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Three-dimensional cone beam computed tomography analysis of temporomandibular joint response to the Twin-block functional appliance

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Objective: To propose a three-dimensional (3D) method for evaluating temporomandibular joint (TMJ) changes during Twin-block treatment. **Methods:** Seventeen patients with Class II division 1 malocclusion treated using Twin-block and nine untreated patients with a similar malocclusion were included in this research. We collected their cone beam computed tomography (CBCT) data from before and 8 months after treatment. Segmentations were constructed using ITK-SNAP. Condylar volume and superficial area were measured using 3D Slicer. The 3D landmarks were identified on CBCT images by using Dolphin software to assess the condylar positional relationship. 3D models of the mandible and glenoid fossa of the patients were constructed and registered via voxel-based superimposition using 3D Slicer. Thereafter, skeletal changes could be visualized using 3DMeshMetric in any direction of the superimposition on a color-coded map. All the superimpositions were measured using the same scale on the distance color-coded map, in which red color represents overgrowth and blue color represents resorption. **Results:** Significant differences were observed in condylar volume, superficial area, and condylar position in both groups after 8 months. Compared with the control group (CG), the Twin-block group exhibited more obvious condyle-fossa modifications and joint positional changes. Moreover, on the color-coded map, more obvious condyle-fossa modifications could be observed in the posterior and superior directions in the Twin-block group than in the CG. **Conclusions:** We successfully established a 3D method for measuring and evaluating TMJ changes caused by Twin-block treatment. The treatment produced a larger condylar size and caused condylar positional changes.
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Key words: Temporomandibular joint, Computed tomography, Three-dimensional cephalometrics, Functional

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INTRODUCTION

The Twin-block appliance has been widely used to correct mandibular retrognathism. It enhances and/or redirects mandibular growth to achieve a normal dental relationship and facial esthetic. However, whether Twin-block has a significant influence on mandibular growth remains unclear.

Several clinical studies have concentrated on evaluating the skeletal effects of Twin-block treatment.[1-6] While some studies found that Twin-block treatment produced obvious mandibular growth, others claimed that it caused dentoalveolar changes with minute skeletal effects. Mandibular growth depends on temporomandibular joint (TMJ) response. Nevertheless, TMJ changes associated with Twin-block treatment need to be evaluated.

Cone beam computed tomography (CBCT) is widely used in clinical diagnosis. The volumetric analysis afforded by CBCT has proven reliable and accurate in the evaluation of condylar size.[7] Recent studies investigated the effects of the Twin-block appliance on the TMJ by using CBCT and reported the presence of forward condylar positioning and remodeling.[8-10] However, "effective" TMJ changes include three components (each separately or all three in combination): condylar modifications, glenoid fossa modifications, and condylar displacement in the fossa.[11] In addition, there is still a lack of three-dimensional (3D) methods to more comprehensively evaluate TMJ changes.

Three methods for processing 3D superimposition are currently available: (1) landmark-based, (2) surface-based, and (3) voxel-based 3D superimposition. Only voxel-based superimposition can avoid the interferences caused by the placement of landmarks. Cevidanes et al. were the first to use the voxel-based method for fully automated 3D superimposition in dentistry.[12,13] Different characteristics of growth can be observed when superimposing on different structures. The method of superimposition on the cranial fossa can help assess maxillary positional and remodeling changes relative to those of the anterior cranial fossa.[14] The method of superimposition on the mandibular body mask (mandible without teeth, alveolar bone, rami, and condyles) can help evaluate the therapeutic effect on the condyle.[15]

The objective of this study was to develop a 3D CBCT virtual evaluation method based on voxel-based superimposition to analyze effective TMJ changes occurring when using the Twin-block appliance in patients with Class II division 1 malocclusion and in a comparable control group (CG) of untreated patients.

MATERIALS AND METHODS

Patients

This study was approved by the Nanjing Medical University Research Ethical Committee (IRB No. 2012.03.1 v1.1). The Twin-block sample consisted of 17 patients (9 males and 8 females), while the untreated sample that showed an inclination towards later treatment consisted of 9 patients (4 males and 5 females). The Twin-block sample was classified as the experimental group (EG) and the untreated sample as the CG.

All these patients had the following characteristics: (1) Class II division 1 malocclusion, (2) overjet greater than 5 mm, (3) Class II skeletal pattern with A point-Nasion-B point angle > 5°, (4) stage 3 or 4 cervical vertebrae maturation indicators (CVMIs),[16] and (5) no TMJ diseases.

Data collection

The patients underwent CBCT using NewTom VGi evo (Cefla S.C., Imola, Italy) with a 17 seconds scan time, 18 × 16-cm field of view, and 0.5-mm voxel size. All the scans were performed before (T0) and approximately 8 months after treatment (T1).

The flow chart in Figure 1 describes the overview of the analysis procedures for evaluating TMJ changes.

Quantitative evaluation of temporomandibular joint changes

We constructed segmentations of the mandible and glenoid fossa based on the CBCT data by outlining the boundaries using semiautomatic discrimination procedures, wherein we could edit and check each slice (ITK-SNAP ver. 3.6, http://www.itksnap.org).

Head orientation was achieved along two planes: the midsagittal and Frankfort horizontal planes. The midsagittal plane was defined by the basion, crista galli, and glabella landmarks. The Frankfort horizontal plane was defined by the right and left orbitale landmarks and the midpoint of the right and left porion landmarks.

To eliminate the influence of growth on condylar volumetric measurements, the first cut was parallel to the Frankfort horizontal plane, and the following cut was parallel to the first cut and was set at the most inferior part of the sigmoid notch.[17] The surface model was constructed, and condylar volume and superficial area were measured using 3D Slicer (3D Slicer ver. 4.6.0, http://www.slicer.org).

