Original Article

The effects of gradually induced backward movement of the mandible by a Twin Inclined Plane Device in rats

Xianming Hua[a]; Hui Xiong[b]; Guangli Han[b]; Xiangrong Cheng[c]

ABSTRACT

Objective: To develop a model of gradually induced backward movement of the mandible under normal masticatory action and to examine morphological changes in the mandible and condylar cartilage in rats.

Materials and Methods: The newly developed Twin Inclined Plane Device (TIPD) was composed of upper and lower posterior metal crowns with a long inclined plane on both sides separately and was applied in experimental groups of 6-week-old male Wister rats. After 3, 14, 30, and 60 days, the rats were euthanazied and samples were collected. Various measurements and hematoxylin-and-eosin stains were performed.

Results: From day 30 on, the length of the condylar process was shorter in the TIPD groups than in the control groups ($P < .05$). The angulation of the condylar process axis to the mandibular plane was greater in the TIPD groups ($P < .01$). The thickness of the condylar cartilage in the posterior part of the posterior region was thinner in the TIPD groups ($P < .05$) on day 30 and even thinner ($P < .01$) on day 60; from day 30 on, the thickness in the anterior part of the posterior region was thicker in the TIPD groups ($P < .01$).

Conclusion: TIPD can successfully induce backward movement of the mandible under normal masticatory action. TIPD can cause region-specific changes in condylar cartilage and leads to a continuous remodeling. (*Angle Orthod.* 2012;82:839–845.)

KEY WORDS: Mandibular retrusion; Functional action; Condylar cartilage adaptive remodeling; Temporomandibular joint

INTRODUCTION

Normal masticatory force is a physiological stress to the temporomandibular joint (TMJ). It is of great importance not only for the development of TMJ structures during adolescence but also for condylar remodeling in adults.[1,2] The force generated by the incisor guiding appliance, which is attached to the upper incisors and leads to a mandibular retrusion of 4 mm by one step in rats, may be harmful for the condyle.[3] Furthermore, the incisor guiding appliance cannot be used in patients who have Class III malocclusions as a result of the structure limit of the TMJ in humans. Thus, a new device that could be placed between the upper and lower posterior teeth to gradually induce backward movement of the mandible with comfortable, nearly physiological mechanical force under normal masticatory function would be of great interest.

We hypothesize that an inclined plane device between the upper and lower molars is capable of generating gentle masticatory force to maintain the backward movement of the mandible during normal masticatory function, and, thus, it can stimulate an adaptive modeling of the mandibular condyle. For this reason, we developed the Twin Inclined Plane Device (TIPD) and tested its effectiveness in an animal experimental model.

