±13.37	0.964	160.98±11.74	161.31±9.35	0.924
L7	154.34±13.73	149.92±14.24	0.321	156.94±11.75	154.02±7.65	0.259

T0: pre-treatment, T1: post-treatment, L1: mandibular central incisor, L2: mandibular lateral incisor, L3: mandibular canine, L5: mandibular second premolar, L6: mandibular first molar, L7: mandibular second molar.

Values are presented as mean±standard deviation.

Paired t-test was performed to find out the difference between right and left side measurements.

Table 3. Intraclass correlation coefficients of intra-examiner reliability on the linear and angular variables

Variable	Intra-examiner reliability			
	Right side	P-value	Left side	P-value
Vertical displacement				
L1	0.927	<0.001	0.922	<0.001
L2	0.920	<0.001	0.922	<0.001
L3	0.915	<0.001	0.903	<0.001
L5	0.887	<0.001	0.859	<0.001
L6	0.844	<0.001	0.865	<0.001
L7	0.736	<0.01	0.826	<0.01
Anteroposterior displacement				
L1	1.000	<0.001	1.000	<0.001
L2	1.000	<0.001	1.000	<0.001
L3	1.000	<0.001	1.000	<0.001
L5	0.999	<0.001	0.999	<0.001
L6	1.000	<0.001	1.000	<0.001
L7	0.998	<0.001	0.999	<0.001
Lateral displacement				
L1	0.994	<0.001	0.998	<0.001
L2	0.998	<0.001	0.998	<0.001
L3	0.998	<0.001	0.993	<0.001
L5	1.000	<0.001	0.999	<0.001
L6	0.999	<0.001	0.999	<0.001
L7	0.999	<0.001	0.999	<0.001
Inclination				
L1	0.998	<0.001	0.999	<0.001
L2	0.997	<0.001	0.994	<0.001
L3	1.000	<0.001	0.994	<0.001
L5	0.997	<0.001	0.992	<0.001
L6	0.981	<0.001	0.995	<0.001
L7	0.991	<0.001	0.999	<0.001
Angulation				
L1	0.911	<0.001	0.840	<0.001
L2	0.968	<0.001	0.972	<0.001
L3	0.982	<0.001	0.979	<0.001
L5	0.984	<0.001	0.977	<0.001
L6	0.941	<0.001	0.980	<0.001
L7	0.991	<0.001	0.997	<0.001
Rotation				
L1	0.984	<0.001	0.989	<0.001
L2	0.998	<0.001	0.993	<0.001
L3	0.999	<0.001	0.993	<0.001
L5	0.993	<0.001	0.998	<0.001
L6	0.998	<0.001	0.983	<0.001
L7	0.994	<0.001	0.997	<0.001

L1: mandibular central incisor, L2: mandibular lateral incisor, L3: mandibular canine, L5: mandibular second premolar, L6: mandibular first molar, L7: mandibular second molar.

Landmarks were digitized twice and all the variables were measured twice with four months interval by one examiner (H.J.O.). Intraclass correlation coefficients value was significantly different from 0.

Table 4. Intraclass correlation coefficients of intra-examiner reliability on arch dimension variables

Variable	Intra-examiner reliability	P-value
ICW	0.999	<0.001
IP2W	1.000	<0.001
IM1W	1.000	<0.001
IM2W	0.983	<0.001
CD	1.000	<0.001
MD	1.000	<0.001

ICW: intercanine width (the distance between the facial axis [FA] point of right and left canines), IP2W: inter-second premolar width (the distance between the FA point of right and left second premolars), IM1W: inter-first molar width (the distance between the FA point of right and left first molars), IM2W: inter-second molar width (the distance between the FA point of right and left second molars), CD: canine depth (the shortest distance from a line connecting the FA point of right and left canines to the midpoint between FA point of the right and left central incisors), MD: molar depth (the shortest distance from a line connecting the FA point of the mandibular right and left first molars to the midpoint between FA point of the mandibular right and left central incisors).

Landmarks were digitized twice and all the variables were measured twice with four months interval by one examiner (H.J.O.).

Intra-examiner reliability was obtained by one-way random effects model.

Intraclass correlation coefficients value was significantly different from 0.