To assess TMJ position, we measured the width of the joint spaces via 3D landmarks by using Dolphin (ver. 11.9.20, Dolphin Imaging & Management Solutions, Chatsworth, CA, USA). On the coronal views, the anterior point of the condyle was defined where the first radiopaque point was viewed on the computed tomography (CT) image. The anterior joint space (AJS) was defined

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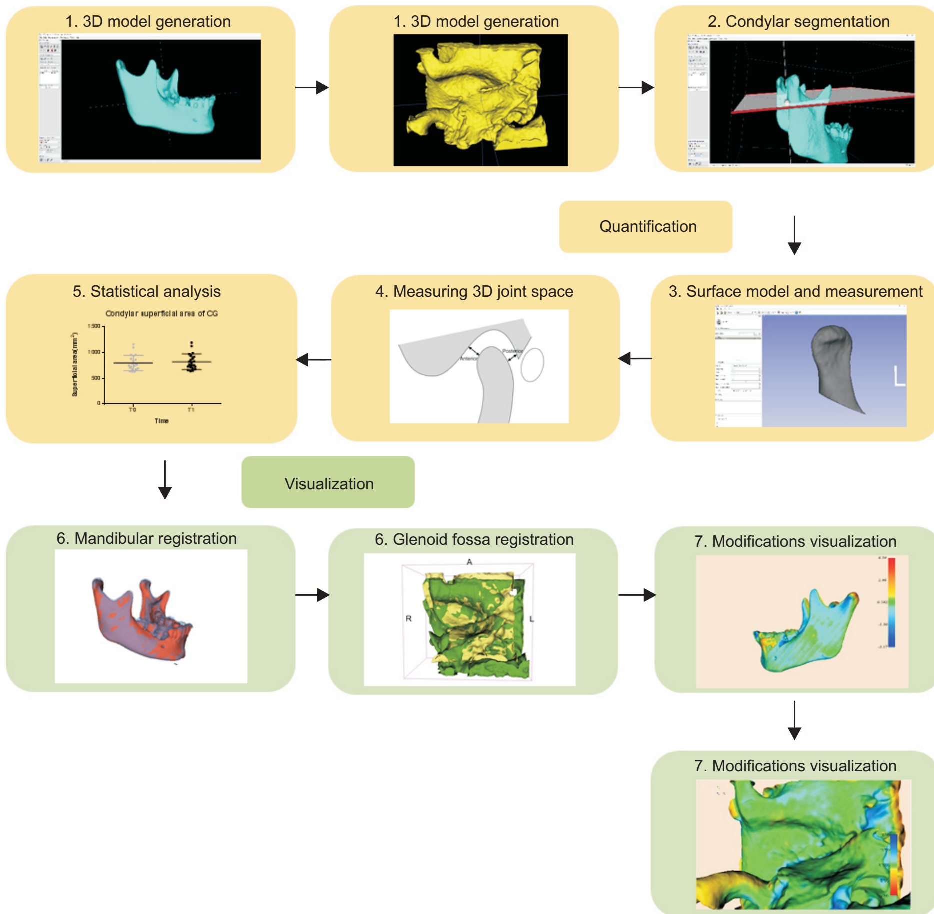

Figure 1. Technical route of the experiment. 1, Construction of the three-dimensional (3D) segmentations of the mandible and glenoid fossa. 2, Performing condylar segmentation. 3, Generating the surface model and performing volumetric measurements of the condyle. 4, Measuring the joint space by using 3D landmarks. 5, Performing the statistical analysis. 6, Registering the condyle-fossa based on the voxels. 7, Visualization of condyle-fossa modifications using the distance color-coded map.

as the shortest distance from the most anterior point of the condyle to the articular eminence on the sagittal view. The posterior point of the condyle was defined where the last radiopaque point was viewed on the CT image. The posterior joint space (PJS) was defined as the shortest distance from the most posterior point of the condyle to the tympanic part of the temporal bone. The joint space index (JSI) was calculated to compensate for individual variations in TMJ sizes by using the following equation:[18]

$$JSI = [(PJS - AJS)/(PJS + AJS)] \times 100$$

Qualitative assessment of temporomandibular joint changes

The segmentations limited the anatomic region of interest for the 3D Slicer CMF Tool (3D Slicer ver. 4.6.0, http://www.slicer.org) to perform voxel-based superimposition. Different characteristics of growth could be observed when superimposing different structures. To assess condylar growth and changes, the stable structures of the mandible were selected for mandibular registration, including the mandible without teeth, alveolar bone, rami, and condyles.[15] The cranial fossa was selected for maxillary superimposition. The anterior cranial base structures were composed of the anterior wall of the sella, anterior clinoid processes, planum sphenoidale, lesser wings of the sphenoid, superior aspect of the ethmoid and cribriform plate, cortical ridges on the medial and superior surfaces of the orbital roofs, and inner cortical layer of the frontal bones. These structures had completed growth by the time an individual was 7 years old.[14,19]

To explore the skeletal changes of the condyle-fossa, 3DMeshMetric (3DMetricTools ver. 1.4.3, http://www.nitrc.org/projects/meshmetric3d/) was used to visualize growth and remodeling in each patient. 3DMeshMetric is a visualization tool based on the visualization toolkit library. This tool can visualize meshes on the basis of color and opacity. It is also available as an extension in 3D Slicer. All the superimpositions were measured using the same scale on the distance color-coded map, in which red color represents overgrowth and blue color represents resorption. Moreover, the skeletal changes could be observed along each direction.

