Changes in the Condyle and Disc in Response to Distraction Osteogenesis of the Minipig Mandible

Petra Thürmüller, MD,* Maria J. Troulis, DDS, MSc,† Andrew Rosenberg, MD,‡ and Leonard B. Kaban, DMD, MD§

Purpose: Distraction osteogenesis (DO) is a commonly used technique for mandibular lengthening, but changes in the temporomandibular joint have not been well documented. The purpose of this study was to evaluate the effect of DO, at varying rates, on the mandibular condyle and articular disc.

Materials and Methods: Semiburied distractors were placed via submandibular incisions in 15 minipigs. Two unoperated animals served as controls. The protocol consisted of 0 day latency and rates of 1, 2, or 4 mm/d for a 12-mm gap. After the animals were killed (0, 24, or 90 days), ipsilateral and contralateral condyles and discs were harvested and evaluated to determine changes in 1) condylar form and size, 2) condylar surface, and 3) the articular disc.

Results: Articular surfaces of the condyles in control animals were smooth, with no irregularities or erosions. In animals undergoing distraction, ipsilateral condyles showed increasing changes in morphology and AP dimension, and surface contour irregularities as the DO rate increased. These changes were present, but to a lesser degree, in the contralateral condyles. Articular discs of both ipsilateral and contralateral sides showed variable thinning at the medial aspect at end DO. After 90 days, changes in the condyles and discs were reduced by remodeling except in the 4 mm/d DO groups.

Conclusions: Results of this preliminary study indicate that gross changes occur in condyles and discs after unilateral mandibular DO. These changes are more severe at faster distraction rates (4 mm/d) and tend to resolve during neutral fixation when a rate of 1 mm/d is used.

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Distraction osteogenesis (DO) is a commonly used technique for skeletal expansion in the maxillofacial region. Many experimental and clinical reports on its use have appeared in the orthopedic, craniomaxillofacial, and basic science literature.1-8 The effects of latency, rate, and duration of neutral fixation on the healing of distraction wounds have been described.2-5,7,9-11 However, there are only a few reports on changes in the temporomandibular joint (TMJ) as a result of DO.12-16

Karaharju-Suvanto et al14 performed unilateral mandibular DO creating a gap size of 4.5 to 8.5 mm in a
sheep model. They found no correlation between total amount of distraction and morphologic changes in the TMJ. McCormick et al.\textsuperscript{12} described morphologic changes of the TMJ in dogs after unilateral DO. They used a distraction rate of 1 mm/d for a gap size of either 10 or 20 mm. The observed changes were flattening of the condylar head, thinning of cartilage, and new bone deposition. These changes were more pronounced in the 20-mm distraction group.

Nakamura et al.\textsuperscript{17} reported the effect of tibial DO on the articular cartilage of the knee in rabbits. They performed bilateral distraction at a rate of 1 mm/d. The rhythm was twice per day on the right side and continuous on the left. The experimental animals were further divided into 3 subgroups based on gap size. They found increased degenerative joint changes with a twice-daily rhythm compared with continuous distraction. Degenerative changes also increased with increasing gap size.\textsuperscript{17}

The influence of different distraction rates, with a standard gap size, on the ipsilateral and contralateral condyles and articular discs has not been reported in the craniomaxillofacial literature. Because expansive forces are used to move osteotomized bone segments, a critically important biomechanical consideration is the feature of force transduction during active distraction. Higher distraction rates might generate increased reactive compressive forces at distant sites such as the TMJ.

In this study, a standardized minipig model of unilateral mandibular lengthening was used.\textsuperscript{7} The aim of the experiment was to evaluate the effects of varying distraction rates on the size, shape, and surface of the ipsilateral and contralateral condyles and articular discs.

**Materials and Methods**

**MINIPIG MODEL**

The use and care of animals in this study was approved by the Massachusetts General Hospital Subcommittee on Research Animal Care and conformed to Association for Assessment and Accreditation of Laboratory Animal Care (AAALAC) standards. Female Yucatan minipigs were housed for 1 week to become acclimated to diet, water, and housing. The animals were monitored for general appearance and demeanor, activity level, excreta level, weight, temperature, heart rate, and respiratory rate.

Fifteen female Yucatan minipigs (Charles River Laboratories, Wilmington, MA) in the mixed dentition stage (age, 4 to 6 months), weighing between 26 and 30 kg, underwent placement of a single vector semi-buried distraction device (Synthes Maxillofacial, Paoli, PA) at the right mandibular angle. Details of this model have been described previously.\textsuperscript{7} Two unoperated animals served as controls (n = 4 condyles).