(10.6^{o}, P<0.001). There was no significant change in vertical displacement, angulation, and rotation in L2 and L3 between T0 and T1 stages, respectively.

Although mandibular second premolar (L5), mandibular first molar (L6), and mandibular second molar (L7) showed similar amounts of contraction toward the midsagittal plane (medial displacement) (1.1 mm, P<0.01; 1.2 mm, P<0.01; 1.2 mm, P<0.001, respectively), they did not exhibit significant change in vertical displacement, forward displacement, inclination, angulation, and rotation.

During extraction space closure, backward movement of L1, L2, and L3 and forward movement of L5, L6, and L7 occurred approximately 6 : 1 ratio, and distraction of L1, L2, and L3 and contraction of L5, L6, and L7 happened approximately 1 : 3 ratio to maintain the continuity of dental arch.

2. Comparison of the Arch Dimension between T0 and T1 Stages (Table 7)

Although the inter-canine width increased (0.8 mm, P<0.05), the inter-second premolar width, inter-first molar width, and inter-second molar width decreased with similar amounts (2.2 mm, P<0.05; 2.3 mm, P<0.01; 2.3 mm, P<0.001, respectively).

Although canine depth (CD) remained unchanged due to small amount of anterior crowding at the T0 stage, molar depth (MD) was significantly decreased (6.7 mm, P<0.001) mainly by backward movement of L1, L2, and L3 during retraction process.

Discussion

Although Shapiro[12], Shearn and Woods[13], and Chen et al.[14] assessed the change in the mandibular arch dimension and the movement of a few teeth using 2D-cephalometric superimposition, individual tooth movement of the whole mandibular dentition using 3D-superimposition has not been reported yet.

The finding that the amount of vertical displacement did not show significant changes in every tooth (Table 5) seems to be occurred because orthodontic treatment without any anchorage reinforcement or without usage of intermaxillary elastics did not significantly change the vertical dimension and cant of occlusal plane[15-18]. According to Cho et al.[3], most of the maxillary teeth displaced vertically (from 2.9 mm extrusion to 1.0 mm intrusion). These results were consistent with Deguchi et al.[19], which showed a greater amount of tooth movement in the vertical direction in the maxillary teeth compared to the mandibular teeth.

In terms of the anteroposterior displacement, L1, L2, and L3 showed significant backward movement with similar amounts (6.3 mm, 6.3 mm, and 6.4 mm,

Table 5. Linear variables between T0 and T1 stages

Linear variable	T0	T1	P-value	T0~T1	Power (1−β)
Vertical (mm)					
L1	22.81±2.67	23.27±3.06	0.404	–0.45±2.04	0.125
L2	22.82±2.54	23.19±3.00	0.455	–0.37±1.85	0.112
L3	23.09±2.11	23.30±2.71	0.635	–0.21±1.69	0.073
L5	21.69±2.03	22.03±2.37	0.205	–0.34±0.98	0.240
L6	21.51±1.95	21.51±2.10	0.968	–0.01±0.62	0.050
L7	20.21±2.17	20.21±2.19	0.999	0.00±0.98	0.050
Anteroposterior (mm)					
L1	40.74±2.79	34.41±2.08	<0.001	6.33±1.85	1.000
L2	38.96±2.28	32.65±1.91	<0.001	6.31±1.66	1.000
L3	35.43±1.92	28.99±1.62	<0.001	6.44±1.46	1.000
L5	21.46±1.62	22.34±1.65	0.051	–0.88±1.58	0.519
L6	12.98±1.57	13.53±1.69	0.089	–0.55±1.16	0.402
L7	1.82±0.97	2.51±1.34	0.065	–0.69±1.33	0.465
Lateral (mm)					
L1	2.78±0.75	3.07±1.46	<0.001	–0.30±0.21	0.999
L2	8.81±1.00	9.24±1.46	<0.05	–0.42±0.57	0.756
L3	15.03±0.93	15.42±1.34	<0.01	–0.39±0.49	0.817
L5	21.81±1.50	20.67±1.37	<0.01	1.13±1.39	0.833
L6	25.56±1.50	24.37±1.26	<0.01	1.19±1.16	0.958
L7	28.61±1.38	27.45±1.28	<0.001	1.15±0.92	0.994

T0: pre-treatment, T1: post-treatemt, L1: mandibular central incisor, L2: mandibular lateral incisor, L3: mandibular canine, L5: mandibular second premolar, L6: mandibular first molar, L7: mandibular second molar.

