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Condylar head remodeling compensating for condylar head displacement by orthognathic surgery

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A B S T R A C T

The purpose of this study was to evaluate the association between kind of condylar displacement due to orthognathic surgery and the subsequent adaptive condylar head remodeling.

The sample in this retrospective cohort study consisted of 30 patients (12 female and 18 male; mean age 22.7 y) with skeletal Class III malocclusion who underwent bilateral sagittal split ramus osteotomy (SSRO). Three-dimensional superimpositions of cone-beam computed tomography (CBCT) scan derived images from immediately after and 6 months after surgery were to reveal the type of remodeling, while images from before and immediately after surgery were to identify the type of condylar displacement.

Laterally displaced condyles showed bone resorption on the lateral surfaces and deposition on the medial surfaces, whereas the contrary was found in medially displaced condyles. Anteriorly displaced condyles showed resorption on the anterior surfaces and deposition on the posterior surfaces, whereas the contrary was found in posteriorly displaced condyles. Superior surfaces of the condyles showed bone resorption regardless of displacement direction.

The results indicate that condylar remodeling patterns (resorption/deposition) are determined by the direction of condylar displacement during surgery. However, condylar displacement by surgery is not completely compensated by condylar head remodeling, especially in case of downward displacement.

1. Introduction

Malocclusions with dentofacial deformities are managed by a combination of surgical and orthodontic treatment. Orthognathic surgical procedures often cause displacement of the mandibular condyle in relation to the glenoid fossa (Hollender and Ridell, 1974; Edlund et al., 2009). Resultant altered loading has led to remodeling adaptation in animal experiments and in clinical studies (Voudouris and Kuftinec, 2000; Voudouris et al., 2003; Chen et al., 2009). With the tendency of the condyle to regain its preoperative position, condylar surgical displacement and following remodeling might be a source of postoperative instability and could interfere with subsequent orthodontic treatment (Ware and Taylor, 1968; Franco et al., 1989; Hoppenreijs et al., 1998; Bailey et al., 2004; Borstlap et al., 2004).

Remodeling is an essential biologic response to functional demands, ensuring homeostasis of joint form and function and occlusal relationships (Arnett et al., 1996b). Condylar remodeling has long been recognized to be an adaptive physiologic process that alters the structure of the temporomandibular joint (TMJ) (Arnett et al., 1996a).

In several studies (Eckerdal et al., 1986; Petersson and Willmar-Hogeman, 1989; Katsumata et al., 2006; Edlund et al., 2009), a distinct double contour (as specific radiographic indication of remodeling activity) was found in most of the joints examined after

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surgery. Some of these studies (Eckerdal et al., 1986; Petersson and Willmar-Hogeman, 1989; Edlund et al., 2009) reported that condylar remodeling took place mostly on posterior or postero-superior margin of the condyle using transcranial radiographs. Katsumata et al. (2006) also identified a newly formed layer of bone in the posterior part of the condylar head following mandibular setback osteotomy, using three-dimensional (3D) imaging including computed tomography (CT) and magnetic resonance imaging (MRI). Recent studies (Park et al., 2012; Ha et al., 2013; An et al., 2014) showed that the condylar head underwent remodeling after one-jaw (Ha et al., 2013; An et al., 2014) or two-jaw (Park et al., 2012; An et al., 2014) orthognathic surgery in their studies using cone-beam computed tomography (CBCT).

A significant correlation of condylar remodeling with the degree of condylar displacement was found in surgically treated mandibular prognathism patients (Petersson and Willmar-Hogeman, 1989). Here, the significantly displaced condyle position could be almost completely retrieved, through a combination of repositioning and remodeling. Studies using CT and MRI (Katsumata et al., 2006) and CBCT (An et al., 2014) endorsed these findings, but only evaluated the correlation of remodeling with condylar rotation.

So far, no study has been able to accurately quantify volume and 3D direction of condylar remodeling following surgical displacement. This study tests the hypothesis that condylar remodeling and its extent are determined by condylar displacement due to surgery. The specific aims of this study are i) to measure condylar displacement immediately after surgery and condylar remodeling six months after surgery, and ii) to identify associations between condylar displacement due to surgery and condylar bone remodeling after surgery.

2. Materials and methods

2.1. Study design and sample

This retrospective cohort study included skeletal Class III patients who underwent mandibular setback surgery at Chonnam National University Hospital (Gwangju, Korea) from 2011 to 2013. Inclusion criteria were mandibular prognathism, and 1-jaw bilateral sagittal split ramus osteotomy (SSRO). Exclusion criteria were syndromes, facial trauma, or degenerative joint disease. Surgery was performed by 3 oral and maxillofacial surgeons who had more than 5-years of experience in orthognathic surgery. After SSRO, semi-rigid fixation was applied using one miniplate and four monocortical screws on each side; no proximal-distal segmental clamp was used.

