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Clinical Paper
TMJ Disorders

Counterclockwise maxillomandibular advancement surgery and disc repositioning: can condylar remodeling in the long-term follow-up be predicted?

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L. R. Gomes, L. H. Cevidanes, M. R. Gomes, A. C. Ruellas, D. P. Ryan, B. Paniagua, L. M. Wolford, J. R. Gonçalves: Counterclockwise maxillomandibular advancement surgery and disc repositioning: can condylar remodeling in the long-term follow-up be predicted?. Int. J. Oral Maxillofac. Surg. 2017; 46: 1569–1578.

Abstract. This study investigated predictive risk factors of condylar remodeling changes after counterclockwise maxillomandibular advancement (CCW-MMA) and disc repositioning surgery. Forty-one female patients (75 condyles) treated with CCW-MMA and disc repositioning had cone beam computed tomography (CBCT) scans taken pre-surgery, immediately after surgery, and at an average 16 months post-surgery. Pre- and post-surgical three-dimensional models were superimposed using automated voxel-based registration on the cranial base to evaluate condylar displacements after surgery. Regional registration was performed to assess condylar remodeling in the follow-up period. Three-dimensional cephalometrics, shape correspondence (SPHARM-PDM), and volume measurements were applied to quantify changes. Pearson product–moment correlations and multiple regression analysis were performed. Highly statistically significant correlation showed that older patients were more susceptible to overall condylar volume reduction following CCW-MMA and disc repositioning ($P \leq 0.001$). Weak but statistically significant correlations were observed between condylar remodeling changes in the follow-up period and pre-surgical facial characteristics, magnitude of the surgical procedure, and condylar displacement changes. After CCW-MMA and disc repositioning, the condyles moved mostly downwards and medially, and were rotated medially and counterclockwise; displacements in the opposite direction were correlated with a greater risk of condylar resorption. Moreover, positional changes with surgery were only weakly associated with remodeling in the follow-up period, suggesting that other risk factors may play a role in condylar resorption.

Key words: orthognathic surgery; mandibular condyle; cone beam computed tomography.

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Postoperative instability of counterclockwise maxillomandibular advancement (CCW-MMA) due to condylar displacement during the surgical procedure and/or subsequent long-term condylar resorption remains an area of concern[1,2]. Authors have suggested that condylar torque and altered condylar loading may lead to sagittal relapse and an anterior open bite[3,4].

There is disagreement in the current literature regarding treatment efficacy and the options for preventing degenerative condylar changes after bimaxillary surgical advancement. Although some investigators believe that orthognathic surgery alone reduces or eliminates temporomandibular joint (TMJ) dysfunction and symptoms[5–7], others have reported that performing orthognathic surgery in the presence of a TMJ disorder may cause further harmful effects to the TMJ[8,9].

Some studies have shown that the simultaneous surgical correction of coexisting dentofacial deformities and a TMJ pathology by repositioning and stabilizing the articular disc provides high-quality treatment outcomes for most patients[10–13]. On the other hand, specific condylar displacement changes during articular disc repositioning surgery have been investigated as a potential factor inducing condylar remodeling in the long-term follow-up[14]. Moreover, it has been reported that the degree of mandibular advancement performed may also contribute to skeletal relapse and condylar resorption[11]. Patients with pre-surgical TMJ symptoms requiring large mandibular advancement appear to be at increased risk[15,16].

The use of cone beam computed tomography (CBCT) and new three-dimensional (3D) tools allow for a comprehensive analysis of surgical and post-surgical skeletal changes. Such technologies have the potential to identify individual variability and highlight associations between structural changes and the stability of surgical correction[17,18].

This study investigated whether age, pre-surgical antero-posterior and vertical facial characteristics, and the magnitude of the surgical procedure and/or condylar displacement changes may predict condylar remodeling after CCW-MMA and disc repositioning surgery.

Materials and methods

De-identified CBCT scans from 41 female patients presenting with disc displacement and TMJ osteoarthritis (OA), who underwent CCW-MMA associated with disc repositioning surgery, were included in this study (Fig. 1). Patients were operated on consecutively by the same surgeon (LMW), using rigid internal fixation. Articular disc displacement was assessed by clinical examination and magnetic resonance imaging (MRI) interpreted by two experienced and calibrated doctors (LMW and JRG). Diagnostic criteria for temporomandibular disorders were used to identify TMJ OA[19].

The current study utilized CBCT images obtained before surgery (T1), immediately after surgery (3–9 days) (T2), and at an average 16 months post-surgery (T3). Archives from patients presenting with craniofacial syndromes, systemic degenerative conditions such as rheumatoid arthritis, or who had undergone a previous TMJ intervention were excluded.

A total of 82 condyles were analyzed. Seven condyles were excluded due to a history of previous arthroplasty. The final sample was composed of 75 condyles. All patients signed an informed consent form for hospital admission, surgical procedures, and release of information for research purposes. This study was approved by the university institutional review board and was performed in compliance with the Declaration of Helsinki.

