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# Temporomandibular Joint Adaptations Associated With Herbst Appliance Treatment in Juvenile Rhesus Monkeys (*Macaca mulatta*)

*John E. Peterson, Jr, and James A. McNamara, Jr*

**This study evaluated histologically the temporomandibular joint and posterior ramal regions in juvenile Rhesus monkeys whose mandibles had been positioned forward with a Herbst appliance. Acrylic splint Herbst appliances were bonded to the maxillary and mandibular dental arches of 20 male juvenile animals. The animals were killed at 3-, 6-, 12-, and 24-week intervals after appliance placement. Seven male juvenile Rhesus monkeys served as controls. The TMJ regions, including the posterior border of the rami, then were prepared for qualitative and quantitative histological analysis. Linear measurements were obtained by way of Bioquant microscopic equipment (Bioquant Image Analysis Corp, Nashville, TN). Structural adaptations were noted in the mandibular condyle, infratemporal fossa, and the posterior ramal border of the experimental animals in comparison to controls. Specifically, increased proliferation of the condylar cartilage was noted. These adaptations occurred primarily in the posterior and posterosuperior condylar regions. Bone deposition was noted along the anterior border of the postglenoid spine; bone resorption occurred along its posterior border. Significant bony apposition also was evident along the posterior border of the mandibular ramus during early experimental periods. No gross or microscopic pathological changes were noted in the temporomandibular joint in any of the animals. The results of this study indicate that the response of the temporomandibular joint region in the juvenile animals undergoing forced mandibular protrusion with the Herbst bite-jumping mechanism is similar to previous studies investigating the response to functional protrusion with cast occlusal splints. This study also may provide some insight into the general changes occurring microscopically in the temporomandibular joint regions of growing patients undergoing Herbst appliance therapy. (Semin Orthod 2003;9:12-25.) Copyright 2003, Elsevier Science (USA). All rights reserved.**

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*From the Department of Pediatric Dentistry, Loma Linda University, Loma Linda, CA; and the Department of Orthodontics and Pediatric Dentistry, School of Dentistry, University of Michigan, Ann Arbor, MI.*

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*Address correspondence to James A. McNamara Jr, DDS, PhD, Department of Orthodontics and Pediatric Dentistry, School of Dentistry, University of Michigan, Ann Arbor, MI 48109-1078.*

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Perhaps more than any other type of functional appliance, whether fixed or removable, the treatment effects produced by the banded Herbst appliance in humans have been well documented in clinical studies, especially by Pancherz and coworkers.<sup>1-15</sup> Other investigators have evaluated alternative designs, including the cast Herbst appliance by Wieslander,<sup>16,17</sup> the acrylic splint Herbst appliance by McNamara and coworkers,<sup>18,19</sup> and the stainless steel crown appliance by Burkhardt and coworkers.<sup>20</sup>

Most clinical studies of Herbst appliance treatment, regardless of the design of the appliance, have indicated that in general the effects of treatment are divided more or less equally into dentoalveolar and skeletal effects. The 2 main dentoalveolar effects include the distalization of the maxillary molars and the forward movement of the mandibular dentition. Maxillary molar distalization is similar in many respects to that which might occur after the use of extraoral traction, in that the first molar usually is in a position 2.0 to 2.5 mm posterior to that observed in untreated Class II individuals followed for a similar period of time. The skeletal treatment effects consist primarily of mandibular adaptations, with relatively minor adaptations observed in the maxillary complex. Typically, the length of the mandible increases about 2.5 mm more than in matched untreated controls during the time of Herbst appliance wear.<sup>1,5,9,18</sup>

### Previous Experimental Studies

Although much is known about the effects of the Herbst appliance as observed clinically, relatively few experimental studies specifically have considered the structural adaptations produced by the Herbst appliance, an appliance that forces a forward mandibular position by way of the Herbst bite-jumping mechanism.<sup>21</sup> Rather, the more general experimental model of functional protrusion has been studied extensively, a model in which cast overlays typically have been used to create a Class III occlusal relationship.

### Studies of Functional Protrusion

Breitner<sup>22-24</sup> was the first to conduct such experiments, followed by those of Häupl and Psansky,<sup>25</sup> Hoffer and Colico,<sup>26</sup> Derichsweiler and

Baume,<sup>27,28</sup> Hiniker and Ramfjord,<sup>29</sup> Joho,<sup>30</sup> and Stöckli and Willert.<sup>31</sup> These studies, conducted primarily in nonhuman primates, were characterized by occlusal alterations from a normal to a Class III relationship, similar in concept but different in specifics from the correction of a Class II occlusal relationship to a normal occlusion.

A number of these early investigators<sup>22-26,28,31</sup> showed that the condylar cartilage is capable of exhibiting compensatory tissue responses after experimental alteration of the mandibular functional position. Breitner<sup>22-24</sup> also noted significant adaptive changes in the temporal bone after functional protrusion, concluding that "a mesial migration of the glenoid fossa" had occurred. Similar findings were reported by Häupl and Psansky,<sup>25</sup> but other investigators<sup>26,28,32</sup> did not observe evidence of significant forward migration of the glenoid fossa.

One of the most comprehensive series of investigations dealing with the issue of altering mandibular growth has been conducted by Petrovic, Stutzmann, and colleagues at the University of Strasbourg. Their initial studies<sup>33-35</sup> showed that anterior displacement of the mandibular condyle in rats resulted in increased growth of the condylar cartilage. Charlier and Petrovic<sup>33</sup> reported that the condylar cartilage did not appear to have an independent growth potential when isolated from its environmental structures. After the mandible was displaced anteriorly, however, increased condylar growth occurred through stimulation of the prechondroblastic and chondroblastic (proliferative) layers of cells.<sup>33,34</sup> A later study by Petrovic<sup>36</sup> indicated that mandibular growth augmentation can be achieved in rats when appliances simulating those used in clinical treatment of humans (eg, bionator, Fränkel appliance) are used.

Our group at the University of Michigan also has conducted a series of investigations that have considered craniofacial adaptations to protrusive function, and they are summarized briefly here. To study functional adaptations to changes in mandibular postural position in the Rhesus monkey, we have used many experimental designs, most frequently the model of functional protrusion.<sup>37-41</sup> A unique aspect of these investigations has been that both structural and functional adaptations were considered simultaneously. For example, an increase in lateral

pterygoid activity was associated with the forward positioning of the lower jaw. This new functional pattern was noted first with such phasic activities as swallowing and subsequently with such tonic functions as maintenance of the mandibular postural position. As the experimental period lengthened, however, there was a gradual return toward the preappliance levels of muscle activity, and this change was correlated in time with the skeletal and dentoalveolar adaptations observed in the same animals.

In another study of functional protrusion,<sup>39</sup> the sequence of adaptation within the condylar cartilage was examined on a cross-sectional basis. Proliferation of the condylar cartilage was observed as early as 2 weeks after appliance placement. Maximum cartilage proliferation was observed at 6 weeks, after which time there was a gradual return to condylar morphology similar to that observed in the temporomandibular regions of control animals. A later cephalometric investigation by McNamara and Bryan<sup>41</sup> indicated that the condylar cartilage proliferation indeed was followed by increased bone deposition, leading to a lengthened mandible. In fact, at the end of the active growth period that extended from the mixed dentition to after the eruption of the third molars, the average length of the mandible in the experimental group was 5 to 6 mm longer than that of the control animals.