The distraction protocol consisted of 0 day latency and distraction rates of 1 (n = 5), 2 (n = 5), or 4 (n = 5) mm/d, producing a 12-mm gap. Distraction was performed twice daily for each animal until the 12-mm mandibular lengthening was achieved. Clinical and plain radiographic examinations were performed at 0, 24, 60, and 90 days of neutral fixation. To study longitudinal changes in the TMJ, animals were killed after 0 (n = 6), 24 (n = 6), and 90 (n = 3) days of neutral fixation.

**METHODS OF EVALUATION**

**Clinical Examination and Plain Radiographs**

Throughout the experiment, animals were observed for signs of infection and/or wound dehiscence. Clinical examination included evaluation of mandibular symmetry, occlusion, and mandibular stability by bimanual palpation. Animals were photographed, and lateral cephalometric radiographs were obtained using a custom porcine cephalostat. X-ray exposure was calibrated and standardized using an aluminum, step-wedge penetrometer (E.M. Parker, Wilmington, MA). The size of the distraction gap was recorded as the distance between radiopaque markers (2-mm screws).

After the animals were killed, the control (n = 4), ipsilateral (n = 15), and contralateral (n = 15) condyles with attached articular discs were harvested and fixed in 10% buffered formaldehyde for 14 days. The inferior joint compartment was then opened under a dissecting microscope (Carl Zeiss, Oberlochen, Germany) using a magnification of 6.5×. The discs were completely removed, taking care not to damage the articulating surfaces of the condyles.

**Morphologic Evaluation**

The specimens were photographed, measured, and evaluated for 1) changes in condylar form and size, 2) changes in condylar surface (concavities, irregularities, erosions, exposure of bone), and 3) characteristics of the articular disc (color, thinning, perforation).

Form of the mandibular condyles was evaluated in the axial, sagittal, and frontal planes. Size was documented by measuring the largest mediolateral (D<sub>1</sub>) and anteroposterior (AP) (D<sub>2</sub>) diameters of each condylar head using a caliper accurate to 0.1 mm. The thickness of the articular discs was measured at 5 points using a thickness gauge accurate to 0.1 mm. Each measurement for the condyles and discs was performed twice, and the results were averaged.
Results

CLINICAL AND RADIOGRAPHIC EVALUATION

All animals survived the surgical procedure and the observation period. At the end of distraction, they all had an occlusal crossbite with deviation of the jaw toward the nondistracted side. Two animals developed localized wound infections (which did not affect the outcome) and were treated with cephalosporin 4 times per day for 14 days. In vivo radiographs showed that the desired elongation (mean ± SD, 12 ± 1 mm) was achieved and maintained in all animals during the neutral fixation period.

MORPHOLOGIC EVALUATION

Control Specimens (n = 4)

Condylar form and size. The condyles had an oval form with a slightly concave anterior surface. They were regular and symmetric in the axial, frontal, and sagittal planes. The right and left condyles were mirror images of each other and equal in size (Fig 1). The mean size of the control condyles was 2.1 cm for the mediolateral diameter and 1.5 cm for the AP diameter. The condylar surface was convex in the sagittal and coronal planes, accommodating the form of the glenoid fossa. In the coronal plane, the lateral pole was typically superior to the medial pole, resulting in a convex curvature that sloped down from lateral to medial.

Condylar surface. Control condyles were covered by a smooth, white fibrocartilage layer that reflected light (shiny surface). The grossly visible connective tissue fibers of the articular surface had a concentric arrangement that was more apparent at the periphery than at the center of the condyle.

Articular disc. Control articular discs had a rich, white, shiny surface with no visible evidence of thinning or perforation. The anterior and posterior regions were thicker (mean ± SD, 1.7 ± 0.3 mm and 1.6 ± 0.08 mm, respectively) than the central region (mean ± SD, 0.7 ± 0.17 mm). Both the upper and lower surfaces were concave in the central region, similar to the human articular disc.

Experimental Ipsilateral Condyles (n = 15)

Condylar form and size. No gross changes were observed at 0 days of neutral fixation.

At 24 days of neutral fixation, ipsilateral condyles in all distraction groups exhibited a 13% to 20% decrease in AP diameter relative to the controls and 13% to 14% compared with the experimental contralateral side. Condylar form was narrower and more convex than that of the controls.