2.2. Data collection methods

CT scans were obtained using a CBCT scanner (Alphard Vega; Asahi Roentgen, Kyoto, Japan) prior to surgery, immediately after surgery (range, 3–5 days), and at about 6 months after surgery (range, 4.6–7.8 months). Scanner settings were as follows: 80 kVp, 5 mA, voxel size 0.39 mm × 0.39 mm × 0.39 mm, and field of view 200 mm × 179 mm. To obtain standardized volume data, the patients were scanned using reference ear plug (REP) and head posture aligner (HPA) (Hwang et al., 2013; Lee et al., 2014).

CBCT scan data were exported to Invivo5 (version 5.3; Anatomage, San Jose, CA) as a digital imaging and communication in medicine (DICOM) file, and 3D head images were created.

2.3. Study variables

Predictor variables in this study were direction and magnitude of condylar displacement. Condylar displacement was evaluated from 3D superimposition on the cranial base before and immediately after surgery. Using the *import orientation* function of the program, the paired volume images were oriented in the same position. Four cephalograms (frontal, right lateral, left lateral and basal) were generated from each volume image. In order to visualize the condyles, segments of the condyle were generated at a depth of 10 mm. A segmental view was created removing overlapping areas by means of the *clipping* and *sculpt* functions of the program in addition to generating an overall head image. Photoshop (CS4; Adobe, San Jose, CA) was then used to overlap the segmental and overall head images to construct cephalograms with highlighted condyles (Hwang et al., 2016). Each pair of CBCT-generated cephalograms (i.e., before and immediately after surgery) was used to measure condylar displacement. Cephalograms before and immediately after surgery were precisely placed in the same orientation in the coordinate system. X-directional displacement was measured on frontal cephalograms, whereas y- and z-directional displacement was obtained from lateral cephalograms. Condylar rotation was measured on basal cephalograms (Fig. 1).

Primary outcome variable was amount of condylar remodeling (resorption/deposition). Condylar remodeling was evaluated from 3D superimposition of scan data taken immediately after surgery and six months later. A visual inspection of the 3D surface model was followed by quantitative assessment using CBCT-generated cephalograms. For construction of the 3D surface model, right and left side proximal segments were isolated using the *clipping* and *sculpt* function in the Invivo program. Segmentation threshold

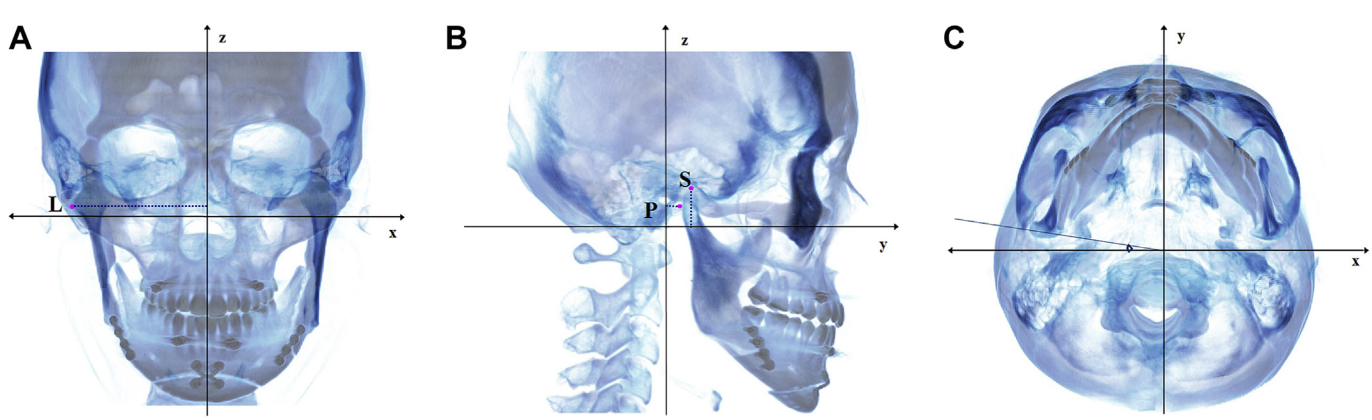

Fig. 1. Measurements of condylar displacement were obtained from cone-beam CT-generated cephalograms using scan data obtained before and immediately after surgery. X-directional displacement was measured on frontal cephalograms (A) whereas y- and z-directional displacement was obtained from lateral cephalograms (B). Condylar rotation was measured on basal cephalograms (C). L, Lateral condylar surface; P, posterior condylar surface; S, superior condylar surface.

values ranged from 250 to 3,071. A pair of proximal segments, immediately and 6 months after surgery, was registered in a 3D reverse engineering software (Rapidform, 2006; INUS Technology, Seoul, Korea). The initial registration was performed by selecting three corresponding points on both models. Subsequently, regional registration was used to finalize the registration. Condylar neck and posterior ramal area above the lingula mandibulae were used as registration area in this surface-based registration. From this superimposition, remodeling patterns on the condylar head surfaces were evaluated with color-mapping methods (Fig. 2).