Statistical analysis

All analyses were performed using IBM SPSS Statistics for Windows, ver. 23.0 (IBM Corp., Armonk, NY, USA). The differences in sex and CVMI distribution were assessed using the chi-squared test, and differences in age were assessed using the independent *t*-test. The measurements were performed two times by the same examiner, with a 1-month interval between measurements, and the measurements were evaluated using intraclass correlation coefficients. The results showed great intraexaminer repeatability (Table 1). The Shapiro–Wilk normality test and Levene's test for homogeneity of variance were applied to each of the continuous variables. Condylar volume and superficial area in the CG and the AJS and PJS in the EG were not normally distributed, and they were then analyzed using the nonparametric rank-sum test. Condylar volume and superficial area in the CG and EG at T0 were also analyzed using the nonparametric rank-sum test. Other continuous variables were normally distributed. The paired *t*-test was chosen to analyze the changes in condylar volume and superficial area in the EG from T0 to T1. The paired *t*-test was also chosen to analyze the positional changes in the CG from T0 to T1.

Owing to significant differences in age between the CG and EG, covariance analysis was used to compare the absolute increase in condylar volume and superficial area between the groups by controlling for age.

The significance was set at $p < 0.05$.

Table 1. The reliability of measurements

Measurement	ICCs	95% CI	
		LL	UL
CGT0-V	0.995	0.986	0.998
CGT1-V	0.991	0.977	0.997
CGT0-S	0.952	0.877	0.982
CGT1-S	0.973	0.963	0.990
EGT0-V	0.909	0.826	0.954
EGT1-V	0.941	0.885	0.970
EGT0-S	0.922	0.850	0.960
EGT1-S	0.910	0.827	0.954

The measurements show great repeatability.
ICCs, Intraclass correlation coefficients; CI, confidence interval; LL, lower limit; UL, upper limit; CGT0-V, the volume of the control group before treatment; CGT1-V, the volume of the control group 8 months after treatment; CGT0-S, the superficial area of the control group before treatment; CGT1-S, the superficial area of the control group 8 months after treatment; EGT0-V, the volume of the experimental group before treatment; EGT1-V, the volume of the experimental group 8 months after treatment; EGT0-S, the superficial area of the experimental group before treatment; EGT1-S, the superficial area of the experimental group 8 months after treatment.

RESULTS

Table 2 provides information about the samples, including sex, age, and CVMIs. No significant differences

Table 2. Information about the samples

Variable	CG	EG	*p*-value
Sex (male/female)	4/5	9/8	> 0.99
Age (yr)	10.80 ± 0.80	11.77 ± 1.26	0.047*
CVMI (CS3/CS4)	4/5	8/9	> 0.99

Values are presented as the mean ± standard deviation.
Sex indicates the composition of men and women in each group; CVMI indicates the composition of stage 3 or 4 cervical vertebrae maturation indicators (CS3 or CS4, respectively).
The chi-squared tests were performed to assess sex and CVMI distributions in the control and experimental groups. Age is assessed using the independent *t*-test.
CG, Control group; EG, experimental group.
*$p < 0.05$.

Table 3. The changes of condylar volume and superficial area in CG and EG

Variable	T0	T1	*p*-value
Volume			
CG	1,454.11 ± 107.38	1,509.79 ± 109.51	0.000***
EG	1,399.73 ± 47.71	1,613.42 ± 64.12	0.000***
Superficial area			
CG	784.12 ± 37.37	805.96 ± 37.66	0.000***
EG	786.44 ± 18.84	860.41 ± 24.14	0.000***

Values are presented as the mean ± standard deviation.
Condylar volume and superficial area in the control group are analyzed using the nonparametric rank-sum test. Condylar volume and superficial area in the experimental group are analyzed using the paired *t*-test.
CG, Control group; EG, experimental group; T0, before treatment; T1, 8 months after treatment.
***$p < 0.001$.

were observed in the distribution of sex (chi-squared $p > 0.05$), stage of skeletal maturation (chi-squared $p > 0.05$), and the length of the observational period (8 months) between the CG and EG. However, a significant difference was observed in age between the CG and EG.

Quantitative assessment

The descriptive condylar volume and superficial area statistics comparing the EG and CG are summarized in Table 3. Quantitative evaluations of condylar volume changes in the EG and CG at T0 and T1 are shown in Figure 2. No significant difference ($p = 0.658$) was observed in condylar volume between the CG and EG at T0. However, the volume in both the CG and EG increased after 8 months. A significant difference ($p = 0.000$) was observed in condylar volume between T0 and T1 in the CG. A significant difference ($p = 0.000$) was also observed in condylar volume between T0 and T1 in the EG.

Quantitative evaluations of condylar superficial area changes in the EG and CG at T0 and T1 are shown in Figure 3. No significant difference ($p = 0.526$) was observed in condylar superficial area between the CG and EG at T0. However, condylar superficial area in both the CG and EG increased after 8 months. A significant difference ($p = 0.000$) was observed in condylar superficial area between T0 and T1 in the CG. A significant difference ($p = 0.000$) was also observed in condylar superficial area between T0 and T1 in the EG.

Quantitative evaluations of the absolute increase in condylar volume and superficial area in the EG and CG by controlling for age are shown in Table 4 and Figure 4. The