### Studies of Forced Protrusion

In contrast to the numerous clinical studies of Herbst treatment, relatively few studies of the Herbst bite-jumping mechanism have been carried out in experimental animals. Woodside and coworkers<sup>42</sup> reported that after placement of a Herbst appliance in a juvenile *Cynomolgus* monkey (*Macaca fascicularis*) for a 13-week experimental period during which a Class III malocclusion was created, a small amount of remodeling was noted in the superior aspect of the condyle. Ground sections with tetracycline vital staining and decalcified sections stained with hematoxylin and eosin showed bone formation on the surface of and within the mandibular condyle. The glenoid fossa also showed extensive bone formation in the posterior region after 13 weeks. Woodside and coworkers,<sup>42</sup> on the basis of the results from this and other experi-

ments also cited within the article, concluded that chronic or continuous alteration in mandibular position within the neuromuscular environment produces extensive condylar remodeling and changes in mandibular size.

In a later study by Woodside and coworkers,<sup>43</sup> 7 *Cynomolgus* monkeys were used in a study of Herbst appliance therapy. Five of the animals wore Herbst appliances for 6 to 13 weeks; 2 additional animals wore inactivated appliances as sham controls. The appliances were bonded to the teeth and activated 2 mm initially. They then were reactivated every 2 weeks for an additional 1 to 2 mm, with a total activation of 7 to 10 mm. One of the primary findings noted by Woodside and coworkers<sup>43</sup> was a progressive anterior remodeling of the glenoid fossa produced by continuous and progressive mandibular protrusion, thus leading to an anterior repositioning of the mandible.

It is important to note that not all of the animals in the Woodside study were of the same age. The investigators classified 1 animal as a juvenile, 1 animal as an adult, and 3 animals as adolescents. The 2 sham control animals were also classified as adolescents. Proliferation of condylar tissue and increased mandibular length were seen only in the juvenile primate. Adolescent primates in the permanent dentition before the eruption of the third molars did not show any condylar response. No condylar response was observed in the adult animal as well.

One additional finding of significance was the adaptations occurring in the posterior part of the fibrous articular disc. Thickening of the tissue in this region caused an eccentric repositioning of the condylar head within the glenoid fossa. This tissue contained enlarged active fibroblasts, most of which appeared in areas in which the anterior displacement of the condyle had increased the tension being exerted on the fibers. These findings suggest that part of the anterior displacement of the mandible may be because of soft-tissue proliferation rather than skeletal adaptations. A subsequent remodeling of this soft tissue after the removal of the Herbst appliance could explain in part some of the relapse occasionally observed during the first few months after the removal of the Herbst appliance in humans.

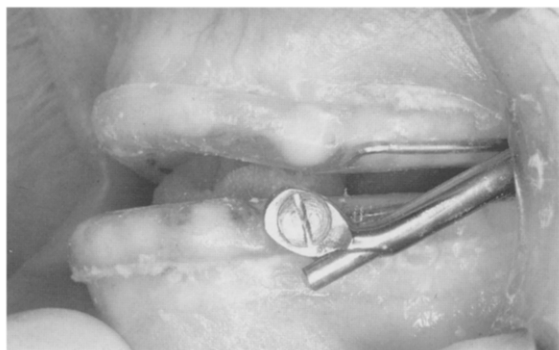
Not surprisingly, a number of questions remain regarding adaptations in the temporoman-

dibular joint that occur during treatment with the Herbst appliance. Thus, it is reasonable to test the assumption that in a juvenile nonhuman primate, the responses at the tissue level observed within the temporomandibular joint with the Herbst appliance will be similar in nature, sequence, and timing to those observed in a functional protrusion model by adapting the Herbst appliance specifically for use in a nonhuman primate. Therefore, the purpose of this study was to investigate histologically the tissue responses produced by the Herbst appliance on the condyle, posterior border of the mandible and portions of the infratemporal fossa.

### Materials and Methods

The experimental group consisted of 20 juvenile male Rhesus monkeys (*Macaca mulatta*). Their average age at the conclusion of the study period was 28 months. Each experimental animal wore an acrylic splint Herbst appliance<sup>44,45</sup> that was bonded to the maxillary and mandibular dentitions (Fig 1). The Herbst bite-jumping mechanism, however, was reversed so that impingement of the mandibular ramus by the protruding end of the plunger was avoided. All animals were maintained uneventfully until they were terminated at regular intervals. Four juvenile animals were sacrificed after 3 weeks, 6 after 6 weeks, 6 after 12 weeks, and the remaining 4 monkeys after 24 weeks. In addition, 7 juvenile male monkeys served as controls.

The Herbst bite-jumping mechanism was connected through acrylic splints of a design similar



**Figure 1.** Intraoral photograph of the bonded acrylic splint Herbst appliance adapted for use in the Rhesus monkey. The Herbst bite-jumping mechanism is reversed to avoid ramal impingement posteriorly.

to that used in human patients.<sup>45</sup> The only variation in the design was the addition of full coverage of the palate and maxillary anterior teeth. The splint was bonded in place using Excel™ adhesive (Reliance Orthodontic Products, Itasca, IL). The actual amount of advancement (2.8 mm) was determined cephalometrically, with the amount of advancement varying slightly among animals. No subsequent reactivations of the appliances were performed.

### Histological Analysis

Before sacrifice, heparin (300-500 U/kg) was injected intravenously into each animal to facilitate tissue preparation for histological sectioning and staining. The animal was anesthetized intramuscularly with Xylazine (Haver-Lockhart Miles Laboratory, Shawnee, KS) (1-2 mg/kg) and intravenously with pentobarbital sodium (8-10 mg/kg), sacrificed by catheterization of the left ventricle or the carotid artery, and perfused with an AFA fixative (acetic acid, formalin, 95% ethyl alcohol). After death, the head was removed surgically from the torso and placed into a solution of 10% neutral buffered formalin before the removal of the temporomandibular joint regions bilaterally. The left and right temporomandibular joint regions were removed en bloc, immersed in Bouin's fixative for 72 hours, and then decalcified in Warshawsky's ethylenediamine tetracetic acid. Decalcification usually was complete in 3 to 6 weeks and verified radiographically.

Tissue preparation followed our routine laboratory dehydration and infiltration protocol. The tissue blocks were imbedded in paraffin, sectioned at 18 to 22  $\mu\text{m}$ , and stained with a hematoxylin and eosin stain. The tissue sections then were evaluated both qualitatively and quantitatively using light microscopy. The portions of the study requiring linear measurements were quantified with Bioquant microscopic equipment (Bioquant Image Analysis Corp, Nashville TN). Various anatomical structures in the temporomandibular joint area were identified and studied based on the locations within the joint from which the sections were cut. Structures studied from central sections included the mandibular condyle and the posterior border of the mandible. The postglenoid spine was studied using more medial sections. Three central sec-

tions and 2 medial sections from each joint were evaluated.