For quantitative assessment of condylar remodeling, segmental CBCT-generated cephalograms were created using the Invivo program. The paired volume images were superimposed using the above-mentioned registration area, separately for right and left side. Using the *volume registration* function of the program, automatic volume-based registration was performed initially; the superimposition was then adjusted manually using the *adjust* function for fine registration. Using the *import orientation* function, two volume images were oriented in the same position. In order to generate cephalograms of the proximal segment, overlapped or

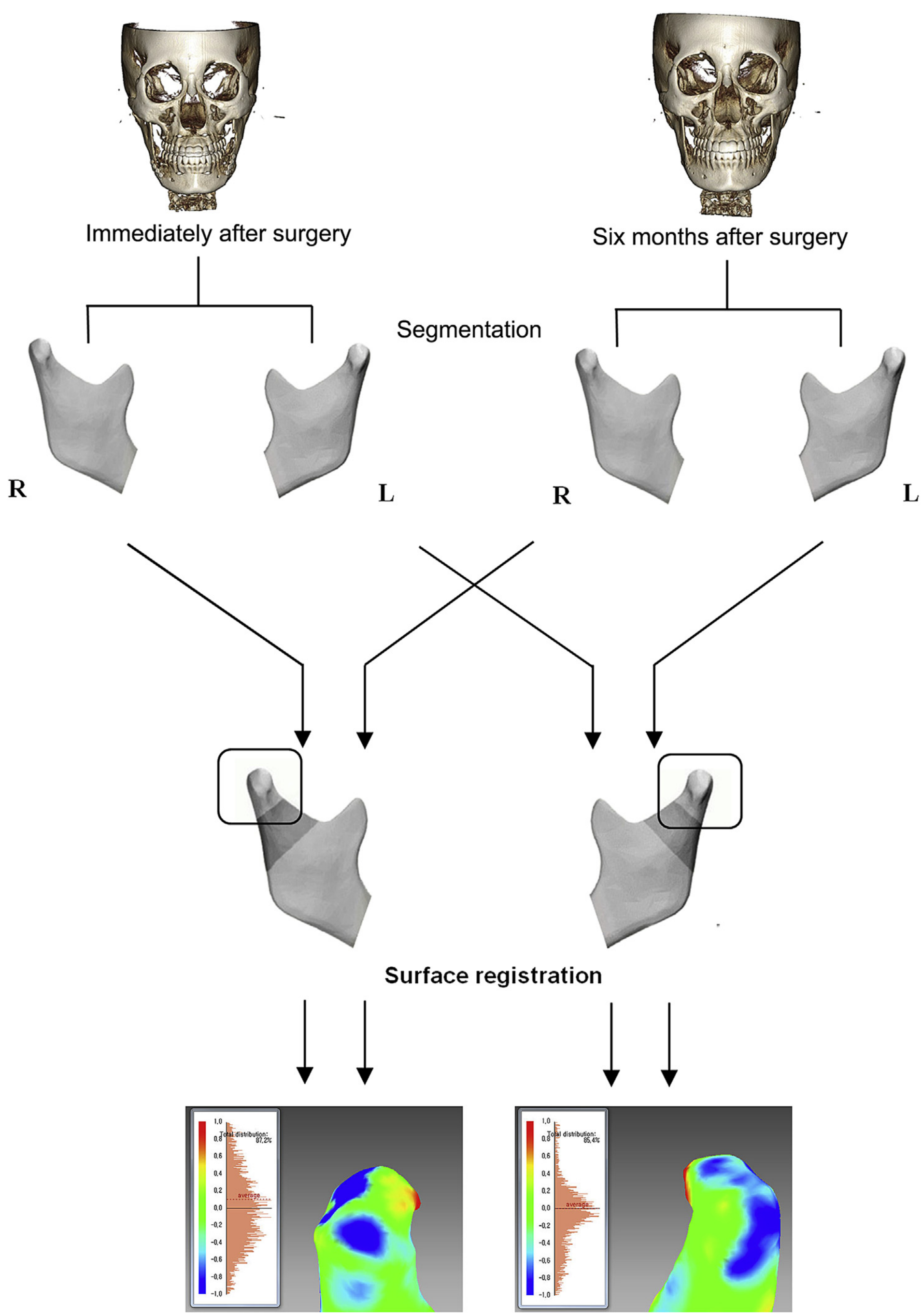

Fig. 2. Construction of a 3D surface model of the proximal segment to evaluate condylar head remodeling using images obtained immediately after surgery and at 6 months. Each proximal segment was isolated using the clipping and sculpt functions of the Invivo program. A pair of proximal segments was registered in Rapidform software. The condylar neck and the posterior ramal area above the lingula of mandible (shaded area) were used as the registration area in this surface-based registration. From this superimposition, the remodeling patterns on the condyle head were evaluated with color-mapping methods.

unnecessary areas were removed. Two pairs of segmental cephalograms, lateral and frontal before remodeling and lateral and frontal after remodeling, were obtained in the same coordinate system (Fig. 3).

