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Three-Dimensional Analysis of Surface and Volume Change of the Condylar Head after Orthognathic Surgery

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이 정 혜

Abstract

Three-Dimensional Analysis of Surface and Volume Change of the Condylar Head after Orthognathic Surgery

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Objective: This study was performed to evaluate condylar surface change and volume change related to condylar remodeling using three-dimensional computed tomography (3D CT) image and to investigate how surface change was related to volume change after orthognathic surgery.

Materials and Methods: Forty patients (20 males and 20 females) who underwent multi-detector CT examinations before and after orthognathic surgery were selected. Nineteen patients among them had facial asymmetry. Three-dimensional images comprising thousands of points on the condylar surface were obtained for pre- and post-surgery. Three-dimensional processing software was used to quantitatively assess condylar surface change through point-to-point (pre-operative-to-post-operative) distances. These point-to-point distances representing condylar surface change were also converted into a color map. To evaluate the condylar remodeling types, the condylar head was divided into six areas (anteromedial, anteromiddle, anterolateral, posteromedial, posteromiddle, and posterolateral areas) and each area was classified into three types of condylar remodeling such as bone formation, no change, or bone resorption based on the color map. Condylar volume change was also derived automatically using Geomagic Studio® 12 (3D Systems Inc., Morrisville, NC, USA). The correlations between surface change, condylar remodeling types and volume change were analyzed. Also, the anlayses were performed according to facial asymmetry and the sexes.

Results: The mean of average point-to-point distance on condylar surface (condylar surface change) was 0.11 ± 0.03 mm. Bone resorption occurred more frequently than other types of condylar remodeling, especially in the lateral areas. However, in the anteromedial area, bone formation was prominent. Condylar volume was reduced after surgery (-0.65 ± 1.90%, $p < 0.05$). There was a weak negative linear relationship between the condylar volume change and condylar surface change (r = -0.296, $p < 0.05$). In addition, bone resorptions in anteromedial, anteromiddle, and posteromedial areas were correlated with condylar volume reduction after surgery. Condylar surface change was significantly greater in males than in females, but condylar remodeling type and volume change was not significantly different between the sexes. Also, there were no significant differences in the condylar surface change, remodeling type, and volume change according to facial asymmetry.

Conclusion: As the change in condylar surface was larger, the condylar volume decreased after surgery. Moreover, bone resorption in anteromedial, anteromiddle, and posteromedial areas of condyle was highly correlated with a reduction of volume.

Key words: Mandibular Condyle; Imaging, Three-Dimensional; Volume; Bone Remodeling; Multidetector Computed Tomography;

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- Contents -

I. Introduction

Condylar remodeling is a physiologic process that aims to adapt the structure of the temporomandibular joint (TMJ) to meet functional demands. It is based on the interactions between mechanical forces sustained by the TMJ and adaptive capacities of the condyle.[1,2]

For patients with skeletal Class III deformities, corrective orthognathic surgery improves both oral function and related esthetics.[3] The effect of orthognathic surgery on condylar remodeling is a poorly understood and controversial issue.[1] However, orthognathic surgery inevitably results in condylar positional changes.[2] These positional changes can induce functional stress on the TMJ structure, and then cause condylar remodeling. It is considered to be a possible etiology of post-operative skeletal relapse following orthognathic surgery.[1]

Three-dimensional (3D) imaging is used effectively for examination and treatment relating to the oral and maxillofacial region.[4] Several studies have used 3D images to assess condylar remodeling and positional changes after orthognathic surgery,[2,5,6] and many have employed a 3D-model superimposition technique. Kawamata et al.[7] used an observer dependent technique to superimpose and rotate the post-surgery computed tomography (CT) until anatomical landmarks overlapped these same structures in the pre-surgery semi-transparent model. Fully automated superimposition using voxel-wise rigid registration of the cranial base was first used by Cevidanes et al.[8] They registered pre- and post-operative models based on the cranial base surface utilizing the gray-value image information instead of landmarks, allowing for image analysis procedures largely independent of observer errors. Then, 3D surface-to-surface matching (best-fit method) was used in several studies. [3,9,10]

Carvalho et al.[6] used a voxel-wise rigid registration superimposition technique using 3D imaging and suggested that the condyles tended to move, on average, ≤ 2 mm supero-posteriorly with surgery, and this small positional displacement was maintained 1 year post-surgery. An et al.[3] used 3D image best-fit superimposition and colored scales to evaluate condylar head deviation between pre- and post-orthognathic surgery. They found that condylar surface change after surgery was significant.

In fact, it is questionable whether condylar surface change and remodeling leads to condylar volume change. Although a number of studies investigated condylar surface change, remodeling, and condylar positional change, there have been few studies that measured condylar volume, and most used a two-dimensional (2D) method.[11-13] Recently, Bayram et al.[12] used the Cavalieri method, which was a stereological method. By this principle, the total area of parallel sections of any object was calculated and this value was multiplied by the slice thickness. The section areas might be calculated with the planimetric method. However, this method was two-dimensional rather than three-dimensional. Even if 3D methods had been used in previous studies, the sample sizes were small, and the 3D reconstruction process required many steps.[13]

Moreover, there has been no study on the analysis of correlation between the condylar surface change and volume change. Condylar volume change induced by condylar surface change after orthognathic surgery could be an important sign to both the patient and surgeon, because this volume change might have a relationship with post-operative TMJ symptoms and relapse.