Values are presented as mean±standard deviation.

Paired t-test was performed.

T0~T1 means the amount of displacement between T0 and T1.

Vertical displacement to the horizontal plane: intrusion (+), extrusion (–).

Anteroposterior displacement to the coronal plane: posterior movement (+), anterior movement (–).

Lateral displacement to the midsagittal plane: contraction movement (+), distraction movement (–).

all P<0.001; Table 5). However, L5, L6, and L7 did not exhibit significant forward movement (0.9 mm, 0.6 mm, and 0.7 mm, all P>0.05; Table 5), which was different from Cho et al.[3] which dealt with the maxillary teeth. This difference seemed to be originated by different anchorage values between the maxilla and mandible. Since the mandibular posterior teeth can resist anchorage loss better than the maxillary posterior teeth, the maxillary teeth tend to move faster than those in the mandible when orthodontic force is applied[20]. Deguchi et al.[19] reported that a greater amount of tooth movement in the mesiodistal direction was observed in the maxillary teeth compared to the mandibular teeth.

In terms of lateral displacement, all the mandibular teeth showed significant displacement with opposite direction (distraction in L1, L2, and L3; and contraction in L5, L6, and L7; Table 5), which was the same results in the maxillary dentition with Cho et al.'s study[3]. This phenomenon seems to be due to change of the dental arch form to restore the continuity between the anterior and posterior teeth which had been separated by extraction of the mandibular first premolars.

Table 6. Angular variables between T0 and T1 stages

Angular variable	T0	T1	P-value	T0~T1	Power (1−β)
Inclination (°)					
L1	80.51±7.27	91.93±6.74	<0.001	−11.42±3.95	1.000
L2	83.22±6.51	93.86±7.23	<0.001	−10.64±3.41	1.000
L3	90.54±7.23	101.08±6.70	<0.001	−10.55±5.45	1.000
L5	114.91±7.56	112.79±7.69	0.152	2.12±5.43	0.291
L6	122.58±6.61	122.54±6.95	0.975	0.04±4.62	0.050
L7	123.33±7.85	126.59±8.53	0.066	−3.26±6.33	0.459
Angulation (°)					
L1	88.40±4.22	90.24±3.16	<0.05	−1.83±3.13	0.559
L2	90.87±5.24	90.33±4.37	0.661	0.54±4.67	0.070
L3	92.63±6.75	92.01±5.17	0.719	0.62±6.51	0.064
L5	100.92±8.84	97.31±6.80	0.103	3.61±8.00	0.370
L6	96.15±9.10	91.66±7.63	0.069	4.50±8.84	0.451
L7	100.49±13.08	97.03±11.26	0.290	3.46±12.18	0.177
Rotation (°)					
L1	89.76±8.91	96.90±2.54	<0.01	−7.14±7.45	0.932
L2	115.82±13.41	114.71±4.50	0.706	1.12±11.23	0.065
L3	137.72±10.88	132.82±6.82	0.056	4.89±9.08	0.493
L5	152.30±14.11	150.19±9.20	0.465	2.10±10.85	0.108
L6	157.58±14.89	161.14±10.55	0.253	−3.57±11.60	0.199
L7	152.13±13.99	155.48±9.70	0.247	−3.35±10.72	0.204

T0: pre-treatment, T1: post-treatemt, L1: mandibular central incisor, L2: mandibular lateral incisor, L3: mandibular canine, L5: mandibular second premolar, L6: mandibular first molar, L7: mandibular second molar.

Values are presented as mean±standard deviation.

Paired t-test was performed.

T0~T1 means the amount of angular change between T0 and T1.

Inclination: labioversion (+), linguoversion (−).

Angulation: distal tipping (+), mesial tipping (−).

Rotation: mesial-in rotation, (+), distal-in rotation (−).