Surgical technique

The TMJ and orthognathic surgeries were performed concomitantly, beginning with the TMJ surgery. Articular disc repositioning surgery was performed using the Mitek anchor technique (Mitek Products, Inc., Westwood, MA, USA). The CCW-MMA technique was then performed beginning with the bilateral mandibular sagittal split osteotomies with counterclockwise rotation and stabilization; one bone plate was positioned in the posterior body area and two to three bicortical 2-mm diameter screws were placed in the ascending ramus on each side. The maxillary osteotomies were then performed for counterclockwise rotation and stabilized with four bone plates using 2-mm diameter screws and bone grafting when indicated. A detailed description of the surgical procedure has been published previously[10].

Image acquisition and 3D analysis

CBCT images were obtained using a 17 × 23 cm extended field of view protocol, with a scan time of 17.8 s and isotropic voxel size of 0.3 mm (i-Cat CBCT,

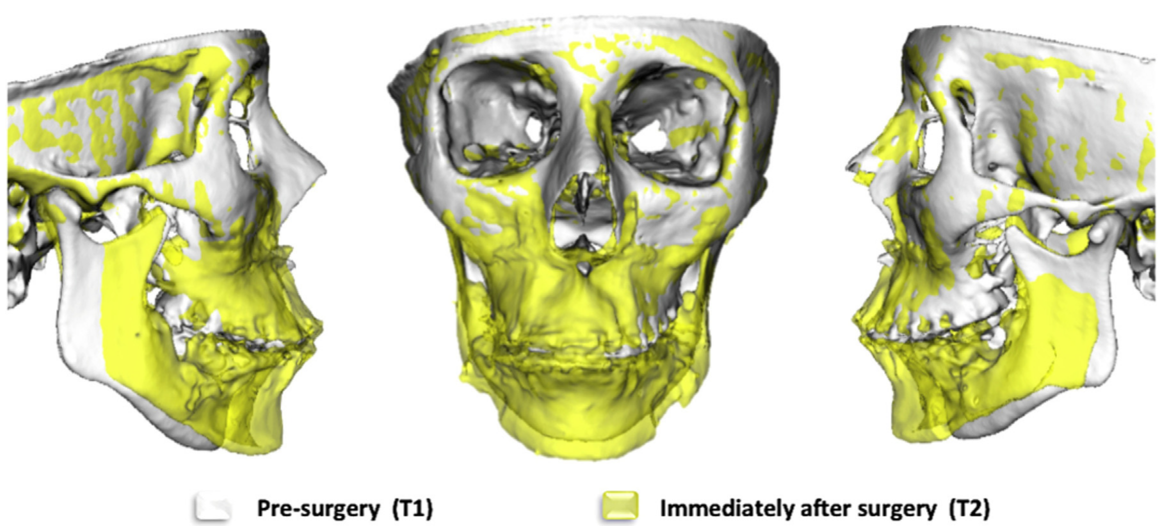

Fig. 1. All patients underwent counterclockwise maxillomandibular advancement surgery. Images obtained from a randomly selected patient. The amount of surgical movement differed from one patient to another.

120 kV, 5 mA; Imaging Sciences, Hatfield, PA, USA). Images were resampled to 0.5-mm isotropic voxel size prior to performing the segmentation of the anatomical structures of interest (CMF Registration, 3D Slicer software, www.slicer.org). 3D models of the cranial base, maxilla, and mandible were constructed by outlining the cortical boundaries using semi-automated discrimination procedures (ITK-SNAP software, www.itksnap.org). A 3D cephalometric analysis was conducted to determine the facial skeletal pattern before surgery (T1) and to assess surgical changes (T1–T2) for sample characterization (Q3DC, 3D Slicer software).

In this study, the images obtained at the different time-points were superimposed using two specific voxel-based registration methods (CMF Registration, 3D Slicer software). Cranial base registration was applied to assess condylar displacement changes[17], and regional registration was used to analyze condylar remodeling[20]. Both procedures were conducted through 3D Slicer software (CMF Registration, 3D Slicer software).

All left condyles were mirrored in the sagittal plane to form right condyles to facilitate the outcomes analysis. Superimposed models were simultaneously cropped (Easy Clip, 3D Slicer software) and compared by subtraction to compute surgical (T1–T2) and post-surgical (T2–T3) changes between corresponding surface meshes using shape correspondence analysis (SPHARM-PDM, 3D Slicer software).

Shape correspondence made it possible to mark the regions of interest (ROI) in one condyle and propagate such regions for the other surgical time-points, obtaining *x,y,z* coordinates for each point (Pick 'n Paint, 3D Slicer software). Then, mathematical formulas were applied to each coordinate of correspondent points in the condylar surface, which allowed the measurement of both translational (antero-posterior, vertical, and lateral) and rotational (pitch, roll, and yaw) displacements. Each condylar translational displacement was measured in millimeters and each rotational change in degrees. Positive and negative signs indicated the direction of displacement (Fig. 2).

Five specific ROI were selected as representative of each condylar surface, i.e., superior, anterior, posterior, medial, and lateral surfaces. Thirty-seven correspondent points were used to analyze changes in the anterior, superior, and posterior surfaces, whereas 19 points were selected as representatives for the analysis of changes in the lateral and medial surfaces (Fig. 3). The referred ROI were marked in the post-surgical 3D models and propagated to the respective follow-up models (Pick 'n Paint, 3D Slicer software). 3D point-wise linear distances between each time-point were then used to calculate remodeling changes in millimeters (Model to Model Distance, 3D Slicer software). Positive and negative signals represented outward and inward movement, respectively. Thus, positive values indicated bone apposition and negative values indicated bone resorption. Condylar volume changes were also calculated in cubic millimeters using the ITK-SNAP software.