With these rationales in mind, this study assessed the frequency of remodeling type in each area of the condyle and analyzed condylar surface change and volume change quantitatively using 3D images between pre- and post-orthognathic surgery based on multi-detector computed tomography (MDCT) data. Furthermore, this study evaluated the correlations between condylar remodeling type, surface change, and volume change depending on facial asymmetry and sexes.

II. Materials and Methods

Selection of patients

The present study was approved by the Institutional Ethics Review Board of Seoul National University Dental Hospital (IRB No.CRI15014). This retrospective analysis included the patients with skeletal Class III malocclusions who underwent mandibular setback sagittal split ramus osteotomy with Le Fort I osteotomy at Seoul National University Dental Hospital from 2012 to 2015. Patients with any underlying disease, facial trauma, or temporomandibular joint disorders (TMDs) were excluded. Ultimately, forty patients (20 males, with a mean age of 21.6 years, and 20 females, with a mean age of 21.0 years) who had undergone 3D MDCT (SOMATOM Sensation 10®, Siemens, Erlangen, Germany) examinations before and after surgery were selected. The image-taking protocol was set at 120 kVp, 100 mAs, a 0.75 mm slice thickness, and a 0.5 mm reconstruction interval. Average periods of the images were 1.3 months (range, 0.6 - 2.0 months) prior to surgery and 6.7 months (range, 5.4 - 13.5 months) after surgery, respectively.

Definition of facial asymmetry

Facial asymmetry was determined based on the median sagittal plane using a 3D simulation program (OnDeman3D®, Cybermed Inc., Seoul, South

Korea). The median sagittal plane was a vertical plane passing through the midline of the skull. The 3D method using 6 landmarks reported in the study by Cheng et al.[14] was used to define the midline. In brief, the nasal bone suture, mid-philtrum ridge, posterior nasal spine, vomer ridge, foramen magnum center, and external occipital crest were selected as the 6 landmarks. Then, the patients with the chin tip deviations of more than 2 mm base on the median sagittal plane were diagnosed with facial asymmetry according to laterality of asymmetry. Nineteen patients had facial asymmetry; among these patients, 12 deviated to the right side and 7 to the left side.

Three-dimensional image analysis

1) **Quantitative analysis of condylar surface change and frequency analysis of condylar remodeling types**

Three-dimensional images of mandibular condyles were reconstructed and reformatted into the WRL data format (the file name extension of a VRML [Virtually Reality Modeling Language] file) using 3D imaging software (Vworks program™, version 4.0, Cybermed Inc., Seoul, South Korea). VRML is a standard file format for representing 3D interactive vector graphics, designed particularly with the World Wide Web in mind. The images were then imported into a 3D data processing program (Geomagic Studio® 12, 3D Systems Inc., Morrisville, NC, USA).

In order to quantitatively evaluate condylar surface change, pre- and post-operative segmented condylar images were superimposed over three prominent registration points around the condylar neck using the manual registration function in Geomagic Studio® 12 (Fig. 1). Because the pre- and post-operative reconstructed images of individual patients were not exactly the same size, three points around the condylar neck were selected to align the images as exactly as possible. The points on other areas, such as the mandibular notch, were excluded since they might be included in the surgical area and could change significantly after surgery. After the manual registration, the global registration function in Geomagic Studio® 12 was applied, and the reconstructed images were fitted automatically. These automatic procedures therefore eliminated observer bias. Then, a Geomagic Studio® 12 tool calculated thousands of distances automatically (in millimeters) between pre- and post-operative points on the registered image. These point-to-point distances were defined as 'condylar surface change'. The maximum distance, average distance, and standard deviation of the point-to-point distances were derived automatically by Geomagic Studio® 12 for each condyle. These numeric values allowed us to identify the amount of condylar surface change after surgery.

A Geomagic Studio® 12 tool was also used to convert the surface distances into a color map for each registered 3D condylar image. Relative to the pre-operative model, red color expressed positive (+) surface distances values (bone formation), blue color expressed negative (-) values (bone resorption), and green expressed values around zero (no change) (Fig. 2).

Color maps were used to evaluate the condylar remodeling types. The registered 3D images were cut through a plane around the condylar neck, and the area below the plane was erased. The plane used in this study was drawn over the thinnest portion of the condylar neck and parallel to a plane having the largest area among a number of areas for cross sections. The cross sections included condylar long axis which intersected the medial and lateral pole of the condylar head. A modified version of the methodology described in An et al[3]'s study was used to classify remodeling types on the rest of the condylar head. The cutting plane used by An et al.[3] intersected the medial and lateral pole areas of the condyle, but the location of the plane in this study was adjusted down to near the condylar neck area. The condylar head was divided into six areas (the anteromedial, anteromiddle, anterolateral, posteromedial, posteromiddle, and posterolateral areas) (Fig. 3) and each area was classified into three types (bone formation, no change, and bone resorption) of condylar remodeling. The process of classifying the remodeling types in each condylar area was carried out twice (two weeks apart), and the degrees of agreement between classifications were evaluated to ensure intra-observer reliability.