### Statistical Analysis

A *t* test was used to evaluate the condylar articular tissues and cartilage for difference between control and experimented animals. The least squares regression analysis was used to detect significant variations within experimental groups for articular tissue and condylar cartilage width.

The postglenoid spine, presence of ossified cartilage in the condyle, and the posterior border of the mandible were evaluated by assigning them a degree of expression rating of 0 to 3 (0, none; 1, minimal; 2, moderate; 3, extensive). A bony cap underlying the condylar cartilage was judged simply to be present or not. A chi-square analysis was used to evaluate the postglenoid spine, ossified cartilage, and posterior border of the mandible. Two histological sections per joint were used to evaluate the postglenoid spine, and 3 sections per joint were used for the ossified cartilage and posterior border of the mandible. To use the chi-square analysis, the combined readings of each joint and ramus were collapsed into either a 0-1 or 2-3 category. Occasionally, the combined rating for a joint or ramus was between the 0-1 or 2-3 category. In these instances, the particular joint or ramus was eliminated from the chi-square analysis.

To evaluate differences among the experimental groups, a  $2 \times 4$  chi-square test was used.

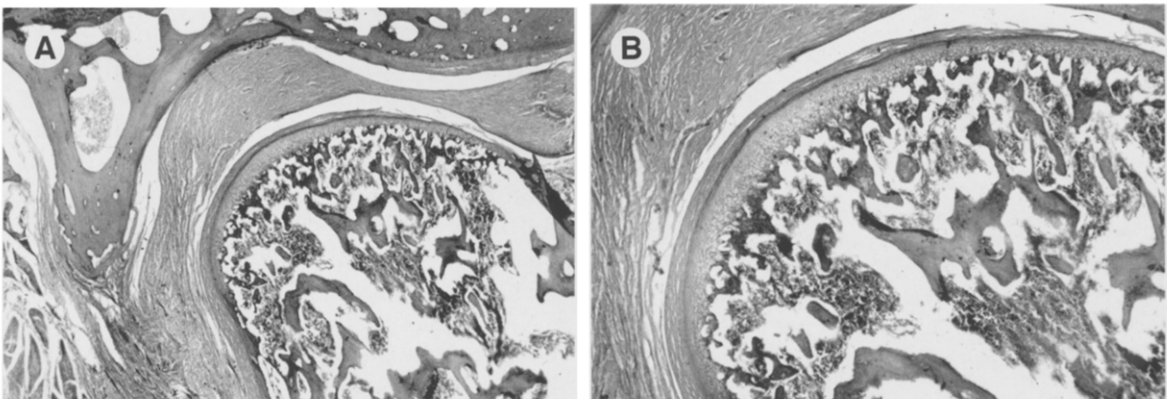
Even with small sample size, these tests adequately protect against incorrectly rejecting the null hypothesis (ie, committing a type I error).<sup>46</sup> To compare the respective experimental groups with the control group, a  $2 \times 2$  chi-square test was used. Because adequacy of power is at issue,<sup>47</sup> we did not correct the test statistics or use Fisher's exact probability test.<sup>48</sup>

The error of the measurement for the quantitative data was determined by repeating the measuring of 10 control and 10 experimental sections. The error was within acceptable limits.

### Results

Although the general anatomic configuration of the temporomandibular joint of the monkey is similar to that of man, there are some structural differences. The temporomandibular joint regions of both species are characterized by the presence of a mandibular condyle, articular disk, glenoid fossa, and articular eminence (Fig 2A). The most striking difference between the 2 species is the postglenoid spine, a vertical structure that is located just anterior to the external auditory meatus.

The results from this study will be considered according to each anatomic area (ie, articular and cartilaginous tissues of the condyle, postglenoid spine, condylar tissues beneath the cartilage, and the posterior border of the mandibular ramus).



**Figure 2.** The temporomandibular joint of a juvenile control animal. Lower power view shows the mandibular condyle, the articular disk and retrodiscal region, the articular eminence, and the postglenoid spine. The external auditory meatus (not shown) is located posterior to the postglenoid spine (A). Higher power view showing the articular cartilage covering the mandibular condyle and the prechondroblastic-chondroblastic layer of condylar cartilage overlying the bony trabeculae of the condyle. The retrodiscal region also can be observed (B).

### Condylar Cartilage

Two distinct soft-tissue layers were identified in the external surfaces of the mandibular condyle (Fig 2B), the condylar cartilage layer covered by the dense articular tissue layer. The condylar cartilage resembled actively growing secondary cartilage and was divided arbitrarily into prechondroblastic and chondroblastic zones. The thickest portion of the cartilage was found in the posterosuperior area (312  $\mu\text{m}$ ) of the condyle followed by the posterior (272  $\mu\text{m}$ ) and superior (248  $\mu\text{m}$ ) regions (Fig 3).

The hyperplasia and hypertrophy of the prechondroblastic and chondroblastic layers of cartilage was evident in both the posterior and posterosuperior areas by three weeks (Fig 4). The increase in cartilage thickness was significant particularly in the posterior region, in which the mean width increased from 272  $\mu\text{m}$  to 511  $\mu\text{m}$  (Fig 3). In contrast to these 2 areas, however, the minimal width increase in the thickness of the superior cartilage was not statistically significant (Table 1).

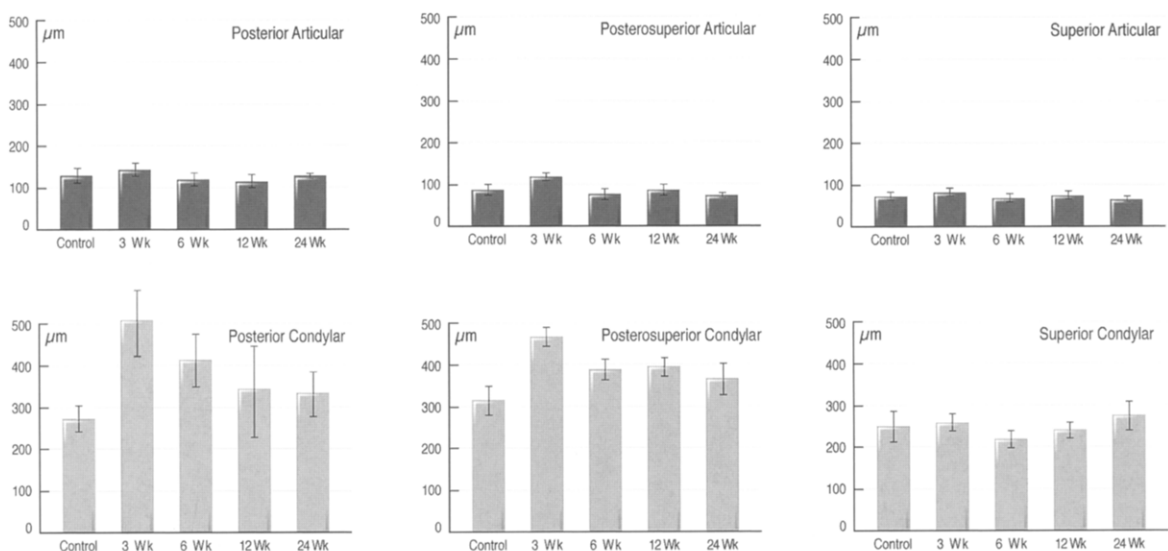
The adaptive hyperplasia and hypertrophy of the condylar cartilage varied from 6 (Fig 5), 12 (Fig 6), and 24 (Fig 7) weeks after appliance placement. On the superior portion of the condyle, the cartilage decreased in width ( $P < .05$ ) briefly at 6 weeks but then resumed a width that

was not significantly different from the controls in the 6-week ( $P < .001$ ), 12-week ( $P < .01$ ) and 24-week ( $p < .01$ ) intervals (Fig 3, Tables 1 and 2). The cartilage of the posterior region responded in a manner similar to the posterosuperior aspect, except at the 12th-week period when the width difference from the control was significant at only  $P < .05$  (Fig 3, Tables 1 and 2). Thus, it can be seen that the adaptive response of the posterior and posterosuperior condylar cartilage was significantly greater in experimental animals than in the controls.