Measurements of condylar head remodeling were obtained from each pair of segmental cephalograms. The resorption/deposition on the medial and lateral surfaces was measured on frontal view cephalograms whereas anterior, posterior, and superior surface remodeling was evaluated on lateral view cephalograms (Fig. 4).

2.4. Statistical analysis

In order to assess the measurement errors (MEs) of condylar displacement and condylar remodeling measurements, the images of 20 condyles in 10 subjects were selected randomly, and the measurements were repeated twice at an interval of 2 weeks by a single investigator. The MEs of double registration of all measurements were calculated using the Dahlberg formula (Dahlberg, 1940):

$$ME = \sqrt{\sum d^2/2n}$$

where d is the difference between the two measurements and n is the number of subjects. The MEs were less than 0.09 mm in linear measurements, and 0.6° in angular measurements.

Based on the measurement errors, condylar displacement or the lack of it was determined for each condyle; displacement values within the measurement error (0.1 mm for linear measurements and 0.7° for angular measurements) were regarded as no displacement of condyle in the present study. Means and standard deviations were computed for each directional displacement/rotation. One sample t-test was used to test the significance of condylar head remodeling 6 months after surgery for five surfaces: medial, lateral, anterior, posterior and superior. The significance of condylar head remodeling according to condylar displacement was tested using one sample t-test for the x-, y-, and z-directions. In addition, Pearson's correlation analysis was used to evaluate the correlation between condylar head remodeling and condylar displacement. Statistical evaluations were performed at the 5% level of significance with SPSS software (version 21.0; SPSS Inc., Chicago, IL).

3. Results

During the study period, 95 adult patients with mandibular prognathism were evaluated; 30 patients (12 female, 18 male; mean age 22.7 y ± 3.5 y) met the inclusion criteria. Eight of 30 patients received genioplasty to improve facial esthetics.

Immediately after surgery, condylar displacement, exceeding the measurement error, occurred predominantly in lateral (75%), posterior (76.7%), or downward (93.3%) direction. Regarding rotation, the condyles showed mainly inward rotation (80%) (Table 1).

Six months after surgery, the condyles presented distinct resorption/deposition patterns depending on the surface. Medial and anterior surfaces showed deposition (+0.14 and + 0.10 mm; $P < .05$), whereas lateral and posterior surfaces showed resorption (−0.19 and −0.17 mm; $P < .05$). Superior surfaces also showed predominantly resorption (−0.19 mm; $P < .05$) (Fig. 5 and Table 2).

Table 3 shows the results of bone remodeling according to condylar displacement in the x, y, and z-directions. Laterally