Statistical analysis

Descriptive statistics were used to report clinical characteristics before surgery (T1), as well as surgical (T1–T2) and post-surgical changes (T2–T3). Pearson product–moment correlations were used to determine the relationships of clinical and surgical factors with condylar remodeling in the follow-up period. Stepwise multiple linear regression analysis was used to identify the independent variables that best predict condylar remodeling at specific sites. A significance level of $P \leq 0.05$ was applied. The statistical analyses were performed using SPSS version 16.0 software (SPSS Inc., Chicago, IL, USA).

3 Results

Patient demographic and clinical characteristics are listed in Table 1. The sample was composed mostly of hyperdivergent retrognathic patients. Fifteen percent of the subjects presented a sella–nasion to mandibular plane (SNGoMe) angle of $<33.2°$ and/or sella–nasion to B-point (SNB) angle of $>79°$. The maxilla was

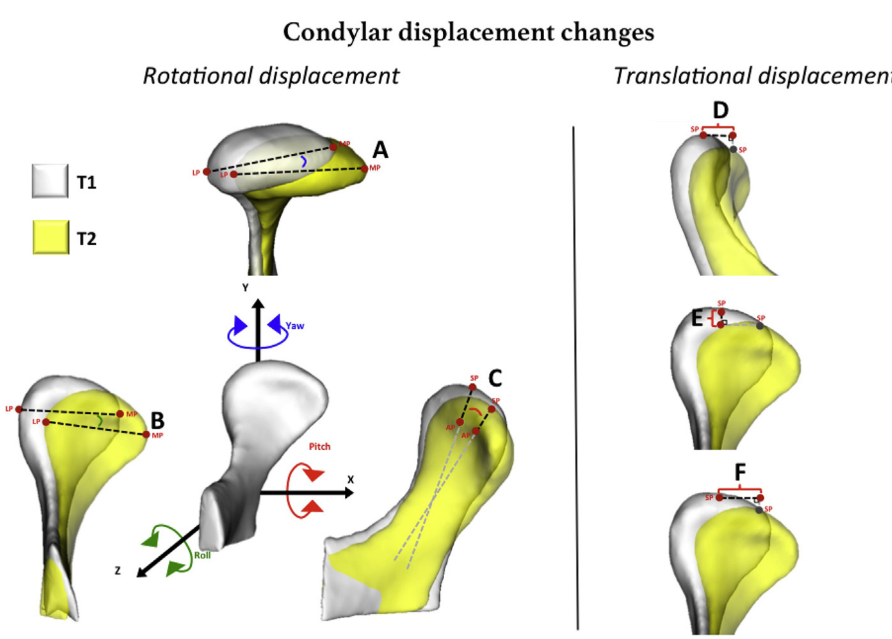

Fig. 2. Rotational and translational measurements used to assess condylar changes: (A) yaw, rotation around the *y*-axis (axial view); (B) roll, rotation around the *z*-axis (coronal view); (C) pitch, rotation around the *x*-axis (sagittal view); (D) antero-posterior displacement (sagittal view); (E) vertical displacement (coronal view); (F) lateral displacement (coronal view).