After 90 days of neutral fixation, the AP diameter of the condyle in the 1 mm/d group was slightly increased (7%) relative to the controls. In the 1 mm/d group the condylar morphology (the convexity) returned to normal.

The 2 and 4 mm/d ipsilateral condyles continued to exhibit AP shortening, proportionate to the rate of distraction, after 90 days of neutral fixation (Figs 2, 3). The 2 and 4 mm/d distracted condyles were 7% and 27%, respectively, smaller than the controls and 15% and 31% smaller than the contralateral condyles. This was accompanied by an increase in convexity of the condylar heads that was also proportionate to the rate of distraction (Fig 4).

Condylar surface. At 0 day fixation, the articular surfaces (n = 6) of condyles distracted at 1, 2, or 4 mm/d revealed a small flattened-concave region located at the medial pole. However, the articular cartilage layer in this region was intact with no thinning or erosions.

At 24 days of neutral fixation (n = 6), the region exhibiting these changes in articular surface increased in size in all experimental groups, with the largest in the 4 mm/d distracted condyles. No exposure of bone was observed. The affected regions were covered by a dense layer of connective tissue. Condyles distracted at rates of 2 and 4 mm/d were noted to exhibit slight irregularities at the anterior surface.

At 90 days of neutral fixation (n = 3), the condyle distracted at a rate of 1 mm/d exhibited no contour changes of the articular surface relative to controls. The 2 and 4 mm/d condyles continued to have significant flattening of the medial pole. The cartilage in this region was more transparent and underlying condylar bone was visible. Specimens of both distraction groups (2 and 4 mm) continued to exhibit contour irregularities with loss of bone mass (concavity) at the anterior aspect of the condylar head. No exposure of bone was observed. The affected regions were covered by dense connective tissue (Fig 5).

Experimental Ipsilateral Articular Discs (n = 15)

At 0 days of neutral fixation, 2 of the 6 experimental articular discs revealed irregularities in surface contour with a localized, well-circumscribed concavity at the medial aspect. These changes matched the observed flat-concave condylar regions at the medial pole and were seen in articular discs of condyles distracted at a rate of 2 and 4 mm/d. Thickness in this region was 0.2 and 0.3 mm, respectively, and showed a more transparent color. No perforation was observed. No other gross changes of the articular discs were seen at this time point.

At 24 days of neutral fixation, the 1 mm/d distraction group showed no thinning of the articular discs, but a yellowish color at the medial aspect was ob-
FIGURE 1. Ipsilateral (left) and contralateral (right) control condyles showing a regular and symmetric form. The articular cartilage is smooth with a shiny rich-white color and no visible pathology (original \( \times 1.65 \)).

FIGURE 2. Experimental ipsilateral condyles after 90 days of neutral fixation. Top left, Ipsilateral control condyle for comparison. Top right, Image of a 1 mm/d distracted condyle showing no changes in condylar morphology. Bottom left, Image of a 2 mm/d distracted condyle exhibiting AP foreshortening of the condylar head and marked changes in condylar form. Bottom right, Image of a 4 mm/d distracted condyle with even more AP foreshortening and lack of the anterior concavity. Contralateral condyles of all distraction groups exhibited no significant changes in AP diameter at this time point (original \( \times 1.65 \)).

FIGURE 3. Line graph of mean AP diameter of ipsilateral condyles versus fixation time. The control condyle is represented by the black diamond. At 24 days of neutral fixation, condyles exhibited a decrease in AP diameter with an average of 18%. At 90 days of neutral fixation, the AP diameter of the condyle distracted 1 mm/d returned to normal. The condyle distracted 4 mm/d exhibited a decrease in AP diameter (27%).

FIGURE 4. Experimental ipsilateral condyles from the true lateral view after 90 days of neutral fixation. Top left, Ipsilateral control condyle for comparison. Note the rounded shape of the control condyle progressing to the triangular peaked condyle in the 4 mm/d distracted group (bottom right). Changes in the contralateral condyles were not significant (original \( \times 1.65 \)).

FIGURE 5. Experimental ipsilateral condyles after 90 days of neutral fixation. This series of panels shows a coronal view of the anterior aspect of the condyles in the region of the joint capsule attachment. Top left, Ipsilateral control condyle exhibiting a very straight and regular junction of the lateral pteryoid muscle with the condylar cartilaginous surface. Top right, Image of a 1 mm/d distracted condyle showing very little changes in this region. Image of a 2 mm/d distracted condyle (bottom left) and a 4 mm/d distracted condyle (bottom right) exhibiting a thickened, irregular, and broadened region of junction, as delineated by the red arrows. (original \( \times 2.25 \)).