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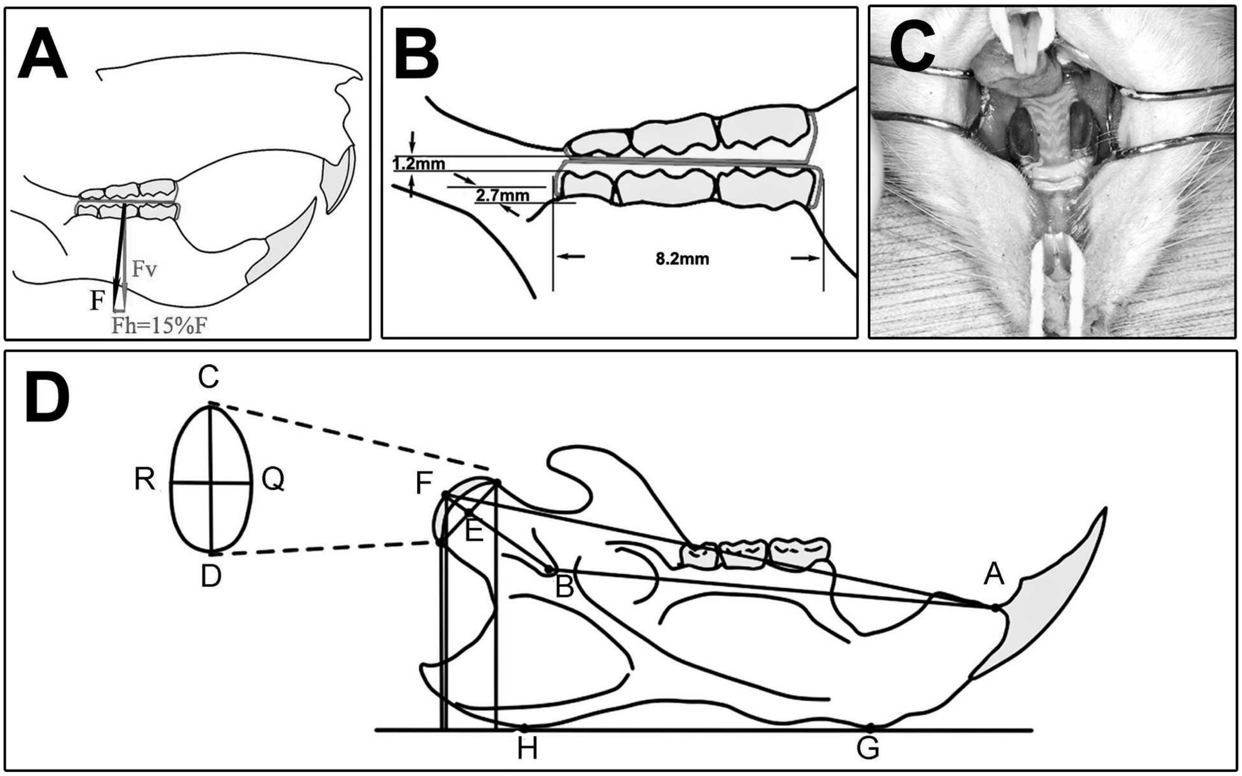

Figure 1. TIPD design and landmarks. (A) Principle of TIPD action. F indicates total masticatory forces; Fh, horizontal component of forces (about 15% of F); and Fv, vertical component of forces. (B) Construction of TIPD. TIPD was composed of upper and lower posterior crowns with a long inclined plane in both sides separately. (C) TIPD were fitted to rat posterior teeth. (D) Illustration of landmarks and linear measurement. A indicates the most anterior point of the lingual alveolar bone; B, the midpoint of the mandibular foramen; C, the most anterior point of condylar cartilage; D, the most inferior (posterior) point of the condyle; E, the middle of points C and D; F, intersection point of B–E extension line and outer contour of condyle; G, posterior-inferior point of attachment of the digastric muscle; H, the most inferior point of the lower border of the angular process; Q, the outmost point of vertal contour of the condyle; R, the outmost point of dorsal contour of the condyle; BF, condylar process axis; and GH, mandibular plane.

MATERIALS AND METHODS

Twin Inclined Plane Device

The TIPD was composed of upper and lower posterior crowns with one long inclined plane on each side (Figure 1A). Impressions were obtained with the use of a self-made tray and application of silicon rubber (3M ESPE ExpressTM, St Paul, Minn, USA) under anesthesia (10% ketamine and 2% xylazine, 2:1, 0.1 ml/100 g). Afterwards, stone casts were created (Kopo-rock, Kopo Ltd, Jingmen, China). Another impression of the pretest posterior teeth relationship was made with wax. Wax models of TIPD were developed on the articulated stone casts. In the position of molars coming into occlusion, the thickness between the upper and lower third molar was carefully adjusted to result in a vertical displacement of 1.2 mm (Figure 1B). The TIPD was constructed with metal alloy (Figure 1C) (Degussa Dental, Hanau, Germany). Under anesthesia, the posterior teeth were sand-blasted, washed, and dried; this was followed by etching, washing, and drying. Then the TIPD was fitted