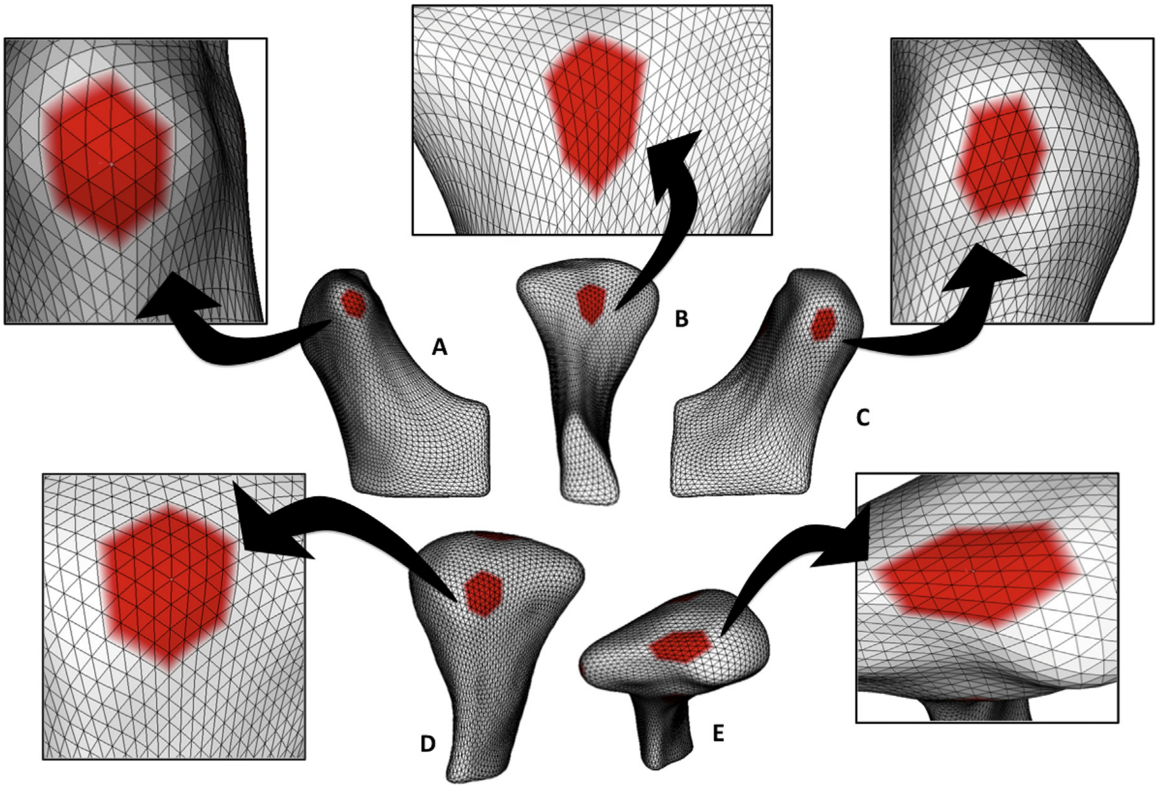

Fig. 3. Regions of interest (ROI) for investigating condylar remodeling changes: (A) lateral surface; (B) anterior surface; (C) medial surface; (D) posterior surface; (E) superior surface.

often retruded as well. All patients underwent mandibular advancement and counterclockwise rotation of the maxillomandibular complex simultaneously with disc repositioning surgery. The mean counterclockwise rotation and advancement at B-point were $5.6^\circ \pm 3.1^\circ$ and $6.0^\circ \pm 2.3^\circ$, respectively. Descriptive statistics for the surgical displacement changes are shown in Table 2.

On average, the condyles (proximal segment) were displaced backward, downward, and medially during the surgical procedure (T1–T2). However, it was observed that for the great majority of patients this translational displacement was less than 1 mm (Fig. 4). About 30% of the sample showed forward, upward, and lateral displacement of the mandibular condyle. Taking into account the rotational displacements, most of the condyles had lateral yaw, medial roll, and upward pitch with surgery.

Condylar remodeling changes were observed during the follow-up period (T2–T3). Medial, lateral, superior, and posterior surfaces of the mandibular condyle presented more than 1.5 mm of bone resorption in about 30% of the cases. The condylar lateral and superior surfaces were the most affected. On the other hand, the anterior surface showed bone apposition. It was also noticed that although most of the ROI in the study showed bone resorption, 42% of the sample did not experience a reduction in the overall condylar volume, i.e., bone resorption was compensated for by bone apposition. About 18% of the sample showed a volume increase of more than 75 mm^3 (Table 3; Fig. 5).

Pearson product–moment correlations aimed to determine the relationships of clinical and surgical factors with condylar remodeling in the follow-up period. Among the clinical characteristics studied, age and facial pattern before surgery showed weak but statistically significant correlations with condylar remodeling (Table 4). The older the patient, the greater the bone resorption at the lateral surface ($P \leq 0.05$) and the overall condylar volume reduction ($P \leq 0.001$). The more vertical the patient's facial pattern (i.e., high SNGoMe angle at T1), the smaller the bone resorption at the anterior surface of the condyle ($P \leq 0.05$) and the overall volume reduction ($P \leq 0.05$). Maxillary and mandibular retrusion (i.e., low SNA and SNB angle at T1, respectively) were associated with larger medial surface resorption ($P \leq 0.05$). The greater the mandibular retrognathism, the smaller the anterior surface resorption ($P \leq 0.01$). The duration of the follow-up period in months showed no

Table 1. Demographic data and clinical characteristics before surgery.

	Age, years	Follow-up (months)	Before surgery (T1)		
			SNGoMe (°)	SNA (°)	SNB (°)
Mean	26.4	16.1	40.9	79.1	74.4
SD	12.5	8.2	7.4	3.7	4.6
Min	16.0	6.0	25.1	69.5	59.4
Max	58.0	52.0	61.0	85.8	81.6
Percentile					
15th	16.0	10.0	33.2	75.1	71.1
50th	21.0	14.0	41.4	79.4	74.9
85th	41.9	23.9	46.3	83.2	79.0

SD, standard deviation; Min, minimum; Max, maximum; SNGoMe, sella–nasion to mandibular plane angle; SNA, sella–nasion to A-point angle; SNB, sella–nasion to B-point angle.

Table 2. Surgical changes (T1–T2).

	Magnitude of the surgical procedure			Condylar displacement changes					
	SNGoMe (°)[a]	SNA (°)[b]	SNB (°)[c]	AP (mm)[d]	Vertical (mm)[e]	Lateral (mm)[f]	Yaw (°)[g]	Roll (°)[h]	Pitch (°)[i]
Mean	5.6	−3.3	−6.0	0.6	1.0	1.5	4.5	−5.2	−7.5
SD	3.1	2.0	2.3	1.3	1.3	1.8	6.0	7.3	8.0
Min	0.7	−7.4	−12.6	−3.2	−2.3	−2.5	−11.8	−30.5	−32.3
Max	14.6	1.2	−1.8	3.5	5.0	7.3	18.3	8.7	14.0
Percentile									
15th	2.3	−5.5	−8.4	−0.6	−0.2	−0.6	−1.2	−11.4	−14.5
50th	5.4	−3.1	−5.7	0.8	0.9	1.2	3.5	−4.4	−7.8
85th	7.9	−1.4	−3.4	1.8	2.4	3.4	12.0	1.8	−1.3

SD, standard deviation; Min, minimum; Max, maximum; SNGoMe, sella–nasion to mandibular plane angle; SNA, sella–nasion to A-point angle; SNB, sella–nasion to B-point angle; AP, antero-posterior displacement; Vertical, vertical displacement; Lateral, lateral displacement; Yaw, rotation around the *y*-axis; Roll, rotation around the *z*-axis; Pitch, rotation around the *x*-axis.