2) Quantitative analysis of condylar volume change

The volume of the condylar head after being cut by the above cutting plane was calculated automatically using Geomagic Studio® 12. Then, the volume of the pre-operative 3D model was subtracted from the volume of the post-operative 3D model. Negative (-) values for the difference between pre- and post-operative models represented a reduction in condylar volume, and positive (+) values indicated an increase in volume after surgery. The ratio of the volume change ([post-operative model – pre-operative model] / pre-operative model × 100) was also calculated. Comparisons of the volume change (i.e., the difference) depending on the facial asymmetry and the sexes were also evaluated. A single oral and maxillofacial radiologist performed all of the above procedures.

Statistical analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences for Windows version 21.0 (SPSS Inc., Chicago, IL, USA). Differences were considered to be significant at $p < 0.05$. The mean values of the maximum distances, average distances, and standard deviations of each condyle for condylar surface change were calculated.

To evaluate the condylar remodeling, the frequencies of the remodeling types were obtained. To compare the frequencies of condylar remodeling types depending on the facial asymmetry and the sexes, χ^2 test and Fisher's exact test were used. A student's t-test, Mann-Whitney test, paired t-test and Wilcoxon signed rank test were conducted to compare the condylar surface change and condylar volume change depending on the facial asymmetry and the sexes.

In order to compare the frequency of condylar remodeling types between the deviated side and the contralateral side in the facial asymmetry group, a test of marginal homogeneity was conducted. Marginal homogeneity indicated a uniform distribution of two related variables.

To measure the correlation between the condylar surface change and condylar volume change, Pearson’s and Spearman’s correlation analysis were used. Analysis of variance (ANOVA) and the Kruskal-Wallis test with post-hoc tests were used to examine the correlations between condylar remodeling types and condylar volume change. According to the Bonferroni correction, the level of significance was 0.0167 (= 0.05/the number of multiple comparisons = 0.05/3). A measure of intra-observer reliability was obtained using Cohen’s kappa index.

III. Results

The mean values of the maximum distances, average distances, and standard deviations for condylar surface change after orthognathic surgery were 0.41 ± 0.06 mm, 0.11 ± 0.03 mm, and 0.09 ± 0.02 mm, respectively.

The intraobserver reliability for the classification of condylar remodeling types showed almost perfect agreement (Cohen's kappa index; average, 0.895). Regarding the post-operative condylar remodeling types, bone resorption occurred more frequently (38.33%) than other types. Specifically, bone formation in the anteromedial area, as well as bone resorption in the anterolateral and posterolateral areas, was significantly higher (>50%) than other remodeling types (Table 1).

The mean condylar volume change after surgery was -9.25 ± 27.13 mm^3. Compared to pre-orthognathic surgery models, the condyles showed significant reductions in volume (-0.65 ± 1.90%, $p < 0.05$).

Table 2 shows the correlation between the condylar volume change and condylar surface change. The average distance of the surface change had a weak negative linear relationship with condylar volume change (r, Pearson's correlation coefficients = -0.296, $p < 0.05$, Fig. 4). The maximum distance and standard deviation of the condylar surface change were not significantly correlated with condylar volume change.

Regarding the condylar volume change and condylar remodeling types, the remodeling types in the anteromedial, anteromiddle, posteromedial, and posterolateral areas of the condyle were correlated with condylar volume change ($p < 0.05$). Specifically, bone resorption (R) was correlated with volume reduction in these areas ($\alpha < 0.0167$ by Bonferroni correction, Table 3).

No significant difference was found regarding the frequencies of condylar remodeling types between the sexes (Table 4). However, regarding the condylar surface change according to the sexes, males exhibited significantly larger changes in the maximum distance, average distance, and standard deviation of the condyles ($p < 0.05$; Table 5). Also, in the comparison of condylar volume change according to the sexes, there was no significant difference (-9.92 ± 27.84 mm^3 in male and -8.58 ± 17.92 mm^3 in female).

The frequencies of condylar remodeling types were not significantly different between the facial symmetry and the asymmetry groups, except in the anterolateral area. However, bone resorption in the anterolateral area was dominant in both groups (Table 6). Table 7 shows the surface change and volume change of the facial symmetry and the asymmetry groups. The maximum distance of surface change in the facial symmetry group was significantly larger than that in the asymmetry group ($p < 0.05$). However, there were no significant differences in other measures of surface change and volume change between the groups.

The frequencies of condylar remodeling types were not significantly different between the deviated side and contralateral side in the facial asymmetry group (Table 8). Table 9 shows the surface change and volume change according to the deviation side in the facial asymmetry group. The maximum distance for the surface change on the contralateral side was significantly greater than on the deviated side ($p < 0.05$). However, there were no significant differences in other measures of the surface change and volume change between the groups.

IV. Discussion

Evaluation of condylar morphological change after orthognathic surgery is critical to predict the clinical prognosis. Progressive condylar resorption has been found to be an irreversible complication and a factor in the development of late skeletal relapse after a bilateral sagittal split, Le Fort I, or bimaxillary osteotomy procedure.[15] Recently, 3D images have been widely used to assess condylar morphology. Xi et al.[13] presented a reproducible tool for 3D rendering of the condyle, which allowed for longitudinal follow-up and quantitative analysis of condylar changes. Schilling et al.[16] showed that condylar registration was reliable and could be used to quantify subtle bony differences in 3D condylar morphology.