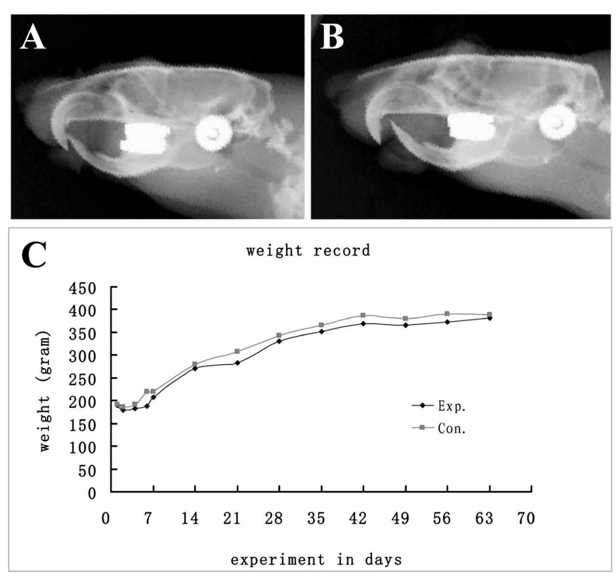

Figure 2. The changes in the radiographs and body weights. (A) The radiograph reflecting the beginning of the insertion of TIPD. (B) The radiograph reflecting days 60 postinsertion of the TIPD. (C) The changes in body weights of the control and TIPD groups over the 60-day period.

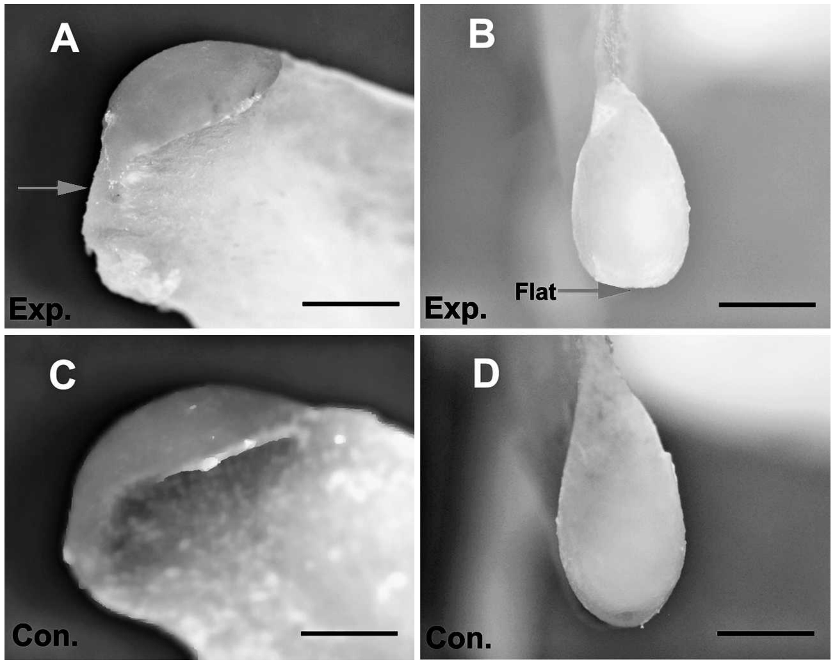

Figure 3. The changes in condylar morphology. (A, B) The posterior surfaces of the condyle were flattened (arrow) in the TIPD groups at day 60, and the most posterior point D also shifted up. (C, D) The posterior surfaces of the condyle were normal in the control groups at day 60. Bar: 1000 μm.