[a] Positive values indicate counterclockwise rotation and negative values indicate clockwise rotation.

[b] Negative values indicate the maxilla moved anteriorly and positive values indicate it moved posteriorly.

[c] Negative values indicate the mandible moved anteriorly and positive values indicate it moved posteriorly.

[d] Negative values indicate the condyle moved anteriorly and positive values indicate it moved posteriorly.

[e] Negative values indicate the condyle moved upward and positive values indicate it moved downward.

[f] Negative values indicate the condyle moved laterally and positive values indicate it moved medially.

[g] Negative values indicate posterior rotation of the medial surface and/or anterior rotation of the lateral surface. Positive values indicate anterior rotation of the medial surface and/or posterior rotation of the lateral surface.

[h] Negative values indicate the condyle moved medially and positive values indicate it moved laterally.

[i] Negative values indicate the condyle underwent counterclockwise rotation and positive values indicate it rotated clockwise.

statistically significant correlations with condylar remodeling.

Among the surgical changes (T1–T2), the amount of counterclockwise rotation (SNGoMe) and mandibular advancement (SNB) showed weak but statistically significant correlation with condylar remodeling in the follow-up period (Table 4). The greater the amount of counterclockwise rotation, the smaller the overall volume reduction ($P \leq 0.05$) and bone resorption at the lateral ($P \leq 0.05$) and posterior surfaces ($P \leq 0.001$). On the other hand, counterclockwise rotation was associated with larger bone resorption at the superior surface ($P \leq 0.05$). It was also observed that the greater the mandibular advancement, the larger the bone resorption at the superior surface ($P \leq 0.05$) and the lower the condylar resorption at the posterior surface ($P \leq 0.05$).

Condylar displacement changes during surgery (T1–T2) also showed some weak but statistically significant correlations with remodeling changes (T2–T3) (Table 4). Upward condylar displacement correlated with greater condylar resorption at the posterior surface of the condyle ($r = 0.26$, $P \leq 0.05$). Lateral and anterior condylar displacement correlated with greater condylar resorption at the lateral ($r = 0.3$, $P \leq 0.01$) and anterior surfaces ($r = 0.29$, $P \leq 0.05$), respectively. Medial displacement was correlated with a greater overall volume reduction ($P \leq 0.05$). Lateral roll and medial yaw correlated with greater condylar resorption at the posterior ($r = -0.26$, $P \leq 0.05$) and lateral surfaces ($r = 0.24$, $P \leq 0.05$), respectively.

Stepwise multiple linear regression analysis identified the independent variables (clinical characteristics and/or surgical changes) that best predict condylar remodeling at specific sites (Table 5). Mandibular position relative to the cranial base at T1 (SNB) was the independent variable that best explained condylar remodeling at the medial and anterior surfaces. For each degree of mandibular retrognathia, an increase in medial surface resorption and anterior surface apposition of about 0.09 mm was observed. However, such prediction models explained only 5% of the medial surface changes and 9% of the anterior surface changes.

Condylar lateral displacement best explained condylar remodeling at the lateral surface. For each millimeter of lateral displacement, an increase in lateral surface resorption of about 0.30 mm was suggested. This prediction model explained 9% of the lateral surface changes. The superior surface remodeling was best explained by the association of two independent variables: age and SNGoMe (T1–T2), expressing the amount of counterclockwise rotation. For each year older and for each degree of counterclockwise rotation, an increase in superior surface resorption of 0.04 mm and 0.22 mm, respectively, was found. The model explained 15% of the superior surface changes ($r^2 = 0.15$). SNGoMe (T1–T2) also explained posterior surface remodeling changes. For each degree of counterclockwise rotation, the posterior surface resorption was reduced by 0.20 mm ($r^2 = 0.14$). Age best explained the overall volume changes. For each year older, the model suggested a volume reduction of 5.06 mm^3. Age explained 21% of the overall changes in volume.

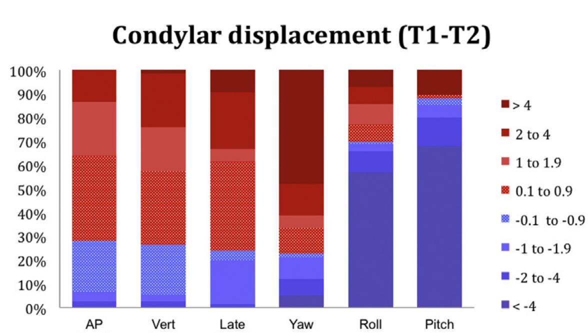

Fig. 4. Percentage of patients according to the direction and magnitude of condylar translational and rotational changes during surgery (T1–T2).