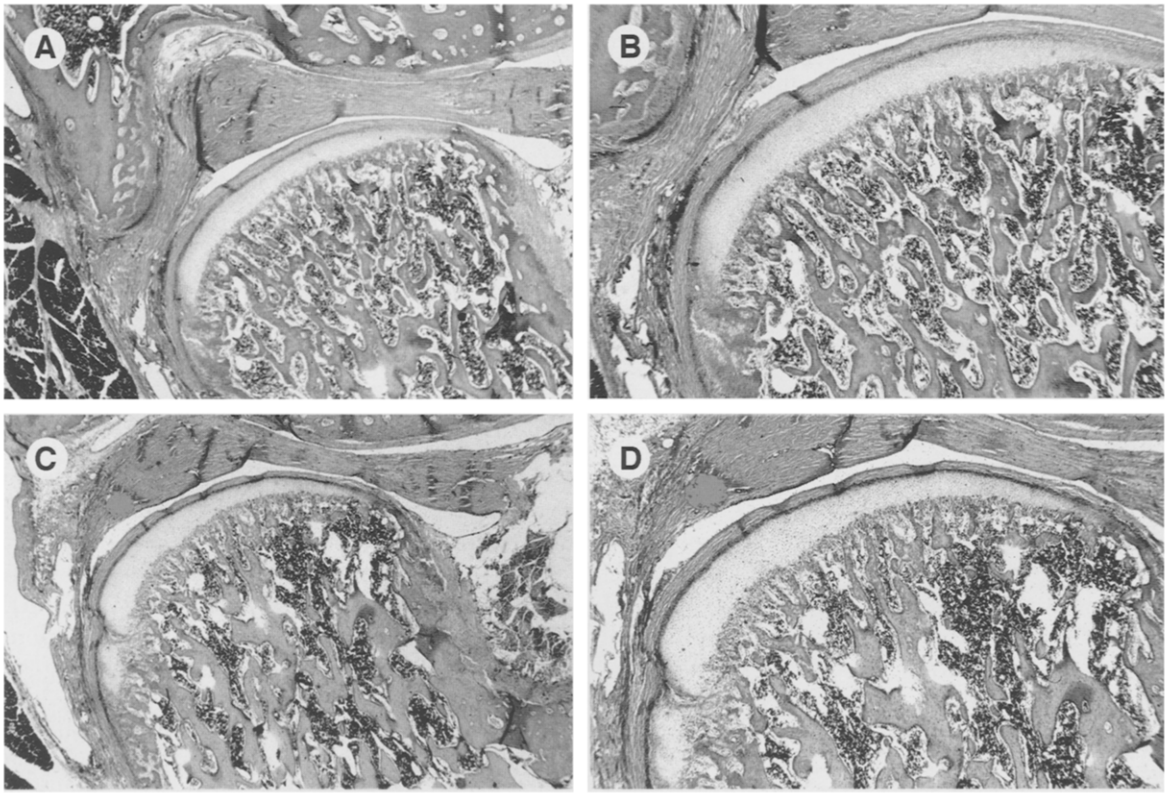
### Articular Tissue

The articular tissue (Fig 2B) consisted of dense irregular connective tissue with fibers generally arranged parallel to the cartilaginous surface of the condyle. The width of this tissue varied, with the posterior area being thickest (116.4  $\mu\text{m}$ ), diminishing in the posterior superior region, and being thinnest in the superior zone (Fig 3).

The animals terminated after wearing the Herbst appliance for 3 weeks (Fig 4) showed significant, although variable, increases in articular tissue width (Fig 3). The posterior superior and superior areas thickened more ( $P < .001$ ) than did the posterior articular tissues ( $P < .05$ ). After the initial widening of the articular tissue observed at 3 weeks, however, these connective



**Figure 3.** Graphic representation of the relative thicknesses of the articular and condylar cartilages of the mandibular condyle, as determined by the Bioquant measuring system. For each condyle, the thicknesses were determined at 3 regions: superior, posterosuperior, and posterior.



**Figure 4.** The temporomandibular joint region of two 3-week experimental animals. Lower power views of the overall condylar morphology. Note the thickening of the condylar cartilage in both views (A and C). Increased bone deposition can be observed along the anterior border of the postglenoid spine. Increased bone deposition along the posterior border of the glenoid fossa also can be observed (A and C). Higher power views of the mandibular condyles of the same 2 animals (B and D).

tissues maintained a thickness that was not statistically significantly different from the controls.

The consistency in articular width continued through the 6th and 12th experimental week

and for the posterior articular area even to the 24th week (Fig 3). It should be noted that even though the articular tissue widths of the posterior superior areas were different from the con-

**Table 1.** Juvenile Control Versus Juvenile Experimental (*t* test)

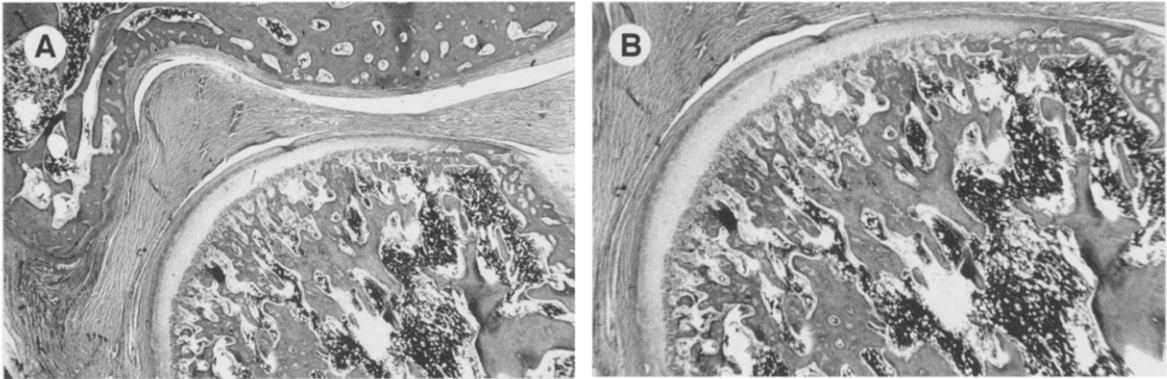
	3 wk (n = 8)	6 wk (n = 12)	12 wk (n = 12)	24 wk (n = 8)
Posterior articular cartilage	*	NS	NS	NS
Posterosuperior articular cartilage	‡	NS	NS	‡
Superior articular cartilage	‡	NS	NS	‡
Posterior condylar cartilage	‡	‡	*	†
Posterosuperior condylar cartilage	‡	‡	†	†
Superior condylar cartilage	NS	*	NS	NS

Abbreviations: NS, not significant; n, number of temporal mandibular joints (includes right and left joints).