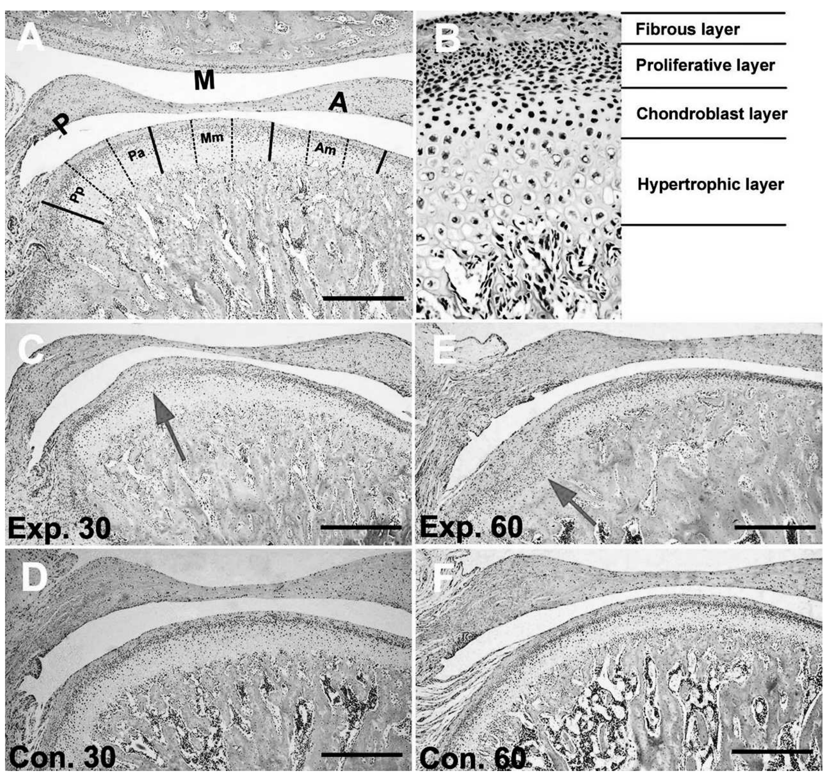

Figure 4. Photographs of the mandibular condyle section stained with hematoxylin and eosin (H&E). (A) Observation area. Posterior (P), middle (M), and anterior (A) regions of the MCC surface. Pp indicates posterior part of posterior region; Pa, anterior part of posterior region; Mm, middle part of middle region; and Am, middle part of anterior region. (B) MCC layers staining with H&E. On day 30, the MCC thickness on Pa was thicker (arrow) in the TIPD groups (C) than in the control groups (D). On day 60, the hypertrophic layer almost disappeared (arrow) in the TIPD groups (E) compared with the control groups (F). Bar: 500 μm.

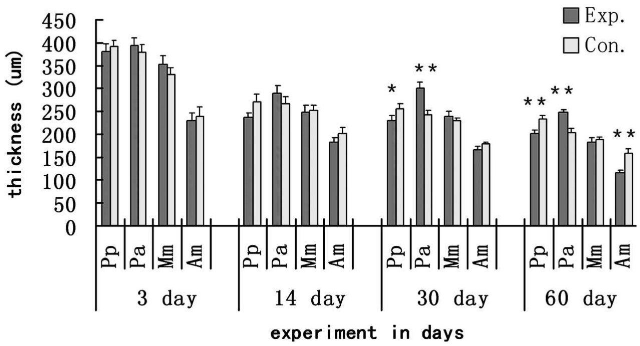

Figure 5. Graphs showing the changes in MCC thickness in the TIPD (n = 8) and control (n = 4) groups.

to the posterior teeth with GC bonding material (Fuji Ortho LC, Tokyo, Japan).

Experimental Animals

Forty-eight 6-week-old male Wistar rats were divided into an experimental group of 32 rats and a control group of 16 rats. The experimental group (with TIPD) and the control group (no device) were randomly divided into four subgroups each. All animals were fed standard rat normal pellets and water and were maintained under standardized conditions with artificial light at a constant temperature of 23°C. Radiographs were taken to confirm the effects of mandibular retrusion (Figure 2A,B). The weight of all rats was recorded from the age of 42 days, once every 2 days during the first week and once a week thereafter (Figure 2C).

Tissue Preparation and Morphometric Analysis

Experimental and corresponding control groups of rats were euthanatized under pentobarbital anesthesia after 3, 14, 30, and 60 days. The animal heads were carefully dissected. Mandibles were divided into left and right halves along the middle sagittal plane and fixed in paraformaldehyde overnight at 4°C.

The left halves of the mandibles were harvested and freed of soft tissue after fixation for gross morphological analysis. Lateral and axial pictures were taken from the dry mandibles in a standardized way using a calibration bar using a true-color video camera (Stereomicroscope, Stemi SV, Zeiss, Gottingen, Germany). The lateral pictures were applied for the angular and linear measurements (Figure 3A,C). The axial pictures were used for the width of the condylar measurements (Figure 3B,D). To increase the accuracy of the quantification of small morphological changes, the images were enlarged to two times their original size and were traced using selected landmarks. Certain linear and angular measurements were performed.[4–7] Reference points for the measurements of the mandibles are shown in Figure 1D. The measurements were done three times on the same variable, and the mean value representing each rat was used.