Table 3. Descriptive statistics for post-surgical condylar remodeling changes (T2–T3).

	Condylar remodeling changes[a]					
	Medial surface (mm)	Lateral surface (mm)	Superior surface (mm)	Anterior surface (mm)	Posterior surface (mm)	Volume (mm^3)
Mean	−0.8	−0.9	−0.8	1.1	−0.5	−52.0
SD	1.8	1.8	1.9	1.3	1.6	137.8
Min	−5.3	−4.8	−5.4	−3.8	−3.6	−364.0
Max	3.3	3.2	3.6	4.2	4.6	243.2
Percentile						
15th	−2.5	−2.8	−2.4	−0.3	−2.0	−191.6
50th	−0.9	−1.2	−1.3	1.4	−0.8	−60.0
85th	1.2	1.3	1.4	2.1	1.0	86.3

SD, standard deviation; Min, minimum; Max, maximum.
[a] Negative values indicate bone resorption and positive values indicate bone apposition.

Discussion

The prognosis of progression of condylar resorption following CCW-MMA with disc repositioning remains unknown. This study investigated the association of clinical and surgical factors with condylar remodeling during the follow-up period, using two different voxel-based rigid registration approaches, as well as shape correspondence analysis (SPHARM-PDM) and volume measurements.

Cranial base superimposition was used to quantify condylar displacement changes during surgery, and regional registration allowed the analysis of condylar remodeling changes. Both 3D automated registration methods have been validated previously[20–22].

Shape correspondence (SPHARM-PDM) was employed to quantify 3D condylar displacement changes during CCW-MMA with disc repositioning and remodeling in the follow-up period[23]. SPHARM-PDM provides a unique point-to-point correspondence across all measured surfaces. Shape differences were calculated between each correspondent point on T2 and T3 models. Besides measuring the depth of bony defects at specific sites, the overall volume change was also computed.

Several studies have shown that signs of condylar resorption are apparent 6 months after mandibular advancement[24–27], with progression for up to 2 years postoperative[24,25,28–30]. In the present study on CCW-MMA with disc repositioning outcomes, the follow-up period in months showed no statistically significant correlations with condylar remodeling, which may suggest that from 6 months onwards it is already possible to verify important condylar remodeling changes. Previous studies have reported that most of the condylar resorption is expected to occur during the first year after surgery[31].

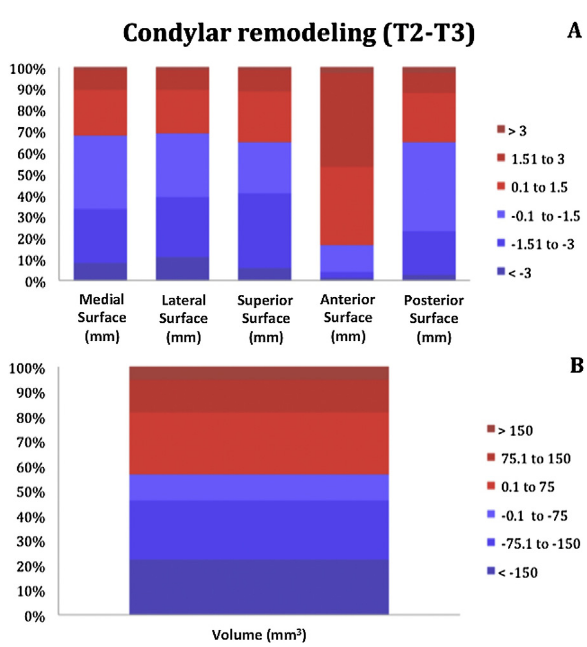

Fig. 5. Percentage of patients according to condylar remodeling changes (T2–T3): (A) changes in each condylar surface; (B) overall volume changes.

The current research also investigated the impact of age on the amount of condylar remodeling during the follow-up period. A highly statistically significant correlation showed that the older the patient, the greater the overall condylar volume reduction. Weak but statistically significant correlation was also observed suggesting greater lateral surface resorption in elderly patients.

Previous studies have shown that a high mandibular plane angle, mandibular retrognathism, and female sex are some of the risk factors for condylar resorption, particularly following mandibular advancement surgery[14,27,30–32]. However, Hoppenreijs et al.[16] reported that the mandibular plane angle might be less important than has been assumed in the literature[24,30]. These authors found progressive condylar resorption in patients with an open bite as well as deep bite.

Xi et al. reported that the mandibular plane angle preoperative was not correlated with surgical relapse[33]. The authors stated that high-angle patients have significantly smaller condyles preoperatively in combination with a tendency for counterclockwise rotation of the proximal segment and a possibly larger average mandibular advancement. Therefore, these facts make high-angle patients more susceptible to condylar resorption and relapse rather than the high mandibular plane angle itself.

In the present study, greater condylar resorption was not associated with a higher preoperative SNGoMe angle. Hyperdivergent patients experienced less bone resorption at the anterior surface and a lower overall volume reduction. However, the most hyperdivergent patients in this sample were also the youngest, which may explain the lower overall volume reduction in this group.