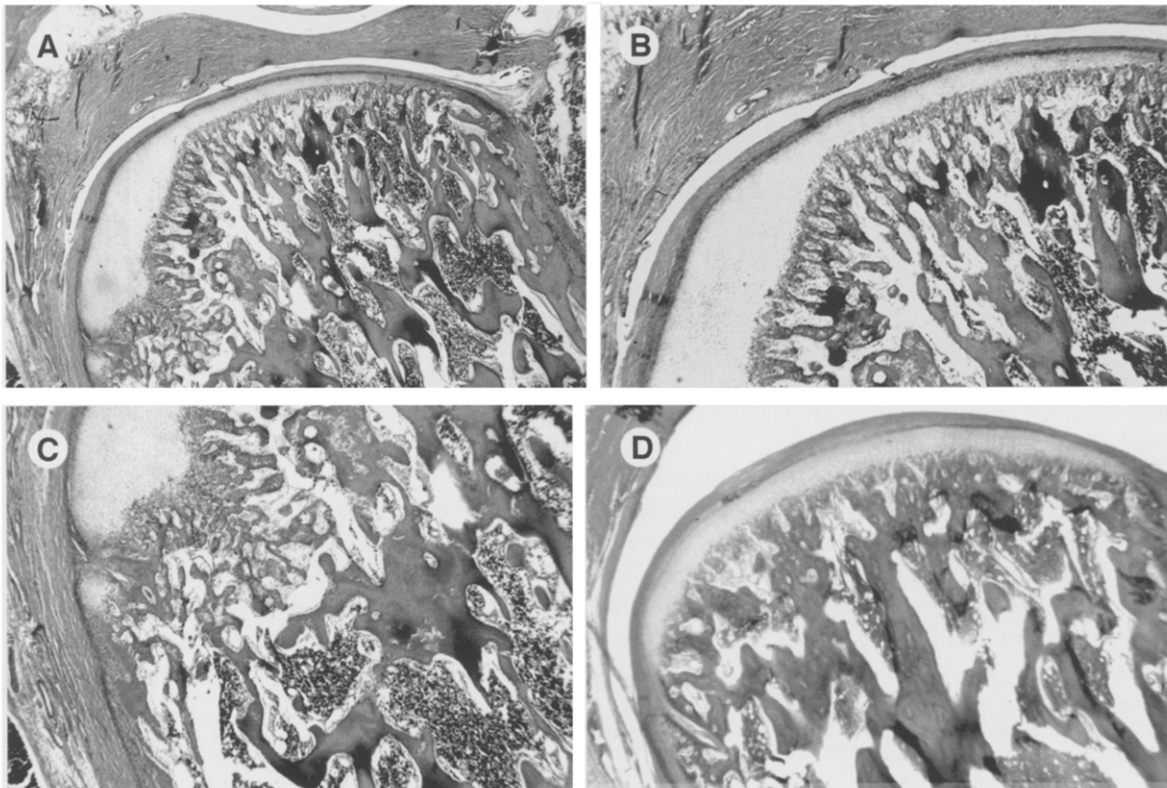
\**P* < .05.

†*P* < .01.

‡*P* < .001.

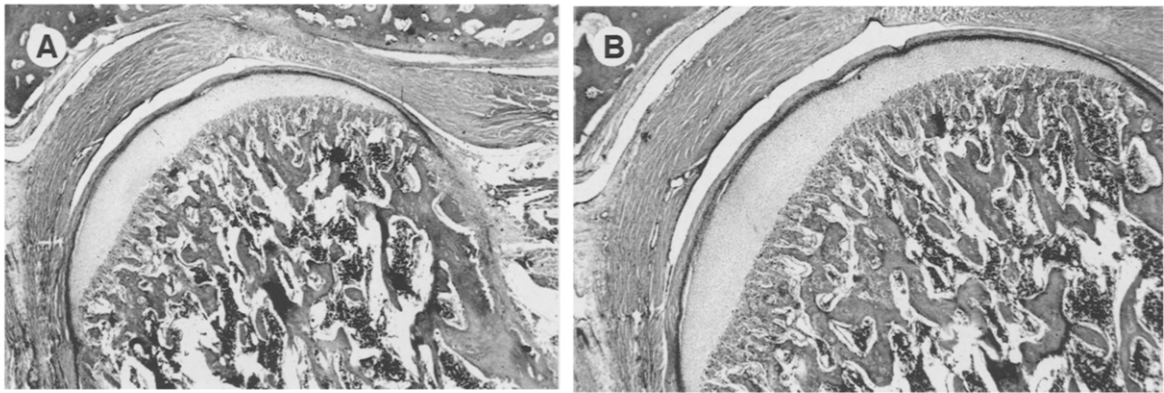


**Figure 5.** The temporomandibular joint region of a 6-week experimental animal. Lower power (A). Higher power of the mandibular condyle. Note the endochondral bone formation occurring under the proliferation of the condylar cartilage. Islands of calcified cartilage matrix can be observed within the trabeculae (B).



**Figure 6.** The temporomandibular joint region of a 12-week experimental animal. Lower power view that features an increase proliferation of the condylar cartilage, particularly in the posterior region of the condyle (A). Higher power view of the mandibular condyle from the same joint (B). Higher power view of the posterior ramal area from the same joint (C). Both intramembranous and endochondral bone deposition is evident. Higher power view of mandibular condyle from a control animal (D).





**Figure 7.** The temporomandibular joint region of a 24-week experimental animal. Lower power view of the temporomandibular joint region. The postglenoid spine is not present in this medial section (A). Higher power view of the mandibular condyle. Note the increased thickness of the condylar cartilage (B).

trols ( $P < .001$ ), their mean values were less than the controls (Table 1).

### Postglenoid Spine

Typically, the posterior surface of the postglenoid spine in the control animals was quiescent, in that no deposition or resorption of bone was evident in any of the sections analyzed (Table 3). In contrast, the posterior surface of the postglenoid spine showed a significant increase in resorption for the 3-, 6-, and 12-week experimental groups; the 24-week experimental group was not significantly different from controls. In contrast, the posterior surface showed no significant differences between any of the groups when examined for bony appositional activity.

In the control animals, bone deposition was not evident along the anterior surface of the postglenoid spine; however, areas of bone resorption were present along this surface. A significant increase in bone deposition activity began to take place immediately in the experimental groups (Fig 8) and continued to be significantly greater than controls through the 12th experimental week (Tables 3 and 4). It is inter-

esting to note that the level of significance declined during the 12th experimental week and disappeared altogether at the 24th week. In contrast, the posterior surface of the postglenoid spine showed no significant resorptive activity in control or experimental animals until the 24th week of appliance use was reached. At this point, half of the specimens examined showed posterior surface resorption.