However, few studies have assessed the condylar volume using 3D images.[11,13] This study obtained the condylar volume using 3D images. Moreover, to the best of our knowledge, this was the first study to analyze the correlations between the condylar surface change, condylar remodeling types, and condylar volume change after orthognathic surgery.

This study included reconstructed 3D images that were processed as part of all procedures in this study. Three registration points on the pre- and post-operative 3D condylar images were used for superimposition. These points were selected from around the condylar neck area, since this area exhibited relatively less changes compared to other areas. Moreover, the registration points were needed to align the images, because the pre- and post-operative reconstructed 3D images from one patient were not exactly the same size. After this manual registration, an automatic global registration was then conducted once more in order to increase accuracy.

In this study, the method detailed by An et al.[3] was used to evaluate the frequency of condylar remodeling types, but the location of the cutting plane on the registered 3D condylar images was adjusted down to near the condylar neck area. The cutting plane used by An et al.[3] intersected the medial and lateral pole areas of the condyle. However, it was supposed that the medial and lateral pole areas could change after surgery, and indeed, this change was confirmed by the color map.

The definition of facial asymmetry was still controversial and various 2D and 3D definitions were used in previous studies.[14,17-19] In the clinic, the patients with the chin tip deviations of more than 4 - 5 mm were diagnosed with facial asymmetry.[20] However, it was established a standard of 2 mm in this study because most patients did not have severe facial asymmetry.

The condylar surface change after surgery, the mean of average point-to-point distances, was 0.11 ± 0.03 mm in this study, which was larger than An et al.[3]'s the mean of average deviation (0.01 ± 0.09 mm) and smaller than Cevidanes et al.[8]'s the average displacement of the entire surface (0.77 ± 0.17 mm).

In this study, the evaluations of the frequency of condylar remodeling types demonstrated that bone resorption occurred frequently (38.3%) compared to other types of condylar remodeling (bone formation: 27.7%, no change: 34.0%). However, it was not possible to conclude that bone resorption after surgery was predominant because the frequencies of these three remodeling types were similar. However, in each area, bone formation in the anteromedial (55.0%) area, as well as bone resorption in the anterolateral (55.0%) and posterolateral (52.5%) areas, were predominant (Table 1). In other words, the condylar remodeling type after surgery was most commonly achieved through bone resorption. These results were in accordance with previous studies.[2,3]

Condylar surface change (average distance) exhibited a weak negative linear relationship with condylar volume change (Table 2). In other words, as the change in condylar surface was larger, the condylar volume decreased after surgery (Fig. 4). Furthermore, the condylar remodeling types in some areas were correlated with the condylar volume change. In particular, the condylar remodeling via bone resorption was associated with the condylar volume reduction in the anteromedial, anteromiddle, posteromedial, and posterolateral areas of the condyle (Table 3). This indicated that total condylar volume tended to decline, and this tendency was affected by bone resorption in some areas of the condyle.

Previous studies did not compare condylar remodeling types between the sexes. In this study, there was no significant difference between the sexes regarding the frequencies of condylar remodeling types in all areas of the condyle (Table 4). However, males exhibited significantly more condylar surface changes compared to females (Table 5).

Condylar volume tended to decrease after surgery ($p < 0.05$). However, there was no significant difference in the volume change between the sexes.

There were no significant differences in the condylar surface change, volume change, and the frequency of condylar remodeling types between the facial symmetry and asymmetry groups, or based on the deviation side (Tables 6-9). However, these results were limited by the small sample size, and further studies with more patients, including those with severe facial asymmetry, would be required.

Some believed that forced condylar positioning in orthognathic surgery could lead to condylar remodeling.[21,22] Hwang et al.[23] suggested that a posteriorly inclined condylar neck should be considered a relevant non-surgical risk factor for condylar resorption following orthognathic surgery. An et al.[3] found that inward condylar rotation after orthognathic surgery was closely related to condylar surface change. Nonetheless, the exact cause behind the changes in the condylar surface is still controversial.

However, these changes on the condylar surface can induce post-operative TMJ symptoms and early or late skeletal post-operative relapse.[2,24,25] This study revealed that the condylar head remodeling type, especially bone resorption, was common after surgery. Moreover, as the condylar surface change (average distance of the point-to-point distances between the pre- and post-operative 3D models) increased after surgery, the condylar volume decreased. Moreover, the condylar volume tended to decline after surgery, and this tendency was affected by the condylar remodeling type, bone resorption, in some areas. Therefore, these results suggested that the condylar surface changes in some areas were correlated with a reduction in the condylar volume after surgery, and this volume reduction could induce post-operative TMJ symptoms and relapse.

The clinical relevance of these findings requires additional study because all quantitative values were smaller than the slice thickness (0.75 mm). However, it could provide sub-voxel accuracy for image superimposition and interpretation, because the global registration algorithm used by Geomagic Studio® 12 iterated until the value of a standard deviation reached the level set by the observer (0.00 mm). The error in this study, that was smaller than the slice thickness, might have occurred during the process of 3D reconstruction. Thinner slice thicknesses, long-term patient follow-up, and larger sample sizes might reduce this error. Therefore, future studies are required.