Section Preparation and Mandibular Condylar Cartilage Thickness Analysis

The right halves of the head were initially cut to 1.5-cm–thick blocks with the TMJ in the center. The blocks were decalcified in 12.5% neutral ethylenediamine tetraacetic acid (pH 7.0) solution for 4 to 6 weeks. After complete decalcification, the TMJ parts were then embedded in paraffin with the desirable orientation. Following the embedding, serial sections of 4 μm were cut through the sagittal plane of the TMJ using a rotary microtome (Leica RM 2155, Nussloch, Germany). Each section was numbered successively. One section in the central area of the condylar cartilage, based on its shape

Table 1. Values of Linear and Angular Measurements of Mandibular Morphology in Experimental and Control Groups on Different Time Points[a]

	3 d			14 d		
	Experiment	Control	Difference	Experiment	Control	Difference
Linear measurement, mm						
B–F	5.90 ± 0.29	5.99 ± 0.11	−0.09 ns	5.94 ± 0.35	5.88 ± 0.11	0.06 ns
A–F	24.27 ± 0.31	24.39 ± 0.79	−0.12 ns	24.52 ± 0.45	24.24 ± 0.74	0.28 ns
A–B	18.73 ± 0.17	19.23 ± 0.65	−0.50 ns	19.09 ± 0.44	19.18 ± 0.52	−0.08 ns
C–D	3.21 ± 0.10	3.36 ± 0.09	−0.15 ns	3.31 ± 0.23	3.37 ± 0.27	−0.06 ns
Q–R	1.47 ± 0.10	1.50 ± 0.05	−0.03 ns	1.53 ± 0.09	1.53 ± 0.09	0.00 ns
C-GH	10.74 ± 0.40	10.97 ± 0.31	−0.23 ns	10.66 ± 0.17	10.55 ± 0.36	0.11 ns
F-GH	10.56 ± 0.36	10.76 ± 0.48	−0.20 ns	10.85 ± 0.51	10.78 ± 0.44	0.07 ns
D-GH	8.89 ± 0.46	9.13 ± 0.30	−0.24 ns	9.36 ± 0.22	9.15 ± 0.24	0.21 ns
Angular measurement, °						
BF/GH	36.96 ± 2.11	37.73 ± 1.43	−0.77 ns	37.81 ± 1.30	36.42 ± 1.18	1.39 ns

[a] B–F indicates the length of condylar process; A–F, mandibular length; A–B, length of mandibular base; C–D, length of condylar; Q–R, width of condylar; C-GH, the distance from point C to GH line; F-GH, the distance from point F to GH line; D-GH, the distance from point D to GH line; and BF/GH, angle of condylar process axis to mandibular plane. All values are mean ± standard deviation (SD). ns indicates not significant.

* $P < .05$; ** $P < .01$; *** $P < .001$ (experiment vs control).

and uniformity compared with peripheral areas, was selected and photographed with a digital camera (Olympus Co Ltd, Shizuoka, Japan). Image processing was performed with the Photoshop software (V 7.01; Adobe Systems Inc, San Jose, Calif, USA). In order to thoroughly investigate changes in mandibular condylar cartilage (MCC) thickness, the periphery of the MCC surface was divided into three equal regions, and each region was further divided into three equal parts (Figure 4A). Since most physical and pathological changes of the TMJ occur in the posterior region,[8,9] we chose the posterior part of the posterior region (Pp) and the anterior part of the posterior region (Pa) as interesting areas at the posterior region. MCC thickness was measured from the lowest border of the hypertrophic layer to the outer border of the fibrous layer (Figure 4B) in different parts using SPOT image software (V 3.5, a division of Diagnostic Instruments Inc, Sterling Heights, Mich, USA).