### Bony Cap

The presence or absence of a coalesced bony cap area below the condylar cartilage may be an indicator of the degree of bone formation activity. There was not significant evidence of a bony cap for either the control or experimental groups (Tables 3 and 4).

### Ossified Cartilage

Cartilage, which is actively proliferating and functioning as a progenitor of new bone, undergoes several morphologic stages. The last stage, which occurs just before ossification and trabeculae formation, has been defined as ossified car-

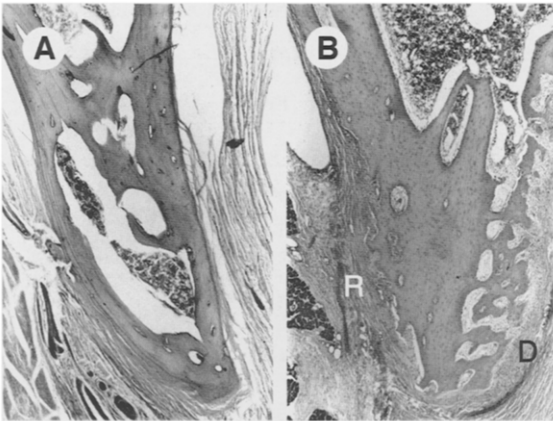
**Table 2.** Least Squares Regression Analysis (3 Weeks, 6 Weeks, 12 Weeks, and 24 Weeks)

	Posterior Articular Cartilage	Post-Sup. Articular Cartilage	Superior Articular Cartilage	Posterior Condylar Cartilage	Post-Sup. Condylar Cartilage	Superior Condylar Cartilage
Juvenile Exp.	NS	‡	‡	†	*	†

\* $P < .05$ .

† $P < .01$ .

‡ $P < .001$ .



**Figure 8.** Postglenoid spine of a control juvenile Rhesus monkey. Neither the anterior (right) nor posterior (left) surfaces of the spine show evidence of bone deposition or resorption (A). Postglenoid spine of a 3-week experimental animal (B). Deposition (D) of new bone is occurring along the anterior aspect of the postglenoid spine; resorption (R) of bone occurs along its posterior border.

tilage, with the presence of calcified cartilage matrix evident. This stage appears to be an indicator of active bone formation. Both control and experimental groups showed significant amount of ossified cartilage, including trapped islands of calcified cartilage matrix. There were no significant differences between the groups, however (Tables 3 and 4, Fig 9).

#### Posterior Border of the Mandibular Ramus

The posterior border of the mandibular ramus was examined for resorptive and appositional activity. The ramus showed essentially no resorption in any group, with no significant difference between control and experimental groups. There was, however, a significant increase in the amount of appositional activity in the 3- and 6-week experimental groups when compared with controls. By the time the 12th and 24th experimental weeks were reached, there once again were no significant differences from controls (Tables 3 and 4, Fig 10).

#### Discussion

The results of this study are similar to our previous experimental studies of adaptation occurring within the temporomandibular joint and infratemporal fossa after alterations in man-

dibular posture in growing nonhuman primates.<sup>38,40,41,49</sup>

#### Condylar Adaptations

The adaptive responses observed in the prechondroblastic and chondroblastic layers of the condylar cartilage reached a maximum at 3 weeks and generally diminished in intensity after that time. The exception to this observation was in the superior cartilaginous area, in which the only statistically significant difference between controls and experimental animals occurred at 6 weeks when the width of the cartilage decreased. Previous studies by McNamara and Bryan<sup>41</sup> indicate that the length of the mandible can be increased significantly (ie, 5-6 mm) over control values at the end of the growth period when a functionally protrusive appliance is used in growing monkeys.

The articular tissues overlying the condylar cartilage also responded somewhat to the change in mandibular posture. There was a significant increase in the width of the articular tissue at 3 weeks, but subsequently it diminished to a width similar to that of controls. It is interesting, however, that the 24-week experimental values for the posterosuperior and superior articular zones were significantly less than the control widths.

The observations that generally show the cartilage and articular tissues to increase in width the most during the first few weeks of appliance wear perhaps can be explained as follows: bony development in the condyle is preceded by the proliferation and maturation of secondary condylar cartilage. Our data show the proliferative effect that a forward positioning of the mandible initiates. There may be, however, a lag period between the time when cartilage proliferation is established and when the subsequent bone formation begins. Thus, it is possible that bone formation plays catch-up for several weeks, and the cartilage layers will appear to be returning to a width similar to controls. This observation should not be interpreted necessarily as a slowing down of cartilage proliferation but rather an indicator that bony trabecular formation has caught up and is now keeping pace with the increased rate of cartilage formation.

**Table 3.** Juvenile Control and Experimental Data Indicating the Presence or Absence of Certain Histological Characteristics for the Anatomic Areas Listed

Anatomic Areas	Control		3-wk Experiment		6-wk Experiment		12-wk Experiment		24-wk Experiment	
	n	%	n	%	n	%	n	%	n	%
Post glenoid spine-posterior surface resorption										
0-1	17	100	5	62	3	43	4	57	6	86
2-3	0	0	3	38	4	57	3	43	1	14
Post glenoid spine-posterior surface apposition										
0-1	19	100	8	100	8	100	8	89	7	88
2-3	0	0	0	0	0	0	1	11	1	12
Post glenoid spine-anterior surface resorption										
0-1	15	88	8	100	8	100	8	89	4	50
2-3	2	12	0	0	0	0	1	11	4	50
Post glenoid spine-anterior surface apposition										
0-1	19	100	0	0	0	0	7	78	7	100
2-3	0	0	8	100	4	100	2	22	0	0
Presence of bony cap-condyle										
Yes	1	5	0	0	0	0	0	0	0	0
No	18	95	8	100	12	100	12	100	8	100
Ossified cartilage-condyle										
0-1	1	6	0	0	0	0	0	0	0	0
2-3	17	94	8	100	12	100	12	100	8	100
Posterior border of ramus- resorption										
0-1	18	95	8	100	12	100	11	92	8	100
2-3	1	5	0	0	0	0	1	8	0	0
Posterior border of ramus- apposition										
0-1	11	73	0	0	2	18	8	73	4	57
2-3	4	27	8	100	9	82	3	27	3	43

Abbreviations: n, number of temporal mandibular joints for each category (includes right and left); 0-1, none-minimal; 2-3, moderate-extensive.

Note. Two or 3 slides were evaluated for each joint area and judged collectively to be either in the 0-1 or 2-3 category. If they were judged to be between the 2 categories, they were omitted from the above data compilation and chi-square analysis.