Table 4. Clinical characteristics (T1) and surgical changes (T1–T2) versus condylar remodeling during the follow-up period (T2–T3): Pearson correlation coefficients.

	Condylar remodeling changes (T2–T3)											
	Medial surface	(Sig.)	Lateral surface	(Sig.)	Superior surface	(Sig.)	Anterior surface	(Sig.)	Posterior surface	(Sig.)	Volume	(Sig.)
Clinical characteristics												
Age (years)	0.06	NS	−0.27	$P \leq 0.05$	−0.15	NS	−0.09	NS	−0.11	NS	−0.46	$P \leq 0.001$
Follow-up (months)	−0.11	NS	−0.06	NS	−0.02	NS	0.05	NS	−0.02	NS	−0.07	NS
Facial pattern before surgery (T1)												
SNGoMe (°)	−0.20	NS	0.19	NS	−0.12	NS	0.27	$P \leq 0.05$	0.21	NS	0.27	$P \leq 0.05$
SNA (°)	0.23	$P \leq 0.05$	−0.08	NS	0.16	NS	−0.16	NS	−0.02	NS	0.03	NS
SNB (°)	0.29	$P \leq 0.05$	−0.22	NS	0.19	NS	−0.31	$P \leq 0.01$	−0.10	NS	−0.20	NS
Surgical changes												
Magnitude of the surgical procedure (T1–T2)												
SNGoMe (°)	−0.07	NS	0.23	$P \leq 0.05$	−0.28	$P \leq 0.05$	0.22	NS	0.38	$P \leq 0.001$	0.25	$P \leq 0.05$
SNA (°)	−0.04	NS	0.20	NS	0.01	NS	0.02	NS	−0.02	NS	0.07	NS
SNB (°)	0.18	NS	−0.14	NS	0.27	$P \leq 0.05$	−0.21	NS	−0.28	$P \leq 0.05$	−0.05	NS
Condylar displacement changes (T1–T2)												
AP (mm)	−0.09	NS	0.11	NS	−0.09	NS	0.29	$P \leq 0.05$	−0.06	NS	0.13	NS
Vertical (mm)	−0.16	NS	0.08	NS	−0.16	NS	0.03	NS	0.26	$P \leq 0.05$	−0.03	NS
Lateral (mm)	−0.05	NS	0.30	$P \leq 0.01$	−0.04	NS	0.08	NS	0.20	NS	−0.25	$P \leq 0.05$
Yaw (°)	0.11	NS	0.24	$P \leq 0.05$	0.11	NS	−0.10	NS	−0.00	NS	−0.13	NS
Roll (°)	0.22	NS	−0.06	NS	0.15	NS	−0.11	NS	−0.26	$P \leq 0.05$	−0.06	NS
Pitch (°)	0.22	NS	−0.07	NS	0.07	NS	−0.12	NS	−0.23	NS	−0.15	NS

Sig., significance; SNGoMe, sella–nasion to mandibular plane angle; SNA, sella–nasion to A-point angle; SNB, sella–nasion to B-point angle; AP, antero-posterior displacement; Vertical, vertical displacement; Lateral, lateral displacement; Yaw, rotation around the *y*-axis; Roll, rotation around the *z*-axis; Pitch, rotation around the *x*-axis; NS, not significant.

Patients presenting with smaller SNB angles at T1 also showed less anterior surface resorption, but larger resorption at the medial surface. Considering that the patients with a more severe hyperdivergent and retrognathic profile were also submitted to a greater amount of surgical advancement and counterclockwise rotation, the associations found regarding such clinical and surgical characteristics may be interrelated.

A greater amount of counterclockwise rotation was associated with lower bone resorption at the lateral and posterior surfaces, as well as a lower overall volume reduction. On the other hand, it was associated with larger bone resorption at the superior surface.

Worms et al.[34] and Hwang et al.[26] reported that condylar resorption was most apparent in mandibular advancement procedures that rotate the mandible in a counterclockwise direction. However, Xi et al. did not find a correlation between counterclockwise rotation of the distal segment and condylar remodeling or skeletal relapse[33].

Actually, the role of mandibular advancement in condylar resorption is controversial. Tension in the surrounding soft tissue components after mandibular advancement produces a posteriorly directed force. This force causes the condyle to be retruded forcefully into the fossa, which generates pressure on the condylar head[26,28]. Therefore, several authors have hypothesized that larger surgical advancements are associated with a higher incidence of condylar resorption[2,14,16,31].

Xi et al. reported a significant correlation between the amount of mandibular advancement and postoperative reduction in condylar volume[33], whereas other authors have not found a direct correlation with resorption of the mandibular condyle[18,26,27]. According to Hwang et al.[26], after mandibular advancement and counterclockwise rotation, the posteriorly directed force does not appear to have a direct influence on the development of condylar resorption because it usually occurs on the anterior-superior surface of the condyle, not the posterior surface[26]; this corroborates other findings reported in the literature[25,27,30].

In the present study, the correlation between the amount of mandibular advancement and overall condylar volume change was not significant. However, larger bone resorption at the superior surface was significantly correlated with larger mandibular advancement. Lower resorption at the posterior surface was also significantly correlated with greater

Table 5. Stepwise multiple linear regression analysis.