There have been few studies measuring the condylar volume because of the complex structure of the temporomandibular joint and the anatomical features of the condyle.[11-13] The condylar head is located very close to the articular fossa, and the cortical bone of the condylar head is relatively thin. As such, it was difficult for the 3D processing software to clearly delineate the margin of the condyle. Instead, the observer had to eliminate the articular fossa in each slice used in this study. This should be addressed in future studies.

V. Conclusion

These results suggested that as the magnitude of condylar surface change increased, the condylar volume decreased after surgery. Moreover, bone resorption in anteromedial, anteromiddle, and posteromedial areas of condyle was highly correlated with a reduction of volume. Therefore, periodic follow-up through radiological imaging, especially 3D CT, is a vital component to detect these morphological changes of the condyle after orthognathic surgery.

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Tables

Table 1. Frequencies of condylar remodeling types using the color map on the registered three-dimensional condylar image (n=80)

Area / Remodeling type	Anteromedial (frequency,%)	Anteromiddle (frequency,%)	Anterolateral (frequency,%)	Posteromedial (frequency,%)	Posteromiddle (frequency,%)	Posterolateral (frequency,%)	Total (frequency,%)
Bone resorption	13 (16.3)	24 (30.0)	44 (55.0)	29 (36.3)	32 (40.0)	42 (52.5)	184 (38.3)
Bone formation	44 (55.0)	26 (32.5)	10 (12.5)	22 (27.5)	13 (16.3)	18 (22.5)	133 (27.7)
No change	23 (28.8)	30 (37.5)	26 (36.3)	29 (36.3)	35 (43.8)	20 (25.0)	163 (34.0)

Table 2. Correlation between condylar volume change and condylar surface change

		Condylar surface change		
		Maximum distance	Average distance	Standard Deviation
Condylar volume change	r*	0.132	-0.296	-0.168
	p-value	> 0.05	< 0.05‡	> 0.05

*: Pearson's or Spearman's correlation coefficients, ‡: $p < 0.05$

Table 3. Correlation between condylar volume change and condylar remodeling types

Area		Condylar remodeling types: Bone formation (F) Mean ± SD (mm³)	No change (N) Mean ± SD (mm³)	Bone resorption (R) Mean ± SD (mm³)	Overall *p*-value†	F vs N *α*-value‡	F vs R *α*-value‡	N vs R *α*-value‡
Anteromedial	n	44	23	13				
	Volume change	-4.94 ± 25.55	-4.04 ± 23.16	-33.05 ± 28.10	< 0.05*	> 0.0167	< 0.0167*	< 0.0167*
Anteromiddle	n	26	30	24				
	Volume change	1.66 ± 25.92	-5.65 ± 22.64	-25.57 ± 26.87	< 0.05*	> 0.0167	< 0.0167*	< 0.0167*
Anterolateral	n	10	26	44				
	Volume change	2.28 ± 22.79	-3.63 ± 25.07	-15.18 ± 28.13	> 0.05	-	-	-
Posteromedial	n	22	29	29				
	Volume change	-0.32 ± 21.16	-2.45 ± 24.64	-22.82 ± 28.85	< 0.05*	> 0.0167	< 0.0167*	< 0.0167*
Posteromiddle	n	13	35	32				
	Volume change	-2.91 ± 27.47	-5.91 ± 30.33	-15.48 ± 22.47	> 0.05	-	-	-
Posterolateral	n	18	20	42				
	Volume change	3.40 ± 18.39	-2.52 ± 29.51	-17.87 ± 26.56	< 0.05*	> 0.0167	< 0.0167*	> 0.0167

†: Kruskal Wallis Test or ANOVA, ‡: post-hoc test ($\alpha = 0.0167$ by Bonferroni correction) , *: $p < 0.05$ or $\alpha < 0.0167$

Table 4. Frequencies of condylar remodeling types using the color map on the registered 3D condylar image according to the sexes (male: n=20 [40 sides], female: n=20 [40 sides])

Area / Remodeling type	Anteromedial (frequency,%)		Anteromiddle (frequency,%)		Anterolateral (frequency,%)		Posteromedial (frequency,%)		Posteromiddle (frequency,%)		Posterolateral (frequency,%)	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
Bone resorption	8 (20.0)	5 (12.5)	10 (25.0)	14 (35.0)	20 (50.0)	24 (60.0)	13 (32.5)	16 (40.0)	15 (37.5)	17 (42.5)	21 (52.5)	21 (52.5)
Bone formation	20 (50.0)	24 (60.0)	14 (35.0)	12 (30.0)	4 (10.0)	6 (15.0)	11 (27.5)	7 (17.5)	7 (17.5)	6 (15.0)	7 (17.5)	11 (27.5)
No change	12 (30.0)	11 (27.5)	16 (40.0)	14 (35.0)	16 (40.0)	10 (25.0)	16 (40.0)	13 (32.5)	18 (45.0)	17 (42.5)	12 (30.0)	8 (20.0)
p-value	> 0.05		> 0.05		> 0.05		> 0.05		> 0.05		> 0.05	

Table 5. Quantitative assessment of condylar surface change using point-to-point distances on the registered 3D condylar image according to the sexes