Table 7. Arch dimension variables between T0 and T stages

Variable	T0	T1	P-value	T0~T1	Power (1−β)
ICW (mm)	30.07±1.09	30.80±1.20	<0.01	−0.81±0.98	0.845
IP2W (mm)	43.60±2.43	41.38±1.66	<0.01	2.23±2.75	0.831
IM1W (mm)	51.10±2.92	48.78±2.07	<0.01	2.32±2.29	0.954
IM2W (mm)	57.12±2.60	54.93±2.33	<0.001	2.26±1.87	0.991
CD (mm)	5.48±1.07	5.47±0.79	1.000	0.00±0.93	0.050
MD (mm)	27.84±1.77	21.09±1.26	<0.001	6.71±1.11	1.000

T0: pre-treatment, T1: post-treatemt, ICW: intercanine width, IP2W: inter-second premolar width, IM1W: inter-first molar width, IM2W: inter-second molar width, CD: canine depth, MD: molar depth.

Values are presented as mean±standard deviation.

Paired t-test was performed.

Compared to Cho et al.'s study[3], the amount of distraction and contraction in the mandibular teeth were smaller than those in the maxillary teeth (distraction: 0.3 to 0.4 mm in this study vs. 0.7 to 2.6 mm in Cho et al.'s study; contraction: 1.1 to 1.2 mm in this study vs. 1.2 to 1.4 mm in Cho et al.'s study; Table 5). These results were consistent with Deguchi et al.'s study[19], which a significantly greater amount of tooth movement in the mesiodistal direction was observed in the maxillary teeth compared with the mandibular teeth.

In terms of the inclination change, the anterior teeth (L1, L2, and L3) inclined more lingually as a result of en-masse retraction procedure (11.4^o, P<0.001; 10.6^o, P<0.001; 10.6^o, P<0.001, respectively; Table 6). However, the posterior teeth (L5, L6, and L7) did not show significant change because they had higher anchorage value and could resist inclination change better than the maxillary second molar[19].

The finding that only L1 showed statistically significant changes in distal-in rotation and mesial-tipping (7.1^o and 1.8^o, respectively; Table 6) seemed to be occurred due to decrowding procedure in mild crowding (less than 4 mm) concentrated on the L1 area at T0 stage. On the other hand, there was no significant change in rotation and angulation in the other teeth.

Compared to Cho et al.'s study[3] which showed mesial-in rotation of the maxillary posterior teeth (4^o to 5^o), the mandibular posterior teeth did not show significant change in rotation (Table 6). This might be due to difference in root shapes between maxillary and mandibular posterior teeth. The maxillary posterior teeth have a thick and round-shaped palatal root which can be a center of rotation when orthodontic force is applied. On the other hand, the mandibular posterior teeth have two or three roots with mesiodistally wide shape and can resist the rotation by orthodontic force. In addition, the sliding mechanics used for en-masse retraction process might be one of the reasons of no significant angulation change. The advantage of sliding mechanics over loop mechanics is known to be less tipping movement.

In the results of changes in arch dimension, increase in inter-canine width (0.8 mm, P<0.01; Table 7) might result from the lateral displacement and decrowding process in L1, L2, and L3. Decrease in inter-second premolar, inter-first molar, inter-second molar widths (2.2 mm, P<0.01; 2.3 mm, P<0.01; 2.3 mm, P<0.001, respectively; Table 7) occurred by contraction of L5, L6, and L7 during extraction space closure. The pattern of changes in arch dimension was in accordance with previous studies[12,13].

Compared to Cho et al.'s study[3] which used the FA points for measuring individual tooth position and the midpoint of incisal edge or the cusp tip of each tooth for measuring the arch dimension variables, this study consistently used the FA points for measuring both arch dimension and individual tooth position. Therefore, the results of this study might give more meaningful data in terms of bracket slot level. However, further studies will be needed to investigate the amount and pattern of tooth movement and the changes in arch dimension in cases with class II or class III malocclusion.

Although the 3D indirect superimposition method in this study showed one of the digital ways of superimposition for mandibular models, there were several procedures that had to be done by the operator. This means that errors could be added to a whole procedure by the manual steps. Further development of automatic algorithm for superimposing palatal rugae areas by computer should be followed.

Conclusion

This study suggested a new 3D-indirect superimposition of the mandibular dentitions using best-fit method and 3D-bite information. The data obtained in this study can be used as a guideline for virtual treatment planning in terms of tooth position and arch dimension in the mandibular dentition.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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