Statistical Analysis

Measurement was evaluated by two independent recordings of measurements, which were performed at an interval of 2 weeks. Hypothesis testing indicated no significant difference between the two registrations. The error of measurement was calculated with the Dahlberg's formula (1940), thus:

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

The error of the method varied between 0.11 mm and 0.18 mm for linear measurements; the error for angular measurements was 0.52°; the error for the thickness in different parts of the MCC varied from 6.1 to 8.9 μm. All data were analyzed (V 17.0 for Windows, SPSS Inc, Chicago, Ill, USA) using one-way analysis of variance followed by the Tukey-Kramer multiple comparison test.

RESULTS

Body Weight

The body weight of the experimental group was slightly reduced after the insertion of TIPD during the first 4 days and increased to its original value on day 6 (Figure 2C). From that point onward, the experimental groups showed similar rates of weight gain compared with the control groups.

Remodeling of Condyle

On day 30, both the length of the condylar process (B–F) as well as the dependent mandibular length (A–F) and the condylar length (C–D) were shorter in the TIPD groups than in the control groups ($P < .05$), and they remained so on day 60 ($P < .01$). In contrast, the angle of the condylar process axis to the mandibular plane (BF/GH) was greater in the TIPD groups ($P < .01$). On day 60, the condylar width (Q–R) also was shorter in the TIPD groups ($P < .05$).

The posterior surface of the condyle was flattened (Figure 3A,B) compared to that of the control groups (Figure 3C,D) in the posterior region on days 30 and 60. The most posterior point, D, also shifted up (Figure 3A).

Different MCC Thickness

In the early stages (days 3 and 14), there was no statistical significant difference in MCC thickness in all regions (Figure 5) between the TIPD and control groups. On day 30, the MCC thickness in Pp was thinner in the TIPD groups than in the control groups

Table 1. Extended

30 d			60 d		
Experiment	Control	Difference	Experiment	Control	Difference
6.35 ± 0.15	6.78 ± 0.20	−0.43*	6.50 ± 0.56	7.49 ± 0.19	−0.99**
25.11 ± 0.37	26.32 ± 0.07	−1.21***	26.59 ± 0.37	27.93 ± 0.16	−1.34***
19.74 ± 0.34	20.09 ± 0.27	−0.35 ns	20.43 ± 0.52	20.85 ± 0.37	−0.42 ns
3.02 ± 0.29	3.58 ± 0.25	−0.56*	3.30 ± 0.21	3.66 ± 0.12	−0.36**
1.57 ± 0.10	1.52 ± 0.03	0.05 ns	1.59 ± 0.09	1.74 ± 0.08	−0.15*
11.36 ± 0.30	11.52 ± 0.01	−0.16 ns	12.09 ± 0.17	12.17 ± 0.16	−0.08 ns
11.31 ± 0.28	11.16 ± 0.08	0.15 ns	11.65 ± 0.20	11.82 ± 0.28	−0.17 ns
10.06 ± 0.34	9.58 ± 0.03	0.48**	10.64 ± 0.22	10.22 ± 0.09	0.42**
37.25 ± 0.88	34.90 ± 0.76	−0.77**	36.18 ± 2.90	31.10 ± 1.15	5.08**

($P < .05$), and this measure was even more thin ($P <$ .01) on day 60. On the contrary, MCC thickness in Pa was thicker in the TIPD groups ($P < .01$) from day 30 onward. On day 60, the MCC thickness in the middle part of the anterior region (Am) was thinner in the TIPD groups ($P < .01$).

DISCUSSION

Animal Model Selection

In this study, we chose rats as experimental subjects because the rat TMJ is widely used for this kind of research.[3,10–12] There was a difference in the potential to resist mechanical loading between genders at different ages,[13] and the age of 42 days represented the stage of late puberty.[14] Furthermore, the second molar erupts enough to allow the use of cement devices at 6 weeks. Considering these factors as well as the obvious clinical interest, the 42-day-old male rats were selected as experimental animals.

Unaffected Body Weight

Unaffected body weight (Figure 2C) indicated the normal growth and development of the animals. The gradually induced backward movement of the mandible by daily masticatory function could be mild and physiological.