	Male (n=20, mm)	Female (n=20, mm)	*p*-value
Maximum distance	0.43 ± 0.05	0.39 ± 0.03	< 0.05*
Average distance	0.11 ± 0.03	0.10 ± 0.03	< 0.05*
Standard deviation	0.10 ± 0.01	0.09 ± 0.01	< 0.05*

SD: Standard Deviation, *: $p < 0.05$

Table 6. Frequencies of condylar remodeling types using the color map on the registered 3D condylar image of the facial symmetry (n=21 [42 sides]) and the asymmetry groups (n=19 [38 sides])

Remodeling type / Area	Anteromedial (frequency,%)		Anteromiddle (frequency,%)		Anterolateral (frequency,%)		Posteromedial (frequency,%)		Posteromiddle (frequency,%)		Posterolateral (frequency,%)	
	Sym.	Asym.	Sym.	Asym.	Sym.	Asym.	Sym.	Asym.	Sym.	Asym.	Sym.	Asym.
Bone resorption	4 (9.5)	9 (23.7)	10 (23.8)	14 (36.8)	20 (47.6)	24 (63.2)	14 (33.3)	15 (39.5)	20 (47.6)	12 (31.6)	20 (47.6)	22 (57.9)
Bone formation	26 (61.9)	18 (40.5)	17 (40.5)	9 (23.7)	10 (23.8)	-	12 (28.6)	10 (26.3)	5 (11.9)	8 (21.1)	11 (26.2)	7 (18.4)
No change	12 (28.6)	11 (29.0)	15 (35.7)	15 (39.5)	12 (28.6)	14 (36.8)	16 (38.1)	13 (34.2)	17 (40.5)	18 (47.4)	11 (26.2)	9 (23.7)
p-value	> 0.05		> 0.05		< 0.05*		> 0.05		> 0.05		> 0.05	

Sym.: Facial symmetry group, Asym.: Facial asymmetry group, *: $p < 0.05$

Table 7. Quantitative assessment of condylar surface change and volume change of the facial symmetry and the asymmetry groups

		Symmetry (n=21)	Asymmetry (n=19)	p-value
Condylar surface change	Maximum distance	0.43 ± 0.05 mm	0.39 ± 0.04 mm	< 0.05*
	Average distance	0.11 ± 0.03 mm	0.10 ± 0.03 mm	> 0.05
	Standard deviation	0.09 ± 0.02 mm	0.09 ± 0.01 mm	> 0.05
Condylar volume change		-5.79 ± 26.94 mm^3	-13.07 ± 17.95 mm^3	> 0.05

SD: Standard Deviation, *: $p < 0.05$

Table 8. Frequencies of condylar remodeling types using the color map on the registered 3D condylar image of the deviated side and the contralateral side in the facial asymmetry group (n=19 [38 sides])

Area / Remodeling type	Anteromedial (frequency,%)		Anteromiddle (frequency,%)		Anterolateral (frequency,%)		Posteromedial (frequency,%)		Posteromiddle (frequency,%)		Posterolateral (frequency,%)	
	Deviated side	Contra. side	Deviated side	Contra. side	Deviated side	Contra. side	Deviated side	Contra. side	Deviated side	Contra. side	Deviated side	Contra. side
Bone resorption	11 (57.9)	13 (68.4)	9 (47.4)	6 (31.6)	11 (57.9)	13 (68.4)	9 (47.4)	6 (31.6)	6 (31.6)	6 (31.6)	10 (52.6)	12 (63.2)
Bone formation	-	-	4 (21.1)	6 (31.6)	-	-	4 (21.1)	6 (31.6)	4 (21.1)	4 (21.1)	4 (21.1)	3 (15.8)
No change	8 (42.1)	6 (31.6)	6 (31.6)	7 (36.8)	8 (42.1)	6 (31.6)	6 (31.6)	7 (36.8)	9 (47.4)	9 (47.4)	5 (26.3)	4 (21.1)
p-value	> 0.05		> 0.05		> 0.05		> 0.05		> 0.05		> 0.05	

Conta. side: Contralateral side

Table 9. Quantitative assessment of condylar surface change and volume change according to deviation side in the facial asymmetry group (n=19 [38 sides])

		Deviated side Mean ± SD	Contralateral side Mean ± SD	*p*-value
Condylar surface change	Maximum distance	0.38 ± 0.04 mm	0.42 ± 0.04 mm	< 0.05*
	Average distance	0.10 ± 0.02 mm	0.10 ± 0.03 mm	> 0.05
	Standard deviation	0.09 ± 0.01 mm	0.09 ± 0.02 mm	> 0.05
Condylar volume change		-13.28 ± 28.33 mm^3	-12.87 ± 14.92 mm^3	> 0.05

SD: Standard Deviation, *: $p < 0.05$

Figure legends, and Figures.

Fig. 1. Superimposition of pre- (upper left) and post-operative segmented images (upper right). These images are superimposed over three prominent registration points around the condylar neck (number 1, 2, 3). The registered image (lower part) is generated automatically.