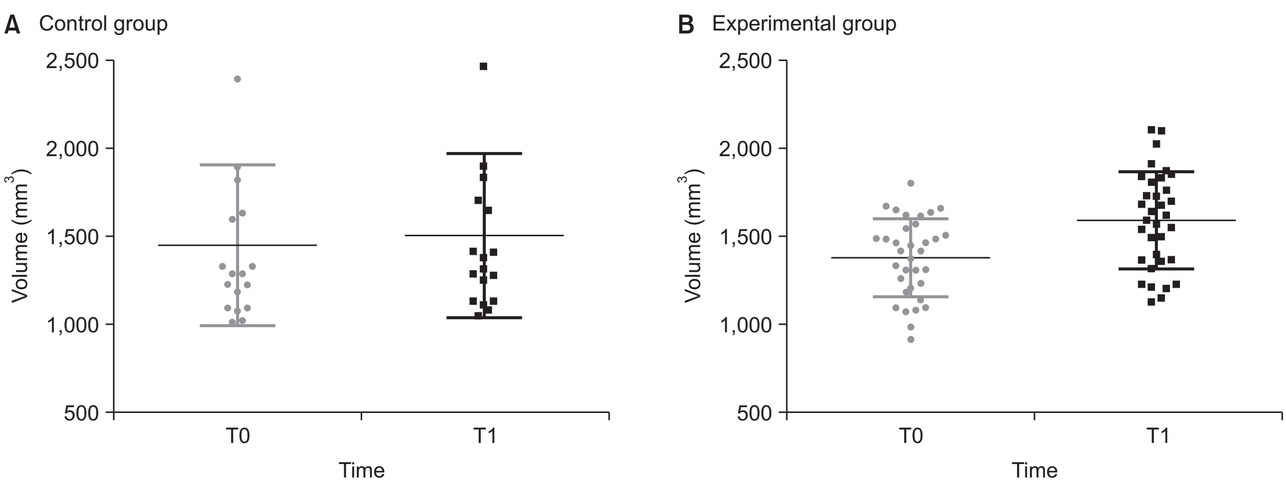

Figure 2. Condylar volume increases significantly 8 months after treatment (T1) compared to before treatment (T0) in both control (**A**) and experimental groups (**B**).

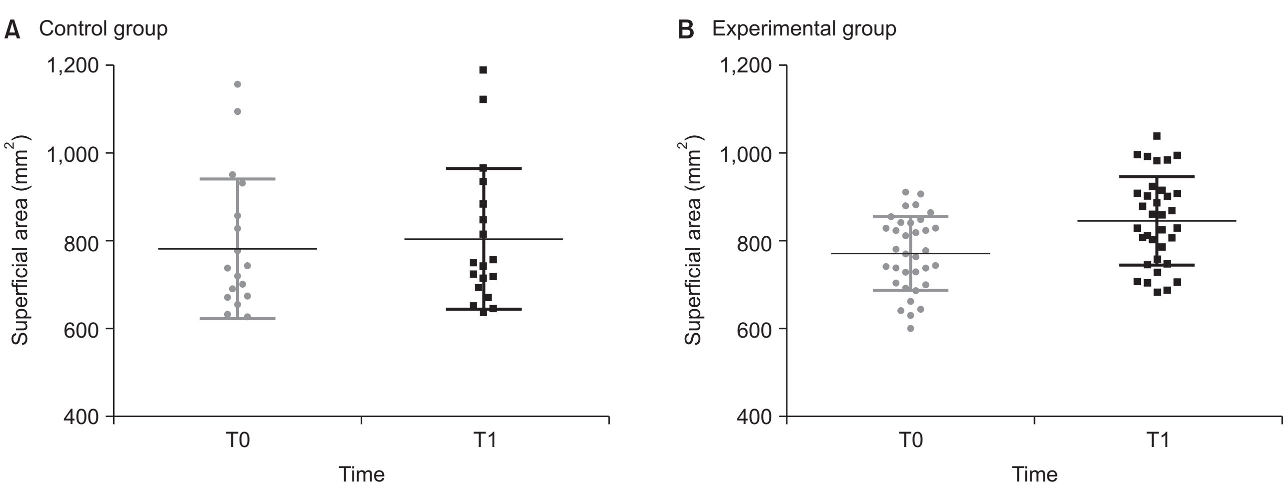

Figure 3. Condylar superficial area increases significantly 8 months after treatment (T1) compared to before treatment (T0) in both control (**A**) and experimental groups (**B**).

absolute increase in condylar volume and superficial area in the EG were significantly higher than those in the CG. Moreover, a significant difference (p = 0.000) was observed in the absolute increase in condylar volume between the CG and EG after 8 months. A significant difference (p = 0.000) was also observed in the absolute increase in condylar superficial area between the CG and EG after 8 months.

The descriptive positional statistics comparing both the EG and CG are summarized in Table 5. No significant differences were observed in the AJS (p = 0.504) and JSI (p = 0.221) after 8 months in the CG. This indicated that the condyle in the CG achieved a stable position after 8 months. However, the PJS in the CG was significantly reduced after 8 months (p = 0.021). Significant differences were observed in the AJS (p = 0.005), PJS (p = 0.000), and JSI (p = 0.004) after 8 months in the EG. This indicated that the condyle in the EG was in a more forward position after 8 months.

Table 4. The absolute increase in volume and superficial area in control and experimental groups

Variable	F	p-value
Absolute increase in condylar volume		
Group	30.78	0.000***
Age (yr)	0.56	0.46
Absolute increase in superficial area		
Group	27.53	0.000***
Age (yr)	0.59	0.45

Covariance analysis is used to compare the absolute increase in condylar volume and superficial area between the groups by controlling for age.
F, Test for homogeneity of variance.
***$p < 0.001$.

Qualitative assessment

Qualitative assessments of the condyle-fossa skeletal modifications were undertaken using color-coded maps of voxel-based superimpositions (Figures 5-7). All the skeletal superimpositions were visualized on a color-coded map and measured using the same scale, in which red color represents overgrowth and blue color represents resorption.

The superimposition of the mandibular color-coded map indicated more obvious modifications in the superior and posterior parts of the condyle in the EG than in the CG. Six directions (lateral, medial, posterior, superior, lateral 45°, and inferior) of superimpositions in the CG and EG are shown in Figure 5. More obvious remodeling can be observed in the posterior and superior directions of condylar superimpositions in the EG than in the CG (Figures 6 and 7). All superimpositions of the left and right glenoid fossa, indicating that the glenoid fossa modifications in the EG tended to adapt to condylar remodeling, are illustrated in Figure 8.