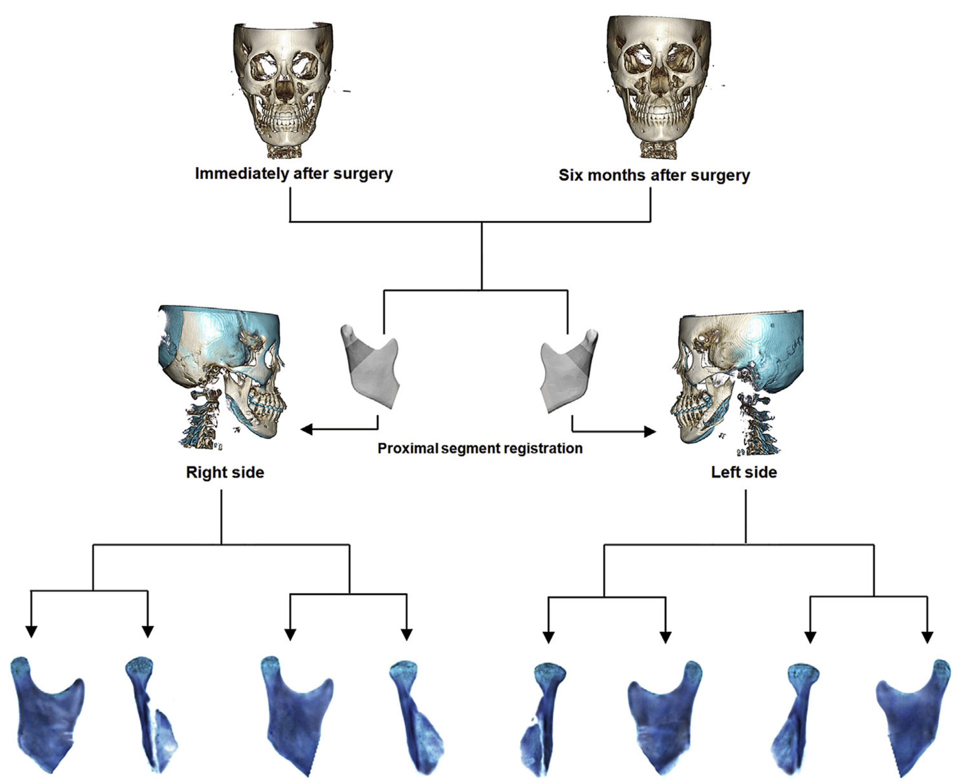

Fig. 3. Construction of segmental cone-beam CT-generated cephalograms to evaluate condylar head remodeling quantitatively. The two images were superimposed using each proximal segment as the registration area with the Invivo program. The condylar neck and the posterior ramal area above the lingula of the mandible (shaded area) were used as the registration area in this voxel-based registration. From this superimposition, a pair of segmental cephalograms, before and after remodeling, could be obtained in the same coordinate system. Overlapping or unnecessary areas were removed using the clipping and sculpt functions of the program to create a lateral or frontal segmental cephalograms. In order to evaluate resorption/deposition on the condyle, each pair of cephalograms was used.

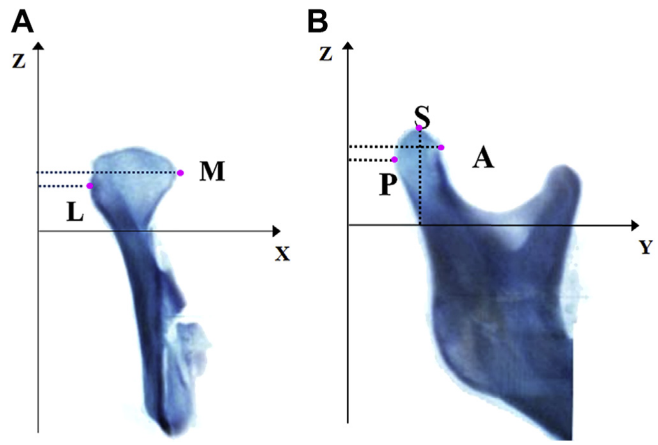

Fig. 4. Measurements on segmental cephalograms to evaluate condylar head remodeling. Remodeling on medial and lateral surfaces was measured on frontal view cephalograms (A) whereas anterior, posterior, and superior surface remodeling was evaluated on lateral view cephalograms (B). M, Medial pole; L, lateral pole; A, anterior condylar surface; P, posterior condylar surface; S, superior condylar surface.

displaced condyles showed statistically significant resorption on the lateral surfaces (−0.26 mm; $P < .05$) and deposition on the medial surfaces (+0.21 mm; $P < .05$), whereas medially displaced condyles showed resorption on the medial surfaces (−0.07 mm; $P > .05$) and deposition on the lateral surfaces (+0.04 mm; $P > .05$) without statistical significance. Anteriorly displaced condyles showed statistically significant resorption on anterior surfaces (−0.11 mm; $P < .05$), whereas posteriorly displaced condyles presented statistically significant resorption on posterior surfaces (−0.21 mm; $P < .05$) and deposition on anterior surfaces (+0.15 mm; $P < .05$). In the evaluation of bone remodeling according to condylar displacement in the z-direction, downwardly displaced condyles (56 of 60 condyles) showed significant bone resorption (−0.20 mm; $P < .05$) on their superior surfaces (Table 3).

Regarding bone remodeling according to condylar rotation, inwardly rotated condyles showed significant resorption or deposition on all surfaces ($P < .05$); superior surfaces showed statistically significant resorption (−0.19, −0.14, and −0.21 mm; $P < .05$) regardless of the direction of rotation (Table 4).

In Pearson's correlation analysis between bone remodeling and condylar displacement, laterally displaced condyles showed significant positive and negative correlations on medial ($r = 0.415$; $P < .05$) and lateral ($r = -0.520$; $P < .05$) surfaces, respectively, whereas medially displaced condyles showed significant negative and positive correlations on medial ($r = -0.822$; $P < .05$) and lateral ($r = 0.716$; $P < .05$) surfaces, respectively. Anteriorly displaced condyles showed significant negative and positive correlations on anterior ($r = -0.683$; $P < .05$) and posterior ($r = 0.624$; $P < .05$) surfaces, respectively, whereas posteriorly displaced condyles showed significant positive and negative correlations on anterior ($r = 0.376$; $P < .05$) and posterior ($r = -0.443$; $P < .05$) surfaces, respectively. In case of z-directional displacement, condylar displacement showed significant correlation only with superior surfaces ($r = -0.398$; $P < .05$).

The analysis of condylar inward and outward rotation showed significant correlations with bone remodeling on the medial, lateral, and superior surfaces ($P < .05$). No significant correlations were noted with anterior or posterior surfaces ($P > .05$). Inwardly rotated condyles showed positive correlation with medial surfaces ($r = 0.410$; $P < .05$) and negative correlation with the lateral surfaces ($r = -0.336$; $P < .05$), whereas outwardly rotated condyles showed the reverse, that is, negative and positive correlations with medial ($r = -0.964$; $P < .05$) and lateral ($r = 0.979$; $P < .05$) surfaces, respectively. Both inwardly and outwardly rotated condyles showed negative correlations with the superior surfaces ($r = -0.377$ and -0.963; $P < .05$) (Table 5).