Remodeling of the Condyle

TIPD made the length of the condylar process (B–F) shorter, the angulation of condylar process axis to mandibular plane (BF/GH) bigger, and the MCC thickness in Pp thinner. These results may be related to the special design of the TIPD. TIPD is considered a functional appliance. When rats bite, sagittally a mild force (Fh) will generate on Pp from the tilted TIPD occlusal surfaces; it is about 15% of the masticatory force (F) (Figure 1A); vertically, the force on the middle part of the middle region (Mm) will decease slightly because of the increased occlusion vertical dimension (iOVD) (Figure 1A); transversally, the rat can move the mandible freely. In this study, a 1.2-mm iOVD between the upper and lower third molar is considered physiologically acceptable, although there is 0.2 mm beyond the freeway space.[15,16] The unique feature of the present study is that the TIPD was designed to create a long twin inclined plane between the upper and lower posterior teeth to gradually induce backward movement of the mandible with a comfortable, nearly physiological F.

From day 30 onward, the length of the condylar process (B–F) was shorter in the TIPD groups (Table 1). This indicated that the period of TIPD has to be sufficiently long to lead to condylar cartilage remodeling. On the other hand, it indicates that this kind of process is gradual and mild. A significant increase in the angulation of the condylar process axis to the mandibular plane (BF/GH) between the TIPD groups and control groups was observed (2.35° and 5.08°, respectively, on days 30 and 60). In the ABF triangle (Figure 1D), the significant decrease of both BF length and ABF angle with no increase in the length of the mandibular base (A–B), the remodeling of the condyle ultimately resulted in the decrease in mandibular length (A–F). This was the reason that the mandibular length (A–F) was shorter in the TIPD groups. Our results give support to the hypothesis that the length of the mandible is not entirely predetermined by genetic factors.[17]

Changes in MCC thickness have been considered to represent functional adaptation.[18] However, in previous studies,[3,19] the decrease of MCC thickness in the posterior region associated with retrusion of the mandible started as early as day 7, while in our experiment changes happened as late as day 30. The reason may be that the retrusive force produced by TIPD was a mild and nearly physiological stress that induced backward movement of the mandible gradually (countless stepwise backward movements under normal masticatory action). In a previous study,[3] the guiding appliance attached to the upper incisor forced the mandible back by one step of 4 mm and without iOVD. This force might be a nonphysiological stress applied to the condyle.

Different parts of the MCC presented different adaptive remodeling patterns (region specific). The proliferation layer of chondrocytes increased dramatically in the Pa area compared with the Pp area on day 30. Furthermore, there was a small increase in the thickness of the Mm region compared with that in the control groups over the whole observation period. This may be related to the fact that the direction and magnitude of the mechanical stress were different in different regions. Pp is located in the lowest posterior part of the posterior region and was likely loaded with a much greater mechanical compressive stress, whereas Pa, which is located superiorly, may be loaded with a traction force because of the iOVD.

Without iOVD, the MCC thickness on Mm was reduced when orthopedic force was used to move the mandible back.[3,19,20] iOVD is critical for remodeling of the Mm thickness of condylar cartilage. It has been shown[21,22] to stimulate the progressive remodeling of the MCC in monkeys and to increase the volume of the MCC in rabbit models, as well as in our rat models. Therefore, we presumed that the increased growth is due to the reduction of functional loading accompanied by iOVD. This result is in accordance with Buchner's report.[23]

The MCC thickness in Am was thinner in TIPD groups on day 60. This may be attributed to the smaller space of the anterior joint produced by the progressive retrusion of the mandible. Posterior condylar displacement with a continuous force can induce a decrease in the proliferation of chondrocytes and the amount of extracellular matrix.[24] Our results indicated that the areas in the most posterior and superior regions of the condylar cartilage are sensitive to microenvironment change, which is in agreement with the findings of Tang and Rabie[25] and Tang et al.[26]

CONCLUSIONS

- TIPD can successfully induce backward movement of the mandible under normal masticatory action.
- TIPD can cause region-specific changes in condylar cartilage and lead to continuous adaptive remodeling.

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