**Table 4.** Chi-Square Test for Statistical Significance for Individual Anatomic Areas

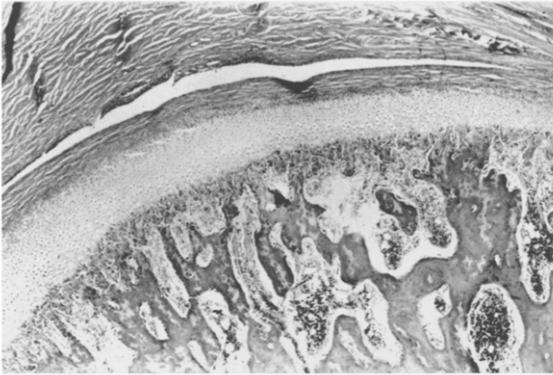
Anatomical Areas	Chi-Square (Control Group Compared With Each Experimental Group Individually)				2×4 Chi-Square all 4 Experimental Groups
	3-wk Experiment	6-wk Experiment	12-wk Experiment	24-wk Experiment	Group Compared Among Themselves
Post glenoid spine-posterior surface resorption	†	‡	†	NS	NS
Post glenoid spine-posterior surface apposition	NS	NS	NS	NS	NS
Post glenoid spine-anterior surface resorption	NS	NS	NS	*	*
Post glenoid spine-anterior surface apposition	‡	‡	NA*	NS	‡
Presence of bony cap-condyle	NS	NS	NS	NS	NS
Ossified cartilage-condyle	NS	NS	NS	NS	NS
Post. border of ramus-resorption	NS	NS	NS	NS	NS
Post. border of ramus-apposition	‡	†	NS	NS	†

Abbreviations: n, number of temporal mandibular joints for each category (includes right and left); NS, not significant; NA = chi-square not appropriate to calculate because of excessive zeros in the 2 × 2 configuration.

\* $P < .05$ .

† $P < .01$ .

‡ $P < .001$ .



**Figure 9.** Mandibular condyle of 6-week experimental animal showing many areas of calcified cartilage matrix within the bony trabeculae.

### Temporal Adaptations

A prominent anatomic feature of the Rhesus monkey is the postglenoid spine, which is located posteriorly and laterally to the glenoid fossa (Figs 2 and 8). Deposition of new bone along the anterior surface of the postglenoid spine can be considered evidence that an anterior repositioning of the glenoid fossa occurred, as originally described by Breitner<sup>22-24</sup> in the 1930s.

In the current study, the posterior surface of the postglenoid spine began to undergo significant surface resorption at three weeks and continued to do so through the 12th experimental week. The posterior surface of the postglenoid spine, however, did not show any significant appositional activity. In contrast, the anterior surface of the postglenoid spine showed significant bony apposition during the same period but did not show any degree of resorption until the 24th week. It would appear from these observations that the postglenoid spine and therefore the glenoid fossa responded to the forward positioning of the mandible by migrating more anteriorly. This observation is consistent with our earlier findings on bony alterations secondary to protrusive function,<sup>39,41,49</sup> as well as with those of Woodside and coworkers.<sup>42</sup>

### Mandibular Ramus

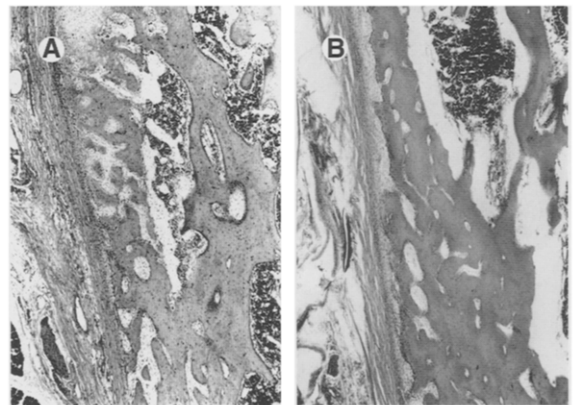
The posterior border of the ramus also showed signs of responding to the forward positioning of the mandible. This was evidenced by a significant increase in the amount of bony apposition

that occurred through the first 6 weeks of the study. This bony apposition of the ramus continued throughout the experimental period, but by the 12th and 24th week periods, it had returned to a degree of activity similar to the controls. These findings concerning forced protrusion also are consistent with our earlier studies involving the functional protrusion model.<sup>39,41,49</sup>

### Summary and Conclusions

The purpose of this study was to evaluate histologically the temporomandibular joint, glenoid fossa, and the posterior border of the mandible in juvenile Rhesus monkeys whose mandibles had been positioned forward with a Herbst appliance. Acrylic splint Herbst appliances were bonded to the upper and lower dental arches of 20 male juvenile animals. The animals were terminated at 3-, 6-, 12- and 24-week intervals after appliance placement. Seven male juvenile Rhesus monkeys served as controls. The temporomandibular joint, infratemporal fossa area, and the posterior border of the ramus then were prepared for and analyzed histologically.

The results of this study indicate that both condylar temporal bone and mandibular ramus adaptations occur after placement of the Herbst appliance. The following adaptations were observed:



**Figure 10.** Deposition of new bone along the posterior border of the mandibular ramus in a 3-week experimental animal (A). Deposition of new bone along the posterior border of the mandibular ramus in a 12-week animal. The bony architecture is more organized than that in the 3-week animal (B).

1. Increased proliferation of the condylar cartilage was noted. These adaptations occurred primarily in the posterior and posterosuperior regions of the condyle.
2. Significant deposition of new bone on the anterior surface of the postglenoid spine occurred, indicating an anterior repositioning of the glenoid fossa.
3. Significant bone resorption on the posterior surface of the postglenoid spine was noted.
4. Significant bony apposition on the posterior border of the mandibular ramus was evident during early experimental periods.
5. No gross or microscopic pathological changes were noted in the temporomandibular joint of the juvenile Rhesus monkey.

The result of any study in animals, even in nonhuman primates, cannot be applied directly to human orthopedic treatment. Because the tissue types and the morphology of the temporomandibular joint are similar between monkey and man, however, the findings of the present study can be used to shed light on the changes occurring in the temporomandibular joint region following Herbst appliance therapy in growing patients.