Table 1
Condylar displacement immediately after surgery (N = 60).

	Frequency	Displacement Mean ± SD
X-direction[a] (mm)		
Lateral displacement	45 (75.0%)	+1.04 ± 0.65
No displacement[e]	1 (1.7%)	+0.02
Medial displacement	14 (23.3%)	−0.57 ± 0.29
Y-direction[b] (mm)		
Anterior displacement	14 (23.3%)	+0.57 ± 0.29
No displacement[e]	NA	NA
Posterior displacement	46 (76.7%)	−0.81 ± 0.46
Z-direction[c] (mm)		
Upward displacement	1 (1.7%)	+0.30
No displacement[e]	3 (5.0%)	−0.02 ± 0.01
Downward displacement	56 (93.3%)	−1.41 ± 0.71
Rotation[d] (°)		
Inward rotation	48 (80.0%)	+4.53 ± 2.22
No rotation[f]	8 (13.3%)	+0.42 ± 0.07
Outward rotation	4 (6.7%)	−2.74 ± 1.58

SD, Standard deviation; NA, not applicable.
[a] (+) denotes lateral displacement, (−) denotes medial displacement.
[b] (+) denotes anterior displacement, (−) denotes posterior displacement.
[c] (+) denotes upward displacement, (−) denotes downward displacement.
[d] (+) denotes inward rotation, (−) denotes outward rotation.
[e] Displacement within 0.1 mm in each direction.
[f] Rotation within 0.7°.

4. Discussion

The present study revealed associations between the direction of condylar displacement immediately after surgery and condylar remodeling (resorption and deposition) six months after surgery. It turned out that the type of condylar displacement that occurred during the surgery determined these condylar remodeling patterns: (i) Laterally displaced condyles showed resorption on the lateral surfaces and deposition on the medial surfaces, whereas medially displaced condyles showed resorption and deposition on the medial and lateral surfaces, respectively. (ii) Likewise, anteriorly displaced condyles showed resorption on the anterior surfaces and deposition on the posterior surfaces, whereas posteriorly displaced condyles showed resorption and deposition on the posterior and anterior surfaces, respectively. (iii) Superior condylar surfaces predominantly showed resorption, regardless of the direction of displacement.

Regarding timing, earlier studies obtained transcranial radiographs 6 months (Hollender and Ridell, 1974) or 1 year (Edlund et al., 2009) after surgery to detect double contour lines, suggestive of condylar remodeling. Katsumata et al. (2006) reported on double contour lines 3 months after surgery using CT slice images; Hollender and Ridell (Hollender and Ridell, 1974) reported that double lines had disappeared by 18 months post-operatively. Accordingly, 6 months after surgery seemed appropriate for evaluating the correlation between condylar remodeling and condylar displacement due to surgery.

Earlier studies (Hollender and Ridell, 1974; Eckerdal et al., 1986; Petersson and Willmar-Hogeman, 1989; Katsumata et al., 2006; Edlund et al., 2009) used detection of two-dimensional (2D) double contour lines to identify condylar remodeling. In 2D, bone formation (deposition) only, but not bone resorption, could be identified on paired images taken at different time points, because of their different orientation. Recent advances in computer technology

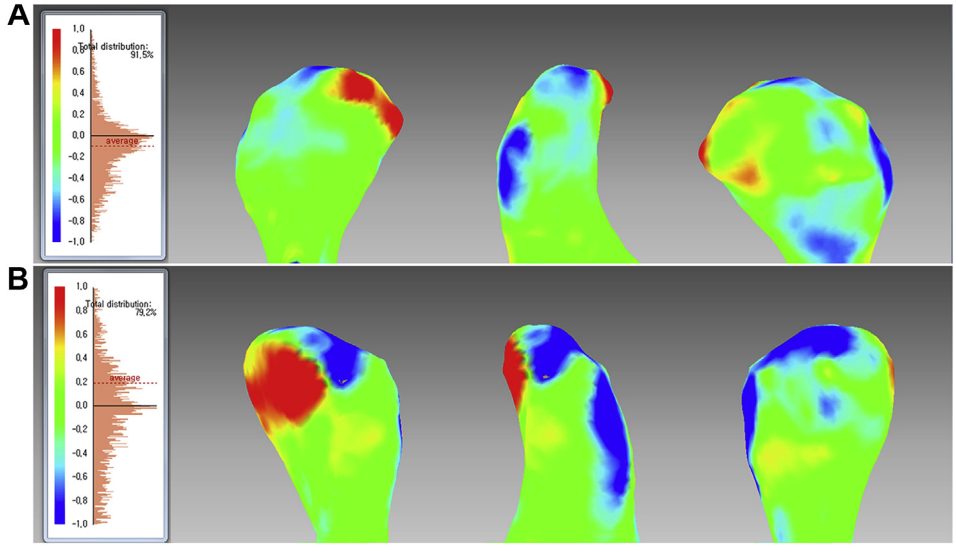

Fig. 5. Color-coded visualization charts show the differences between images obtained immediately after surgery and at 6 months, which indicate bone remodeling patterns on the condylar head. In this example, the medial and anterior surfaces show deposition (in red) whereas the lateral and posterior surfaces show resorption (in blue) for both sides of the condyle. Superior surfaces also show resorption predominantly. A, Anterior, lateral and posterior views of the right condyle; B, anterior, lateral, and posterior views of the left condyle.