FIGURE 6. Experimental ipsilateral articular discs after 90 days of neutral fixation. Top left, Ipsilateral control articular disc for comparison. Top right, Image of the articular disc of the 1 mm/d distracted condyle showing no gross changes. Bottom left, Image of the articular disc of the 2 mm/d distracted condyle exhibiting a thinned region at the medial pole as delineated by the red arrows. Bottom right, Image of the articular disc of the 4 mm/d distracted condyle (original \( \times 1.65 \)).
served. No perforations were observed in any of the discs.

At 90 days of neutral fixation, the articular disc of the 1 mm/d distracted condyle exhibited no gross changes compared with the controls. The articular disc of the 2 mm/d distracted condyle was observed to have a thinned region at the medial pole, with the lateral pole showing a yellowish brown color and increased transparency (Fig 6). The tissue thickness was 0.4 and 0.3 mm at the medial and lateral poles, respectively. The articular disc of the 4 mm/d distracted condyle exhibited 0.4-mm thickness at the medial pole. No changes in color were observed.

**Experimental Contralateral Condyles (n = 15)**

**Condylar form and size.** At 0 days of neutral fixation, no gross changes in condylar form and size were observed. At 24 days of neutral fixation, a slight decrease in AP diameter and a slight increase in steepness of the posterior aspect of the condylar heads were evident in all specimens. At 90 days of neutral fixation, the AP diameter of the condyles at all distraction rates was 7% greater than that of controls. No gross changes of the anterior aspect of the condylar heads were observed. Steepness of the posterior condylar surface was minimally increased in the specimens distracted at 1 mm/d and progressively increased with the faster distraction rates (2 and 4 mm/day).

**Condylar surface.** At day 0 of neutral fixation, surface changes of contralateral condyles (n = 6) distracted 1, 2, or 4 mm/d were similar to those observed in ipsilateral condyles. All condyles revealed small, circumscribed, flattened-concave regions at the medial pole. This was most prominent in the 4 mm/d distraction group. No other gross changes of the condyles could be observed at this time point.

At day 24 of neutral fixation (n = 6), flat-concave regions at the medial pole were increased in size and were the most significant in the 4 mm/d distraction group. No other gross changes of the condyles were observed.

At 90 days of neutral fixation (n = 3), condyles distracted at rates of 1 and 2 mm/d did not exhibit any flat concave regions at the medial pole. The specimen distracted at a rate of 4 mm/d continued to show significant flattening in this region, and the medial pole appeared to be slightly enlarged. There were no erosions, and the condyles were covered with a smooth fibrocartilage layer.

**Experimental Contralateral Articular Discs (n = 15)**

At 0 days of neutral fixation (n = 6), gross changes in the articular discs were similar to those observed on the ipsilateral side. Articular discs of all condyles exhibited irregularities in surface contour, with a localized, well-circumscribed concavity at the medial aspect matching the observed flat-concave condylar regions at the medial pole. The tissue showed an increased transparency in these regions, and the thickness measured 0.3 to 0.5 mm. No perforations were observed. No other gross changes were observed at this time point.

At day 24 of neutral fixation (n = 6), 2 articular discs (1 and 2 mm/d) exhibited irregularities in surface contour, with a localized, well-circumscribed medial concavity. The tissue exhibited increased transparency in this region, and the thickness measured 0.1 and 0.4 mm, respectively. No perforation was observed. In 4 of 6 articular discs, a yellowish color at the medial pole was noted.

At 90 days of neutral fixation (n = 3), the articular disc of the 1 and 2 mm/d distracted condyles exhibited no gross changes compared to the controls. The articular disc of the 4 mm/d distracted condyle exhibited slight thinning at the medial aspect. No perforation was observed. No changes in color were noted.

**Discussion**

There has been a considerable amount of research conducted to improve our understanding of growth and adaptation of the TMJ in response to experimental manipulations and clinical treatments. The healthy TMJ is responsive to changes in its biomechanical and biophysical environment. Exposed to such changes, the TMJ may undergo substantial remodeling, an adaptive capacity not shared by many other joints. Compressive forces on the TMJ have been shown to cause local changes in articular cartilage and in the condyle. Damage to the TMJ alters its physical properties and further affects its ability to withstand compressive and shearing forces. The risks and the degree of severe degenerative changes in the TMJ after orthognathic surgical interventions in the mandible have been documented. These risks are thought to be particularly important when repositioning the proximal (condylar) segment with rigid internal fixation.