DISCUSSION

Class II malocclusion with mandibular retraction is commonly seen in Chinese teenagers. Different functional appliances have been used to correct skeletal discrepancy via forward mandible forward. The Twin-block appliance is commonly used in clinical treatment. Extensive research has shown that the mandibular forward treatment related with the modifications of TMJ.[20-24] However, there is still a lack of 3D method to evaluate the TMJ changes comprehensively.

The TMJ changes are composed of three parts (each part separately or three in combination): condylar modi-

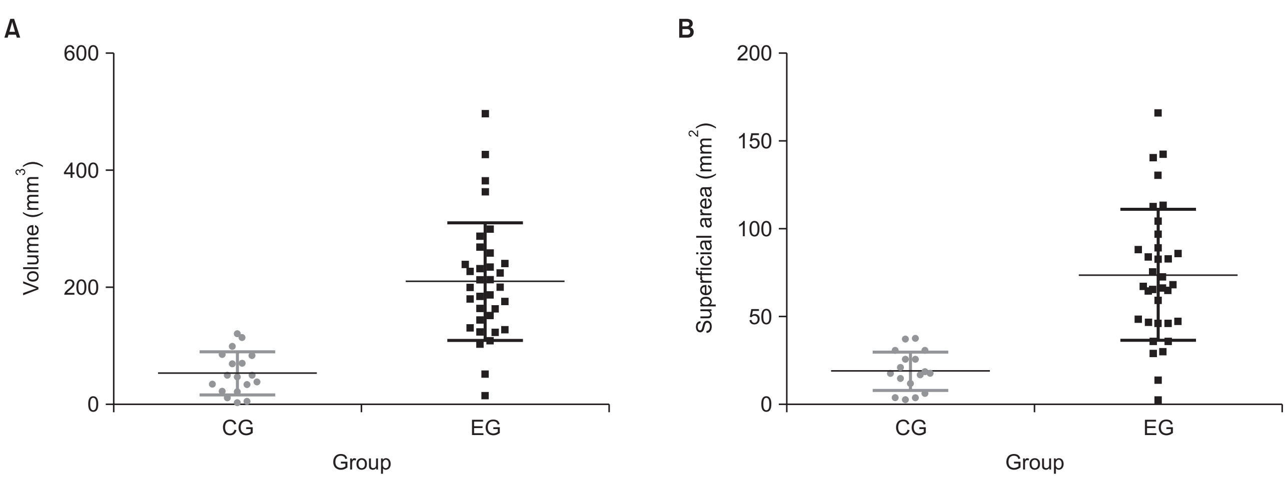

Figure 4. The absolute increases in condylar volume (**A**) and superficial area (**B**) are significantly higher in the experimental group (EG) than in the control group (CG) after 8 months of treatment.

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Table 5. Positional changes of the control and experimental groups

Variable	CGT0	CGT1	EGT0	EGT1	Difference of means (*p*-value)	
					CGT0 vs. CGT1	EGT0 vs. EGT1
AJS (mm)	1.97 ± 0.10	1.88 ± 0.10	2.19 ± 0.12	2.61 ± 0.17	0.504	0.005*
PJS (mm)	2.91 ± 0.16	2.47 ± 0.14	2.19 ± 0.13	3.38 ± 0.24	0.021*	0.000***
JSI	18.55 ± 2.82	13.22 ± 3.43	−0.55 ± 3.19	11.42 ± 3.54	0.221	0.004*

Values are presented as the mean ± standard deviation.
The AJS and PJS in the experimental group are analyzed using the nonparametric rank-sum test. The JSI in the experimental gruop and the AJS, PJS, and JSI in the control group are analyzed using the paired *t*-test.
CGT0, Control group before treatment; CGT1, control group 8 months after treatment; EGT0, experimental group before treatment; EGT1, experimental group 8 months after treatment; AJS, anterior joint space; PJS, posterior joint space; JSI, joint space index.
*$p < 0.05$; ***$p < 0.001$.