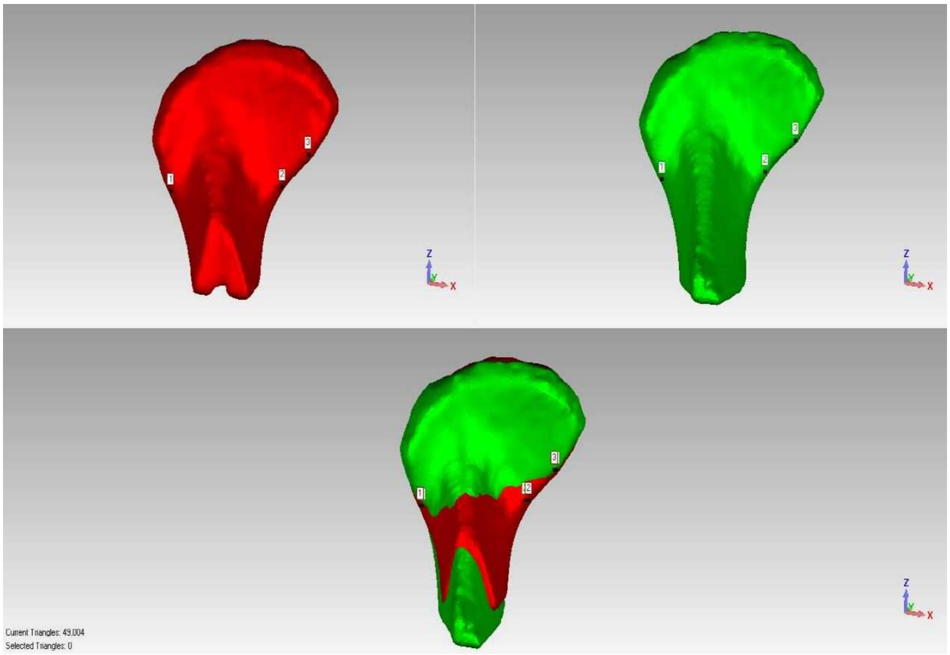


Fig. 2. Color map of condylar remodeling between pre- and post-orthognathic surgery. Red color shows bone formation, blue color shows bone resorption, and green color shows no change.

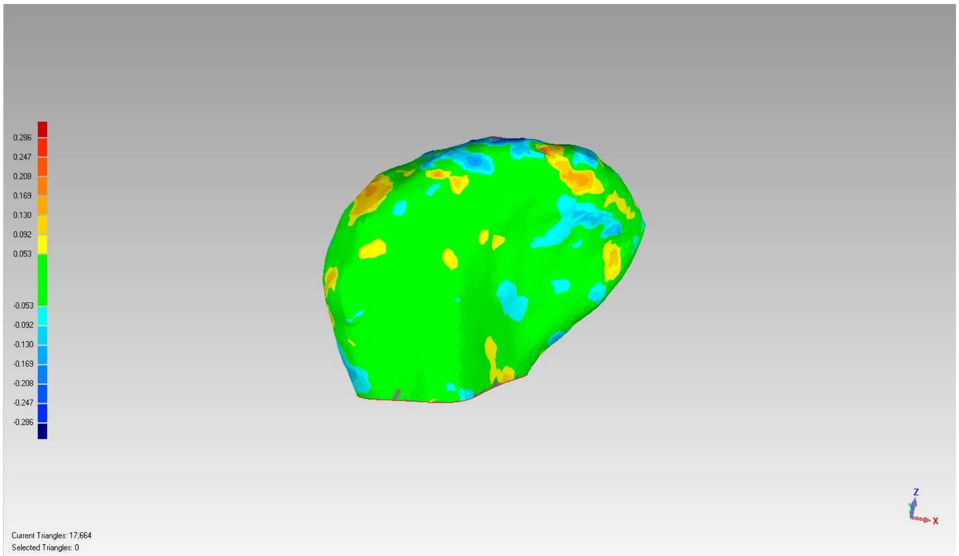


Fig. 3. A six condylar head areas. A. Anterior surface, B. Superior surface, C. Posterior surface. Ant-Lat, anterolateral; Ant-Mid, anteromiddle; Ant-Med, anteromedial; Post-Lat, posterolateral; Post-Mid, posteromiddle; Post-Med, posteromedial.