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## References

1. Pancherz H. Treatment of Class II malocclusions by jumping the bite with the Herbst appliance. A cephalometric investigation. *Am J Orthod* 1979;76:423-442.
2. Pancherz H. The effect of continuous bite jumping on the dentofacial complex: a follow-up study after Herbst appliance treatment of Class II malocclusions. *Eur J Orthod* 1981;3:49-60.
3. Pancherz H. The mechanism of Class II correction in Herbst appliance treatment. A cephalometric investigation. *Am J Orthod* 1982;82:104-113.
4. Pancherz H. Vertical dentofacial changes during Herbst appliance treatment: a cephalometric investigation. *Swed Dent J Supp* 1982;15:189-196.
5. Pancherz H. The Herbst appliance—Its biologic effects and clinical use. *Am J Orthod* 1985;87:1-20.
6. Pancherz H, Anehus-Pancherz M. The head-gear effect of the Herbst appliance. A cephalometric long-term study. *Am J Orthod* 1993;103:510-520.
7. Pancherz H. The nature of Class II relapse after Herbst appliance treatment: A cephalometric long-term investigation. *Am J Orthod Dentofacial Orthop* 1991;100:220-233.
8. Pancherz H, Anehus-Pancherz M. Muscle activity in Class II, division 1 malocclusions treated by bite jumping with the Herbst appliance. An electromyographic study. *Am J Orthod* 1980;78:321-329.
9. Pancherz H, Anehus-Pancherz M. The effect of continuous bite jumping with the Herbst appliance on the masticatory system: A functional analysis of treated class II malocclusions. *Eur J Orthod* 1982;4:37-44.
10. Pancherz H, Fackel U. The skeletofacial growth pattern pre- and post-dentofacial orthopaedics. A long-term study of Class II malocclusions treated with the Herbst appliance. *Eur J Orthod* 1990;12:209-218.
11. Pancherz H, Hansen K. Occlusal changes during and after Herbst treatment: a cephalometric investigation. *Eur J Orthod* 1986;8:215-228.
12. Pancherz H, Hansen K. Mandibular anchorage in Herbst treatment. *Eur J Orthod* 1988;10:149-164.
13. Pancherz H, Hägg U. Dentofacial orthopaedics in relation to somatic maturation. An analysis of 70 consecutive cases treated with the Herbst appliance. *Am J Orthod* 1985;88:273-287.
14. Pancherz H, Malmgren O, Hagg U, et al. Class II correction in Herbst and Bass therapy. *Eur J Orthod* 1989; 11:17-30.
15. Hagg U, Pancherz H. Dentofacial orthopaedics in relation to chronological age, growth period and skeletal development. An analysis of 72 male patients with Class II division 1 malocclusion treated with the Herbst appliance. *Eur J Orthod* 1988;10:169-176.
16. Wieslander L. JCO interviews Dr. Lennart Wieslander on dentofacial orthopaedics. Headgear-Herbst treatment in the mixed dentition. *J Clin Orthod* 1984;18:551-564.
17. Wieslander L. Intensive treatment of severe Class II malocclusions with a headgear-Herbst appliance in the early mixed dentition. *Am J Orthod* 1984;86:1-13.
18. McNamara JA Jr, Howe RP, Dischinger TG. A comparison of the Herbst and Fränkel appliances in the treatment of Class II malocclusion. *Am J Orthod Dentofacial Orthop* 1990;98:134-144.
19. Lai M, McNamara JA Jr. An evaluation of two-phase treatment with the Herbst appliance and preadjusted edgewise therapy. *Semin Orthod* 1998;4:46-58.
20. Burkhardt DR, McNamara JA Jr, Baccetti T. Maxillary molar distalization or mandibular enhancement: A cephalometric comparison of the Pendulum and Herbst appliances. *Angle Orthod*, in press.
21. Herbst E. Atlas und Grundriss der Zahnärztlichen Orthopädie. Munich, Germany: JF Lehmann Verlag, 1910.
22. Breitner C. Experimentelle Veränderung der mesiodistalen Beziehungen der oberen und unteren Zahnreihen. *Ztschr f Stomatol* 1930;28:343-356.
23. Breitner C. Experimental change of the mesio-distal relations of the upper and lower dental arches. *Angle Orthod* 1933;3:67-76.
24. Breitner C. The influence of moving deciduous teeth on permanent successors. *Am J Orthod* 1940;26:1152-1177.
25. Häupl K, Psansky R. Experimentelle Untersuchungen über Gelenktransformation bei Verwendung der Methoden der Funktionskieferorthopädie. *Deutsche Zahn Mund Kieferheilkd* 1939;6:439-448.

26. Hoffer O, Colico GL. Le modificazioni dell'A.T.M. conseguenti a spostamento mesiale della mandibola. *Rass Int Stomatol Prat* 1958;9(suppl 4):27-40.
27. Derichsweiler H. Experimentelle Tieruntersuchungen über Veränderungen des Kiefergelenkes bei Bisslageveränderung. *Fortschr Kieferorthop* 1958;19:30-44.
28. Baume LJ, Derichsweiler H. Is the condylar growth center responsive to orthodontic therapy? An experimental study in *Macaca mulatta*. *Oral Surg Oral Med Oral Path* 1961;14:347-362.
29. Hiniker J, Ramfjord S. Anterior displacement of the mandible in adult rhesus monkeys. *J Pros Dent* 1966;16:503-512.
30. Joho J-P. Changes in form and size of the mandible in the orthopaedically treated *Macacus Irus*: An experimental study. *Trans Eur Orthod Soc* 1968;44:161-173.
31. Stöckli PW, Willert HG. Tissue reactions in the temporomandibular joint resulting from anterior displacement of the mandible in the monkey. *Am J Orthod* 1971;60:142-155.
32. Lieb G. Application of the activator in rhesus monkey. *Trans Europ Orthod Soc* 1968;44:141-147.
33. Charlier JP, Petrovic AG. Recherches sur la mandibule de la rat en culture d'organs: Le cartilage condylien a-t-il un potentiel de croissance indépendant? *Orthod Franç* 1967;38:165-175.
34. Charlier JP, Petrovic A, Herrmann-Stutzmann J. Effects of mandibular hyperpropulsion on the prechondroblastic zone of young rat condyle. *Am J Orthod* 1969;55:71-74.
35. Petrovic AG. Mechanisms and regulation of mandibular condylar growth. *Acta Morphol Neerl Scand* 1972;10:25-34.
36. Petrovic A. Experimental and cybernetic approaches to the mechanism of action of functional appliances on mandibular growth. In: McNamara JA Jr, Ribbens KA, eds. *Malocclusion and the periodontium*. Ann Arbor, MI: Monograph 15, Craniofacial Growth Series, Center for Human Growth and Development, University of Michigan, 1984.
37. Elgoyhen JC, Moyers RE, McNamara JA Jr, et al. Craniofacial adaptation of protrusive function in young rhesus monkeys. *Am J Orthod* 1972;62:469-480.
38. McNamara JA Jr. Neuromuscular and skeletal adaptations to altered function in the orofacial region. *Am J Orthod* 1973;64:578-606.
39. McNamara JA Jr, Carlson DS. Quantitative analysis of temporomandibular joint adaptations to protrusive function. *Am J Orthod* 1979;76:593-611.
40. McNamara JA Jr. Functional determinants of craniofacial size and shape. *Eur J Orthod* 1980;2:131-159.
41. McNamara JA Jr, Bryan FA. Long-term mandibular adaptations to protrusive function: An experimental study in *Macaca mulatta*. *Am J Orthod Dentofacial Orthop* 1987;92:98-108.
42. Woodside DG, Altuna G, Harvold E, et al. Primate experiments in malocclusion and bone induction. *Am J Orthod* 1983;83:460-468.
43. Woodside DG, Metaxas A, Altuna G. The influence of functional appliance therapy on glenoid fossa remodeling. *Am J Orthod Dentofacial Orthop* 1987;92:181-198.
44. McNamara JA Jr. Fabrication of the acrylic splint Herbst appliance. *Am J Orthod Dentofacial Orthop* 1988;94:10-18.
45. McNamara JA Jr, Howe RP. Clinical management of the acrylic splint Herbst appliance. *Am J Orthod Dentofacial Orthop* 1988;94:142-149.
46. Bradley D, Bradley T, McGrath S, et al. Type I error rate of the chi-square test of independence in RxC tables that have small expected frequencies. *Psych Bull* 1979;86:1290-1297.
47. Overall J. Power of chi-square tests for 2X2 contingency tables with small expected frequencies. *Psych Bull* 1980;87:132-135.
48. Haviland M. Yate's correction for continuity and the analysis of 2X2 contingency tables. *Stat Med* 1990;9:363-367.
49. McNamara JA Jr. Neuromuscular and skeletal adaptations to altered orofacial function. Ann Arbor, MI: Monograph 1, Craniofacial Growth Series, Center for Human Growth and Development, The University of Michigan, 1972.