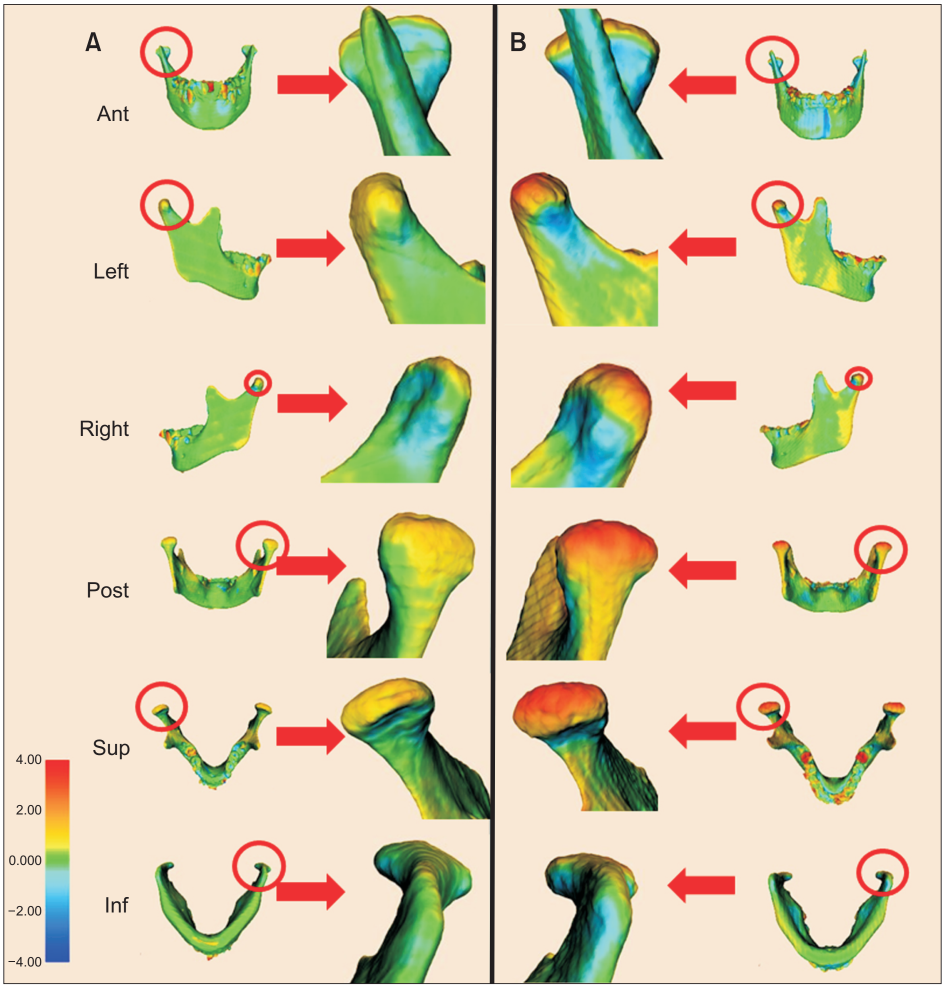

Figure 5. One example of six-directional views of superimposition in the control (**A**) and experimental (**B**) groups (CG and EG, respectively). More obvious skeletal remodeling is observed in the superior and posterior directions of the condyle in the EG than in the CG. All the skeletal superimpositions are visualized on a color-coded map and measured using the same scale, in which red color represents overgrowth and blue color represents resorption.
Ant, Anterior; Post, posterior; Sup, superior; Inf, inferior.

fications, glenoid fossa modifications and condylar displacement in the fossa.[11] The existed evaluation of TMJ changes caused by functional treatment is still limited, because most of the research just concentrated on one or two parts of the changes. Meanwhile, the two-dimensional (2D) method made the results unrepeated and inaccurate for the complicated 3D structure of condyle-fossa.

The aim of our study was to quality and quantity the TMJ changes caused by Twin-block treatment. We improved the materials and methods on the basis of previous research, and increased the accuracy of the experi-

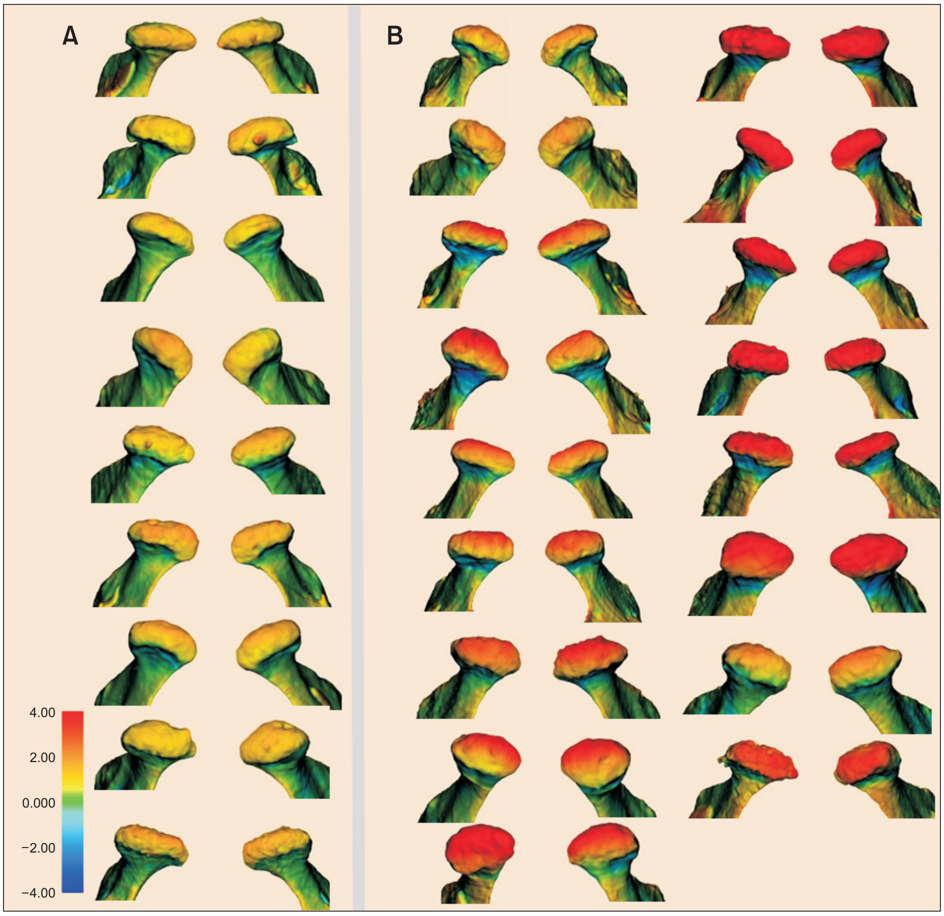

Figure 6. The superior view of all condylar superimpositions in the control (**A**) and experimental (**B**) groups (CG and EG, respectively). More obvious skeletal remodeling is observed in the superior direction of the condyle in the EG than in the CG. All the skeletal superimpositions are visualized on a color-coded map and measured using the same scale, in which red color represents overgrowth and blue color represents resorption.

mental results.

When evaluating the efficiency of functional appliances, previous studies included patients treated using Class II elastics as controls.[25] Moreover, 3D radiographic data on an untreated Class II sample are rare. Untreated patients with Class II malocclusion were selected as the controls in our study, in order to eliminate the influence of growth on the evaluation of the therapeutic effect of the functional appliance.