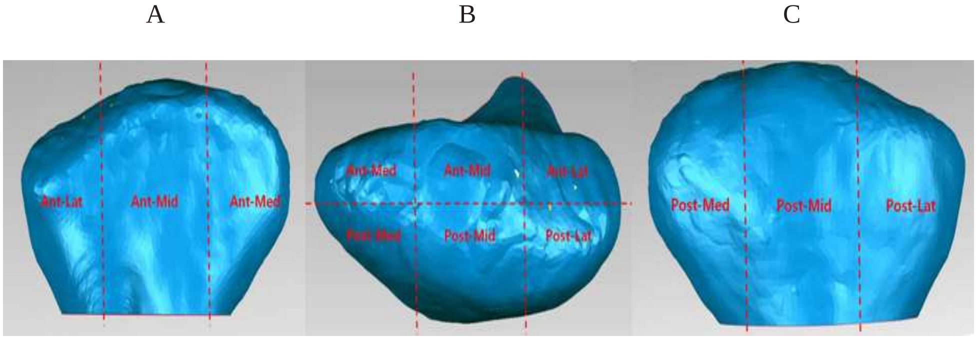
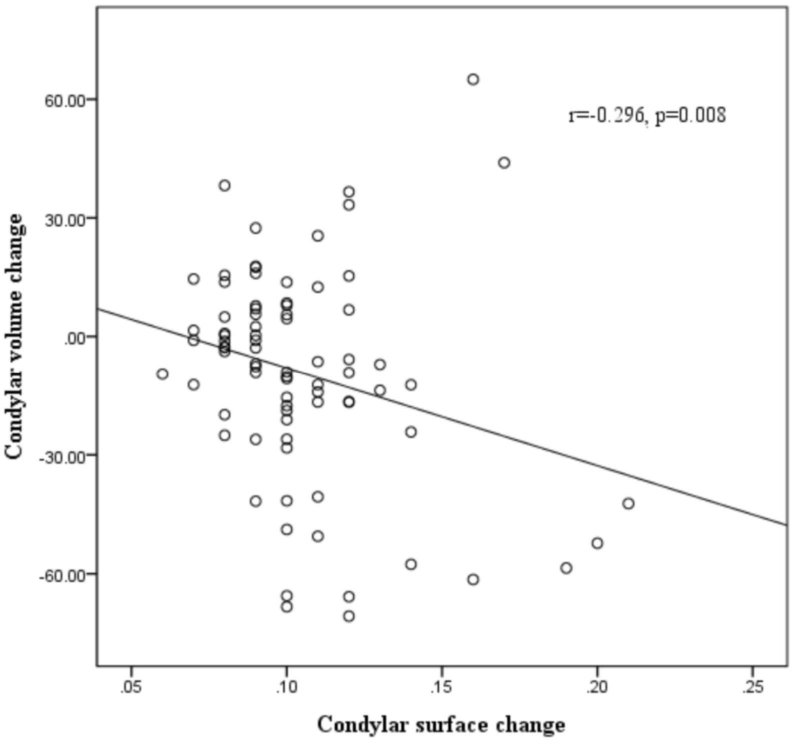


Fig. 4. Plot of correlation between condylar surface change (average distance) and condylar volume change.



국문 초록

악교정 수술 후 하악과두의 표면 변화와 체적 변화의 삼차원 분석

이 정 혜

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1. 목 적

악교정 수술 후 하악과두의 재형성 양상과 연관된 표면 변화, 체적 변화를 삼차원 CT 영상을 통해 정량적으로 평가하고, 표면 변화가 체적 변화에 미치는 영향을 알아보고자 한다.

2. 방 법

악교정 수술 전과 수술 후에 다중 검출 CT(SOMATOM Sensation 10®, Siemens, Erlangen, Germany)검사를 시행한 40 명의 환자(남자 20 명, 여자 20 명)를 선정하여 하악과두의

3차원 영상을 얻었다(Vworks program™, version 4.0, Cybermed Inc., Seoul, South Korea). 이 중 19 명은 안면 비대칭이 있었다. 3 차원 처리 프로그램(Geomagic Studio®12, 3D Systems Inc., Morrisville, NC, USA)을 통해 정합된 술 전과 술 후 3 차원 영상에서, 같은 점들 간의 이동된 평균 거리를 이용해 표면 변화의 양적 평가를 시행하였다.

각 점들 간의 거리를 3 차원 영상에서 색상 지도로 변환하여 하악과두의 재형성 양상을 평가하였다. 하악과두를 6 개 부위(전방내측, 전방중앙, 전방외측, 후방내측, 후방중앙, 후방외측)로 나누고, 하악과두의 재형성 여부를 골 형성, 변화 없음, 골 흡수로 분류하였다.

3 차원 처리 프로그램(Geomagic Studio®12)을 이용하여 술 후 영상과 술 전 영상의 체적의 차이를 측정하여 체적 변화 여부를 조사하였다.

표면 변화와 재형성 양상, 체적 변화를 구하고, 그들 간의 상관관계를 분석하였다. 또한 안면 비대칭 여부와 성별에 따른 각 요소들을 구하고, 비교하였다.

3. 결 과

악교정 수술 후 하악과두의 표면 변화는 그 정도가 미미하였으며(0.11 ± 0.03 mm), 하악과두는 대체적으로 골 흡수의 경향을 보였고, 이는 과두의 외측부위에서 두드러졌으나, 전방내측 부위에서는 골 형성이 높은 비율로 나타났다. 하악과두의 체적은 전반적으로 술 후에 감소하는 경향을 보였다(−0.65 ± 1.90%, $p < 0.05$). 하악과두의 표면 변화와 체적 변화는 약한 음의 상관관계를 보여(r, Pearson or Spearman's correlation coefficients=−0.296, $p < 0.05$), 술 후 표면변화가 증가하면 체적이 감소하는 것으로 나타났다. 또한 과두의 전방내측, 전방중앙, 후방내측 부위의 골 흡수가 수술 후 체적 감소와 연관이 있는 것으로 나타났다.

남녀 간에서는, 표면 변화는 남자가 여자보다 컸으나, 재형성 양상과 체적 변화는 차이가 관찰되지 않았다. 안면 비대칭 여부에 따른 차이도 관찰되지 않았다.

4. 결 론

악교정 수술 후의 과두의 표면변화가 클수록, 체적이 감소하게 된다. 또한, 과두 전방내측, 전방중앙, 후방내측 부위의 골 흡수는 체적 감소와 관련이 있다.

주요어 : 하악과두, 3 차원 영상, 체적, 표면 변화, 다중 검출 CT

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