Dependent variable (T2–T3)	Independent variables	Unstandardized coefficient b	Standardized coefficient beta	r^2	*P*-value[a]
Medial surface	SNB (T1)	0.09	0.23	0.05	0.05
Lateral surface	Lateral (T1–T2)	0.30	−0.30	0.09	0.008
Superior surface	SNGoMe (T1–T2)	−0.22	−0.37	0.15	0.002
	Age	−0.04	−0.27		0.020
Anterior surface	SNB (T1)	−0.09	−0.30	0.09	0.008
Posterior surface	SNGoMe (T1–T2)	0.20	0.38	0.14	0.001
Volume	Age	−5.06	0.46	0.21	0.000

SNGoMe, sella–nasion to mandibular plane angle; SNB, sella–nasion to B-point angle; Lateral, lateral displacement.
[a] Significant if $P \leq 0.05$.

mandibular advancement. This association may be explained by the fact that patients who underwent greater mandibular advancement also experienced more counterclockwise rotation, i.e., such surgical changes are also interrelated.

Sagittal condylar displacements have been reported after a variety of orthognathic surgery procedures; however, the role of condylar torque in progressive condylar resorption is also controversial. It has been advocated that an optimal intraoperative positioning of the proximal segments would ensure stability of the surgical results and reduce the chance of post-surgical condylar resorption[2,4,31,35]. On the other hand, Dicker et al., in an analysis of the static and dynamic loading of the condyles after surgical mandibular advancement, observed that increased postoperative joint loading and sagittal rotation of the condyle were not a serious cause of condylar resorption or relapse[36].

Weak but statistically significant associations were observed between the magnitude of condylar displacement and remodeling changes during the follow-up period in the present study. Upward condylar displacement was correlated with greater condylar resorption at the posterior surface. Lateral and anterior condylar displacements were correlated with greater condylar resorption at the lateral and anterior surfaces, respectively. Lateral roll and medial yaw were correlated with greater condylar resorption at the posterior and lateral surfaces, respectively.

A number of studies have suggested that a counterclockwise rotation of the proximal segments in combination with a posterior inclination of the condylar neck may increase the loading of the anterior-superior surface of the condyle, making it more prone to condylar resorption, with subsequent skeletal relapse[27,29,33,37]. However, the extent of condylar change that is compatible with normal function post-surgically is still unknown. In the present research, no statistically significant correlation was found between counterclockwise rotation of the proximal segment and condylar remodeling in the follow-up period. The literature supports the finding that small condylar rotations do not appear to have a functional compromise[4,38,39].

Previous studies have described different patterns of condylar displacement with consideration of two specific surgical protocols: MMA alone and MMA with disc repositioning surgery. The condyles are translated backward, upward, and medially in patients treated with MMA alone[4,13,18,40], whereas they are translated forward, downward, and medially in patients treated with MMA with disc repositioning[13]. Medial rotation through the *z*-axis (roll), lateral rotation through the *y*-axis (yaw), and upward rotation through the *x*-axis (pitch) occur regardless of TMJ disc repositioning and at similar amounts and frequency[13].

In the current study, CCW-MMA with disc repositioning most often caused the condyles to translate slightly downward, posteriorly, and medially and to rotate in a medial (roll), lateral (yaw), and upward direction (pitch), partially corroborating the findings of Gonçalves et al.[13]. The only difference observed refers to antero-posterior displacements. These authors stated that the disc repositioning procedure generates forward condylar displacement[13]. Thirty percent of the sample in the current study also experienced forward translation, but most of the cases showed an average 0.6 mm of backward displacement, which is a very small change. Considering that the present sample underwent considerable maxillomandibular advancement and counterclockwise rotation, part of the forward displacement generated by disc repositioning may have been canceled by muscular pressure.

Displacement changes generated by CCW-MMA with disc repositioning did not seem to be associated with greater condylar resorption in the follow-up period. Such changes most often showed a direction opposite to those correlated with a greater risk of condylar resorption. Moreover, positional changes were only weakly associated with remodeling in the follow-up period.

Among all clinical and surgical factors studied, the independent variable 'age' comprised the prediction model that best described the overall volume reduction. About 21% of volume reduction was explained by the age of the patient submitted to CCW-MMA with disc repositioning, showing that older patients are more susceptible to greater condylar resorption.

Another relevant observation is related to the amount of counterclockwise rotation of the maxillomandibular complex. The independent variable counterclockwise rotation comprised the prediction model that best described condylar remodeling changes at the superior and posterior surfaces. Higher counterclockwise rotation seems to cause a greater amount of resorption at the superior surface while protecting the posterior one. However, considering that most correlation coefficients found were weak, caution is needed when interpreting these results.

In conclusion, older patients were observed to be more susceptible to overall condylar volume reduction following CCW-MMA with disc repositioning. The magnitude of the surgical procedure as well as condylar displacement changes were only weakly associated with remodeling in the follow-up period, suggesting that other risk factors may play a role in condylar resorption.

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Competing interests

Nothing to declare.

Ethical approval

This study was approved by the Human Research Ethics Committee of the Araraquara School of Dentistry, São Paulo State University and National Ethics Committee, Plataforma Brasil (CAAE 01125412.2.0000.5416).

Patient consent

All patients signed an informed consent form for hospital admission, surgical procedures, and release of information for research purposes.

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