In terms of the quantitative assessment of condylar changes, 3D methods provide more accurate measurements than do 2D methods. Pancherz[20] observed condylar growth on superimposed lateral cephalometry by using linear and angular measurements. However, these findings were not in accordance with those of Arici et al.,[26] who selected slices that represented the largest condylar head dimension in the mediolateral and anteroposterior directions. The selection of these different reference planes may have contributed to the different results. 2D measurements cannot fully show the modifications because lateral cephalometry is performed along the sagittal plane and the anatomic structure of the condyle-fossa is complicated. However, when different reference planes are selected, the actual bone remodeling is either overestimated or underestimated. Meanwhile, the bilateral condyle is always asymmetrical in pathological conditions, but is often ignored in lateral cephalometry. Thus, the 2D method cannot reflect the complex 3D structure of the condyle and the asymmetry of the left and right sides.

Bayram et al.[7] reported the reliability and accuracy of evaluating condylar skeletal changes using volumetric analysis in CBCT. In our study, we measured condylar volume and superficial area at T0 and T1 separately. We concluded that both the untreated and treated groups had significant condylar growth, and that Twin-block treatment produced a larger condylar size, which was consistent with the 3D findings of Yildirim et al.[8]

Mavreas and Athanasiou[27] proposed a 2D method to assess the condyle-fossa positional relationship by using the width of the joint spaces. However, these 2D methods that performed superimposition on the thin plate lacked geometric rigor. On the basis of their 2D method, we chose 3D landmarks to quantify condylar position. We found the condyle to be in a more forward position after 8 months of Twin-block treatment. Some studies have shown a similar positional shift after functional treatment, which can be explained by the forward

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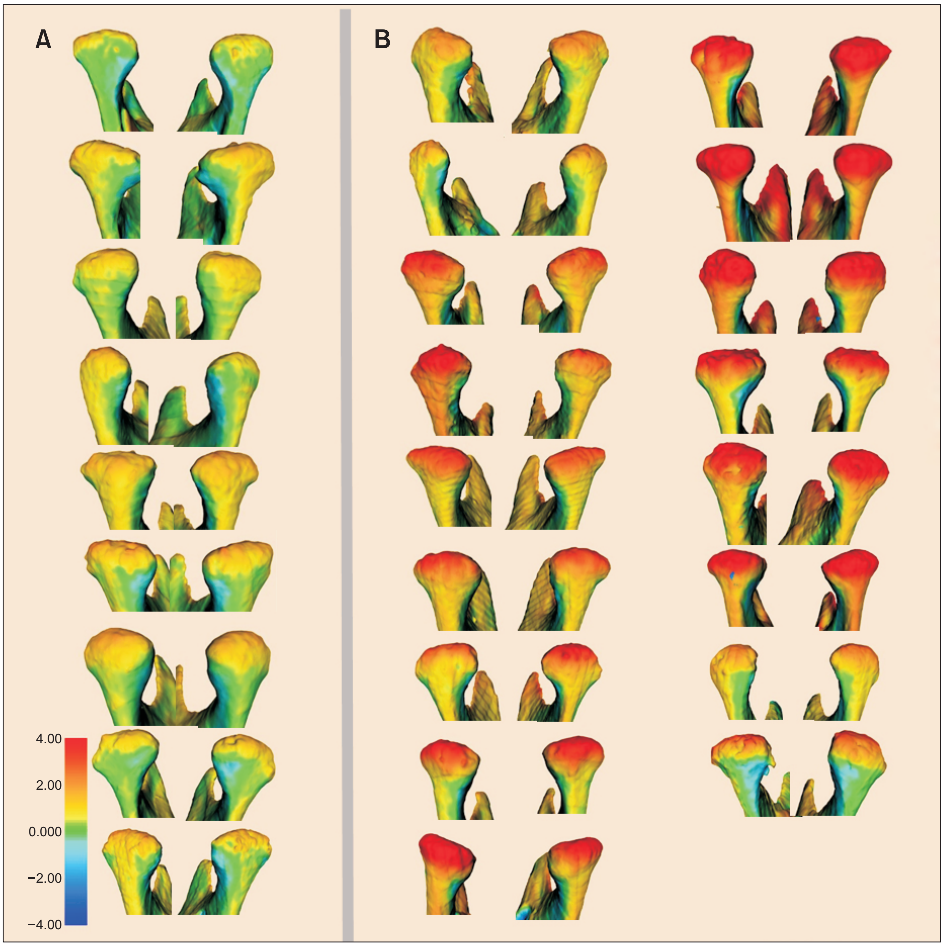

Figure 7. The posterior view of all condylar superimpositions in the contol (**A**) and experimental (**B**) groups (CG and EG, respectively). More obvious skeletal remodeling is observed in the posterior direction of the condyle in the EG than in the CG. All the skeletal superimpositions are visualized on a color-coded map and measured using the same scale, in which red color represents overgrowth and blue color represents resorption.

movement of the condyle caused by the functional appliance.[9,28] The shorter condylar PJS in the untreated group after 8 months was consistent with posterior condylar growth, but the condylar position in the untreated group showed no significant difference. Some studies have shown that the condyle in the untreated group repositioned posteriorly, and that Herbst treatment increased the movement.[26] This may be attributed to the difference in the methods used for evaluating condylar position.