Table 2
Condylar head remodeling (in mm) six months after surgery.

	Medial	Lateral	Anterior	Posterior	Superior
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Right side (n = 30)	+0.14 ± 0.19*	−0.17 ± 0.21*	+0.09 ± 0.16*	−0.17 ± 0.17*	−0.18 ± 0.14*
Left side (n = 30)	+0.15 ± 0.16*	−0.21 ± 0.14*	+0.10 ± 0.14*	−0.17 ± 0.14*	−0.20 ± 0.13*
Combined (n = 60)	+0.14 ± 0.18*	−0.19 ± 0.18*	+0.10 ± 0.15*	−0.17 ± 0.16*	−0.19 ± 0.13*

SD, Standard deviation; (+) indicates deposition, (−) indicates resorption.
* $P < 0.05$ by one sample *t*-test.

Table 3
Condylar head remodeling (in mm) according to condylar displacement in the x-, y- and z-direction.

	Medial	Lateral	Anterior	Posterior	Superior
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
x-direction					
Lateral displacement (n = 45)	+0.21 ± 0.12*	−0.26 ± 0.10*	+0.11 ± 0.13*	−0.19 ± 0.14*	−0.18 ± 0.13*
No displacement[a] (n = 1)	−0.14	−0.05	−0.11	+0.12	0.00
Medial displacement (n = 14)	−0.07 ± 0.16	+0.04 ± 0.18	+0.06 ± 0.19	−0.12 ± 0.18*	−0.21 ± 0.13*
y-direction					
Anterior displacement (n = 14)	+0.10 ± 0.21	−0.17 ± 0.22*	−0.11 ± 0.15*	+0.03 ± 0.14	−0.19 ± 0.12*
No displacement[a] (n = 0)	NA	NA	NA	NA	NA
Posterior displacement (n = 46)	+0.15 ± 0.16*	−0.21 ± 0.16*	+0.15 ± 0.09*	−0.21 ± 0.11*	−0.19 ± 0.13*
z-direction					
Upward displacement (n = 1)	+0.02	−0.12	+0.19	−0.21	−0.12
No displacement[a] (n = 3)	+0.18 ± 0.11	−0.17 ± 0.03*	+0.06 ± 0.06	−0.19 ± 0.20	−0.08 ± 0.11
Downward displacement (n = 56)	+0.14 ± 0.19*	−0.19 ± 0.18*	+0.10 ± 0.16*	−0.16 ± 0.16*	−0.20 ± 0.13*

SD, Standard deviation; NA, not applicable; (+) indicates deposition, (−) indicates resorption.
* $P < 0.05$ by one sample *t*-test.
[a] Displacement within 0.1 mm in each direction.

have enabled us to reorient 3D images of different time points into the same position and superimpose them with a stable registration area (Choi and Mah, 2010). Condylar neck and posterior ramal area above the lingula mandibulae (Park et al., 2012; Ha et al., 2013; An et al., 2014) have been superimposed to evaluate condylar remodeling in this study. Shape changes could be evaluated using multi-planar reformation (MPR) images. From these, bone resorption as well as bone formation was identified.

While recent CBCT studies (Park et al., 2012; Ha et al., 2013; An et al., 2014) were able to distinguish between resorption and deposition, an accurate quantitative assessment was impossible even with 3D superimposition because shape changes were determined on section images, which had been sliced at different levels. To overcome this limitation, we generated cephalograms of proximal segments by capturing volume images after superimposition by pairing these segmental images in the same coordinate

Table 4
Condylar head remodeling (in mm) according to condylar rotation.

	Medial	Lateral	Anterior	Posterior	Superior
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Inward rotation (n = 48)	+0.15 ± 0.19*	−0.20 ± 0.18*	+0.11 ± 0.15*	−0.18 ± 0.15*	−0.19 ± 0.14*
No rotation[a] (n = 8)	+0.10 ± 0.17	−0.16 ± 0.19	+0.11 ± 0.07*	−0.14 ± 0.14*	−0.14 ± 0.04*
Outward rotation (n = 4)	+0.12 ± 0.20	−0.01 ± 0.21	−0.03 ± 0.24	−0.09 ± 0.20	−0.21 ± 0.10*

SD, Standard deviation; (+) indicates deposition, (−) indicates resorption.
*$P < 0.05$ by one sample *t*-test.
[a] Rotation within 0.7°.