Currently, little is known about the adaptability of the TMJ in response to mandibular lengthening by DO. Increase in articular contact pressure with injury and degeneration of cartilage have been reported in experimental DO research on long bones. However, the nature of pressure related alterations in the cartilaginous tissues of the TMJ, in response to DO, is still a matter of controversy. Although there is agreement that DO influences condylar morphology, opinions differ with regard to the extent and the nature of these changes, and to what extent normalization of
the TMJ occurs with time. This lack of consistency in the literature is a result of differences in study design, different DO protocols, and varying animal models. All of these factors make comparison of data difficult.

In the current study, we compared the morphologic changes in the condyle and disc in animals undergoing unilateral mandibular lengthening at rates of 1, 2, or 4 mm/d. The gap size was 12 mm. The purpose was to confirm the hypotheses that TMJ changes would be greater at higher rates of DO and that there would be no long-term adverse consequences of DO at 1 mm/d. The results of the study confirmed the hypotheses. The potential explanation is that the faster distraction rates produced greater compressive forces on the condyle and disc, which resulted in more significant abnormalities.

The vector of movement applied in this study resulted in deviation of the jaw toward the contralateral side with development of a crossbite. Alterations in occlusion and changes in mandibular geometry, due to the distraction process, are likely to result in alterations of condylar position relative to the glenoid fossa. This may result in excessive mechanical loading. The DO protocol was identical for all experimental animals regarding latency, distraction gap, and neutral fixation period. Placement of the distraction device was standardized. Differences in gross changes of the condyle were therefore considered to be the effect of differences in the rate of distraction.

McCormick et al performed unilateral mandibular distraction, at a rate of 1 mm/d, in a canine model. She lengthened the mandibles 10 or 20 mm. Flattening of the posterior aspect of the condylar head was observed in ipsilateral and contralateral condyles, and the severity was more pronounced with a gap size of 20 mm. After 10 weeks, flattening of the posterior aspect was minimal. In the present study, we showed that the accentuation in steepness of the posterior aspect of the condylar head was proportionate to the rate of distraction. Gross changes observed suggest a posterosuperior vector of applied forces.

Forces that successfully distract the mandible could conceivably generate compressive forces at distant sites such as the TMJ. Higher distraction rates and an increased distraction gap may result in increased compressive loads, inducing resorption of bone. Resorption and remodeling of bone occurred not only at the posterior aspect of the condylar head but also at the most anterior surface of the condyle. Compressive forces directed in an AP vector could induce a posterior movement of the condyle. This movement might be expected to subject the anterior intracapsular aspect of the pig condyle to compressive loading that, under normal conditions, does not occur. Such loading may lead to the contour irregularities and resorption of bone observed in our animal model.

At 10 weeks of neutral fixation, McCormick et al reported that flattening of the posterior condylar surface appeared to be reversed. She hypothesized that this represented remodeling after adaptation to the forces of expansion. In the present study, a restoration of normal posterior angulation occurred after 90 days of neutral fixation only in the animal distracted at a rate of 1 mm/d. The 2 and 4 mm/d animals continued to exhibit significant increase in steepness of the condylar head at the 90-day mark. Similar results were observed for morphologic changes at the anterior aspect of the condylar head. Distraction of mandibular segments at a slow rate (1 mm/d) may permit an adaptive response to compressive forces. Higher distraction rates might have a traumatic effect on the condyle, leading to morphologic changes that do not return to normal, at least not over the time course of this study.

Resorption of the posterior condylar surface due to compression has been described after sagittal ramus osteotomy and rigid fixation. These changes have been characterized as adaptive in nature by some authors but have also been cited as a factor in relapse after orthognathic surgery. An association with the development of TMJ disorders has also been described. A distraction rate of 4 mm/d (in a discontinuous mode) also produces rapid movement relative to a rate of 1 mm/d. Such movement, with rapid change in condylar position and with compression of the condyle into the glenoid fossa, could potentially increase the risk of changes in condylar morphology.

In the current study we have shown that DO of the minipig mandible induces gross morphologic changes in condyles and that these changes are more severe at faster distraction rates. A reversal of these changes with time was only observed when a rate of 1 mm/d was used.

It can be argued whether the persistence of gross changes in the more rapidly distracted condyles represents an initial stage of joint disease or merely an adaptive physiologic remodeling in response to DO. To further evaluate the nature of these observed gross changes, histologic examination is ongoing and will be reported in a future study.

References

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