In terms of the qualitative assessment of TMJ modifications, 3D superimposition can help us observe the changes more intuitively. Elfeky et al.[9] established that condylar size increased along three spatial planes in two separate 3D models. However, their results could not clarify the TMJ changes in shape without superimposition. Meanwhile, modifications of the glenoid fossa cannot be measured using lateral cephalometry. Longitudinal implant studies have found stable areas for reference during growth and have indicated the occurrence of bone apposition and resorption.[29] CBCT can be effective in studying 3D growth and treatment results because it can help compare images without magnification. As a standardized and reproducible method for conducting longitudinal studies on facial growth, 3D superimpositions have been used in the clinical and research settings in orthodontics. In 3D studies, three methods for processing 3D superimposition are available: (1) landmark-based, (2) surface-based, and (3) voxel-based 3D superimposition. Voxel-based superimposition has always been chosen to evaluate changes in a growing individual because it helps avoid the error in the placement of landmarks. Cevidanes et al.[30] superimposed 3D models on the cranial base to assess condylar positional and remodeling changes relative to those of the anterior cranial fossa. When registered using different references, different growth features could be observed. In 2016, Ruellas et al. reported that the mandibular body mask (mandible without teeth, alveolar bone, rami, and condyles) can be a reliable reference for 3D mandibular superimposition in growing patients.[15] In our research, the condyle superimposed on the mandibular body mask and the glenoid fossa superimposed on the cranial fossa. Compared with the untreated group, the treated group showed more obvious growth in the superior and posterior directions of the condyle. Moreover, the glenoid

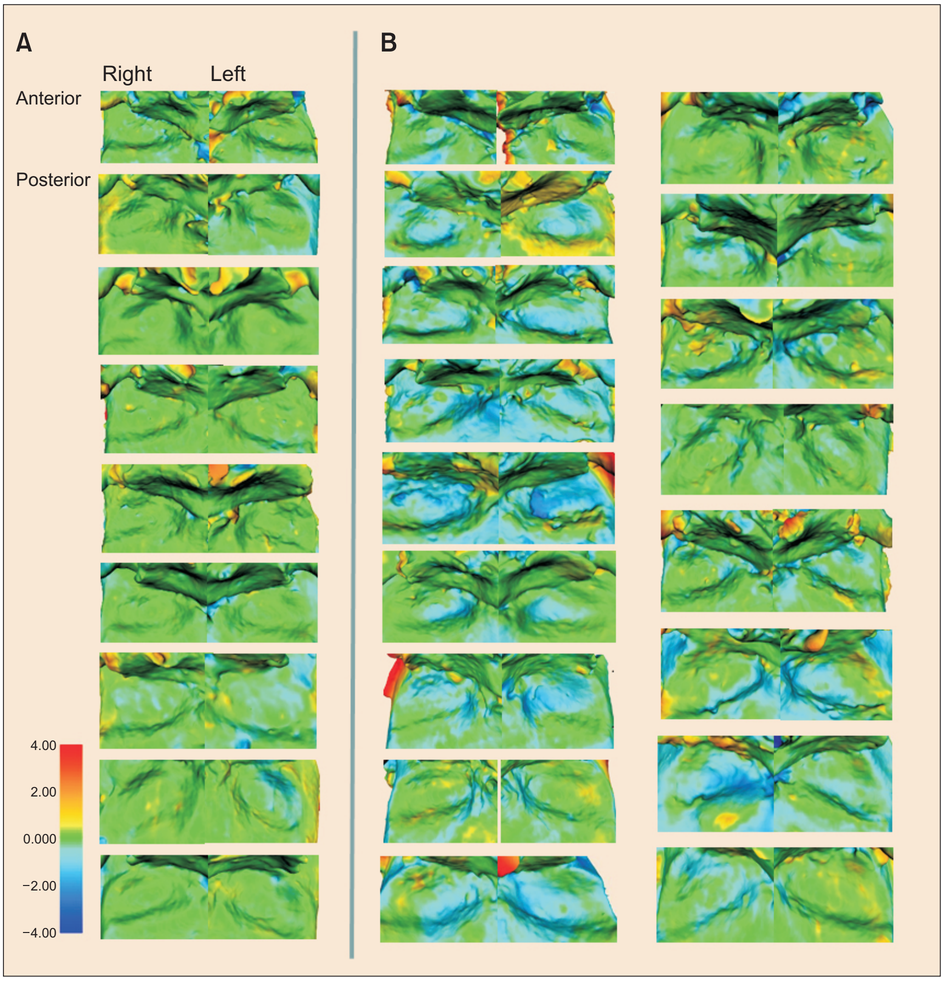

Figure 8. All superimpositions of the left and right glenoid fossa in the control (**A**) and experimental (**B**) groups (CG and EG, respecitvely). More obvious skeletal resorption is observed in the superior direction of the glenoid fossa in the EG than in the CG. All the skeletal superimpositions are visualized on a color-coded map and measured using the same scale, in which red color represents overgrowth and blue color represents resorption.

fossa showed remodeling that adapted to the condyle. These results were in agreement with those reported in the CBCT study by Gazzani et al. and others.[31-33]

The current retrospective study provides a 3D analysis method for the clinical evaluation of TMJ changes. This method has good clinical application prospects for yielding higher accuracy.

One of the limitations of our study was the small sample size of the CG, which was necessary because of ethical constraints. The mandible of patients with Class II malocclusion may show clockwise rotation due to the narrow maxillary arch, while the Twin-block treatment may induce some counterclockwise mandibular rotation.[34,35] Therefore, mandibular rotation may affect the measurements of condylar volume and joint space. Evidence also shows that this is a temporary mandibular growth acceleration and not a true stimulation of mandibular growth.[36] Meanwhile, some studies have shown that Twin-block treatment outcomes returned to the pretreatment state after two-phase therapy.[28,37] However, few studies have evaluated condylar growth over the long term by using 3D methods. Therefore, it is necessary to further explore the long-term TMJ changes after fixed appliance treatment.

CONCLUSION

1. We established a 3D method for the qualitative and quantitative assessments of TMJ changes caused by the Twin-block appliance.
2. Twin-block treatment produced a larger condylar size rather than only accelerating condylar growth during treatment, and this caused condylar positional changes.

CONFLICTS OF INTEREST

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

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