Table 5
Pearson's correlation between the condylar head remodeling and the condylar displacement.

	Medial	Lateral	Anterior	Posterior	Superior
x-direction					
Lateral displacement (n = 45)	0.415*	−0.520*	−0.256	0.234	−0.123
No displacement (n = 1)	NA	NA	NA	NA	NA
Medial displacement (n = 14)	−0.822*	0.716*	−0.260	0.190	−0.236
y-direction					
Anterior displacement (n = 14)	−0.309	0.524	−0.683*	0.624*	0.023
No displacement	NA	NA	NA	NA	NA
Posterior displacement (n = 46)	−0.046	0.200	0.376*	−0.443*	−0.085
z-direction					
Upward displacement (n = 1)	NA	NA	NA	NA	NA
No displacement (n = 3)	NA	NA	NA	NA	NA
Downward displacement (n = 56)	0.092	−0.043	0.007	−0.042	−0.398*
Rotation					
Inward rotation (n = 48)	0.410*	−0.336*	0.117	−0.106	−0.377*
No rotation (n = 8)	0.357	0.067	0.158	−0.395	0.045
Outward rotation (n = 4)	−0.964*	0.979*	−0.232	−0.145	−0.963*

NA, Not applicable.
*$P < 0.05$.

system. This way, condylar remodeling was evaluated quantitatively. Resultant data could then be correlated with condylar displacement.

On comparing CBCT segmental images obtained immediately and 6 months after surgery, we noted distinct resorption/deposition, determined by type of condylar displacement. Hollender and Ridell (Hollender and Ridell, 1974) reported on posterior bone formation in 30 out of 36 condyles after forward-inferior displacement.

Others (Eckerdal et al., 1986; Petersson and Willmar-Hogeman, 1989; Edlund et al., 2009) also revealed new bone formation according to condylar displacement through orthognathic surgery. All these studies showed 2D findings from a lateral view; condylar remodeling in medio-lateral direction could not be evaluated in their studies.

The present study found bone resorption occurring on the superior surfaces of condyles regardless of displacement direction, even following inferior displacement. This finding contradicts the principle that bone is remodeled in a compensatory fashion, adjusting to the new position. Recent CBCT studies (Park et al., 2012; Ha et al., 2013; An et al., 2014) have shown bone resorption occurring predominantly in superior regions of condyles without evaluating condylar displacement.

Since the human mandible functions as a lever during swallowing or biting, to maintain static equilibrium, the muscle force is divided into a reaction force along the bite point and a reaction force along the mandibular condyles (Hylander, 2006). It is likely that bone resorption seen on superior surfaces is related to postoperative changes in compressive forces on the condyle.

In contrast, orthopedic treatment of Class II malocclusion in adolescents is reported to show newly formed bone on superior condylar surfaces, distracting the TMJ in a dorso-cranial direction using Herbst appliance (Paulsen, 1997). Adults may differ from that, owing to less growth potential in the cartilage.

Huang et al. (2006) reported that 40% of cases treated with mandibular setback surgery showed significant vertical remodeling in adults, which is contrary to our results and can be explained by the difference in superimposition. Huang et al. (2006) used fixation wires as reference in their cephalometric superimpositions. We used the condylar neck and posterior ramus as registration areas (Park et al., 2012; Ha et al., 2013; An et al., 2014).

Our results showed that more resorption occurs with more condylar downward displacement. Petersson and Willmar-Hogeman (Petersson and Willmar-Hogeman, 1989) explained an average 3 mm displacement almost completely returning to normal with a combination of reverse movement of the condyle and remodeling. Since we generally found bone resorption on superior condylar surfaces, nearly all condylar repositioning in the superior direction should be relocation of the proximal segment. Importantly, the distal segment might move accordingly, which would interfere with postoperative orthodontic treatment. Semi-rigid fixation might be preferred to rigid fixation to ease relocation of the condyle.

Amounts of remodeling were small (less than a mm or a degree), although all condylar surfaces showed statistical significances. Additional studies need to be performed to identify condylar remodeling contributing to each condyle's repositioning towards its preoperative position. Further studies about other factors influencing condylar remodeling, such as age, sex, and magnitude of setback, will be needed.

5. Conclusion

In conclusion, condylar remodeling (resorption/deposition) and its extent are determined by the direction of condylar displacement during surgery, the exception being the superior surfaces of condyles, which show mostly bone resorption.

Ethical approval

This study was reviewed and approved by the institutional review board at University Hospital (IRB No. CNUDH-2016-001; Protocol No. TMP-2015-028).

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Conflicts of interest

None to declare.

Author contributions

T. Jiang, L. Sun, K.-M. Lee and M.-H. Oh contributed to data acquisition, analysis and interpretation, and drafted the manuscript; H.-S. Hwang, Y. Biao, H.-K. Oh and T. E. Bechtold contributed to conception and design and critically revised the manuscript. All authors gave final approval and agree to be accountable for all aspects of the work.

Patient consent

Not required.

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