American Journal *of* ORTHODONTICS

Volume 76, Number 6 **December, 1979**

ORIGINAL ARTICLES

Quantitative analysis of temporomandibular joint adaptations to protrusive function

James A. McNamara, Jr., D.D.S., Ph.D., and David S. Carlson, Ph.D.
Ann Arbor, Mich.

Much has been published in the clinical and basic science literature on the growth of the temporomandibular joint. An area of significant controversy is the question of whether the growth of the temporomandibular joint, and of the mandibular condyle in particular, can be influenced to any significant degree through therapeutic or experimental intervention. Despite the number of clinical and experimental studies of this question, no universal agreement has been reached regarding the potential for adaptation in response to an alteration of the structural or functional environment by means of growth and/or remodeling of the temporomandibular joint. Part of the reason for this lack of agreement stems from the fact that competing dogmas exist concerning the growth and adaptability of the temporomandibular joint. A precise definition of the mechanisms by which condylar growth takes place also has been hindered, in many cases, by inadequate clinical and experimental samples and by incomparability of treatment plan or experimental design.

Numerous persons have undertaken experimental investigations of temporomandibular joint growth in animal models. An evaluation of the findings from these studies reveals that the age or developmental stage of the animals used in these experiments is a critical factor in determining the potential for temporomandibular joint adaptability. There is little experimental evidence demonstrating that any significant adaptations can occur in the adult temporomandibular joint,[13, 16, 17, 34] and pathologic changes have been reported to occur in some instances.[6] In contrast, other studies have shown that the temporomandibular joint region, particularly the mandibular condyle of young, growing animals, can be a primary site of craniofacial adaptation to altered occlusal function.[1, 2, 5, 12, 28–33, 35]

We have experimentally studied temporomandibular joint adaptability to alteration of the biomechanical environment, using the rhesus monkey *(Macaca mulatta)* as our animal

From the Departments of Anatomy and Anthropology and the Center for Human Growth and Development, The University of Michigan.
This study was supported in part by National Institute of Health Grant DE 03610.

0002-9416/79/120593+19$01.90/0

model.[10, 16–23] The results of our previous investigations indicate that modification of the functional position of the mandible results in an immediate alteration of the neuromuscular activity of the orofacial muscles, which is particularly noticeable in the lateral pterygoid muscle. Depending on the maturational status of the animal, various adaptive responses in the facial skeleton follow closely the neuromuscular alterations. These neuromuscular adaptations continue to be observed until the structural adaptations in the skeletal and dentoalveolar components of the craniofacial complex are complete. We have shown cephalometrically[10, 16, 17, 19, 21] and in a preliminary histologic study[20, 23] that the growth of the temporomandibular joint, particularly of the condylar cartilage, can be increased in comparison to control-level values through the insertion of an appliance which prompts the jaw to function in an anterior position. On the basis of these studies we have hypothesized that the adaptation of the skeletal and dentoalveolar elements of the face following functional protrusion of the mandible leads to a re-establishment of structural and functional balance of the orofacial region, thus leading to a return to the original pattern of neuromuscular activity.[18]

Similar findings have been observed in the rat by Petrovic and associates.[27, 29–31, 33] In these studies, in which young growing rats wore hyperpropulsor devices, the number of dividing prechondroblasts in the condylar cartilage was significantly increased in the treated group. In addition, the mandibular angle (the angle formed by the intersection of a line drawn through the middle of the condyle to the tangent of the inferior border of the ramus) increased an average of 3 degrees. Petrovic and associates[27, 31] also noted a reduction in the number of serially arranged sarcomeres of the lateral pterygoid muscle, indicating that the anatomic length of the muscle was decreased. Furthermore, it was evident from the histologic analysis that the fibers of the lateral pterygoid muscle exhibited considerable hypertrophy.

The results of the above studies in young growing monkeys and rats indicate a relationship between altered muscle function and structural adaptations in the temporomandibular joint region. It is the purpose of the present study to quantify histologically the adaptive responses observed in the temporomandibular joint in young rhesus monkeys following an alteration in the mandibular postural position. Our working hypothesis in this experiment is that the adaptations in the cartilage of the mandibular condyle and its associated osseous tissue can be induced by alterations in the biomechanical or biophysical influences on the temporomandibular joint, the articular disc, the temporal bones, and the adjacent soft tissue.

Materials and methods

Twenty-eight rhesus monkeys *(Macaca mulatta)* from the primate colony of the Center for Human Growth and Development, The University of Michigan, were used in this study. The animals were 18 to 24 months of age at the beginning of the experiment, as determined by the presence of a deciduous dentition and erupted first permanent molars.[14]

Appliance design. Cast ticonium onlays[18, 20] were fabricated for the upper and lower dentitions of each animal so that forward protrusion of the mandible was created without necessitating intermaxillary fixation (Fig. 1). The appliance displaced the mandible approximately 4 mm. in an anterior direction and 3 mm. in an inferior direction. Before cementation, the appliances were equilibrated to allow for maximum occlusal contact.

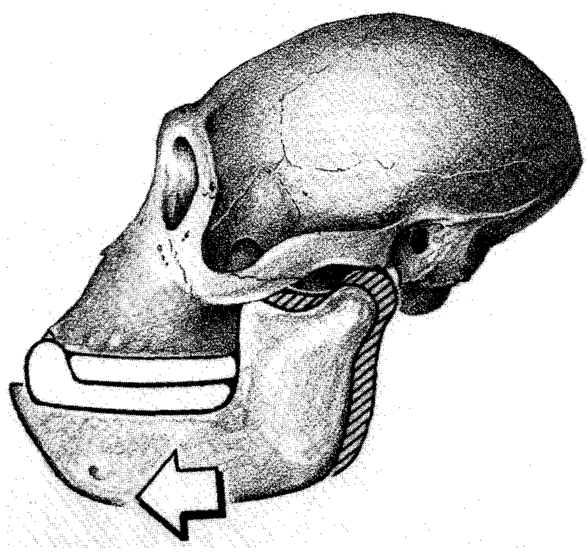

Fig. 1. Schematic representation of the effect of the functional protrusion appliance on mandibular condylar displacement.

Experimental design. The animals were divided into fourteen control animals and fourteen experimental animals. In order to monitor the sequence of adaptations occurring in the temporomandibular region, the experimental animals were killed on the following schedule: three animals at 2 weeks; two animals at 4 weeks; two animals at 6 weeks; one animal at 8 weeks; two animals at 10 weeks; three animals at 12 weeks; and one animal at 24 weeks following appliance cementation.

The animals were perfused with neutral buffered formalin, and tissue blocks were taken from the right and left temporomandibular joint regions. The blocks were decalcified, embedded in paraffin, and sectioned serially in a sagittal orientation.

Normal microanatomy of the mandibular condyle. The normal microanatomy and growth and development of the mandibular condyle have been reported for human beings by Wright and Moffett[37] and for the rhesus monkey by Zimmermann[38] and by Carlson and associates.[4] Each study noted that the general features of the morphology and growth of the condyle were similar in both species.

The cartilaginous covering of the mandibular condyle can be perceived as two distinct tissue layers. The *articular tissue,* which consists of dense fibroelastic connective tissue whose collagen fibers are oriented parallel to the articular surface of the condyle, is continuous with the fibrous layer of the periosteum. The articular layer is avascular and contains only a small number of fibroblasts which, according to Kanouse and coworkers,[15] function primarily to maintain the articular tissue. The articular tissue generally varies in thickness along the condyle, increasing in thickness posteriorly.

The subarticular cartilaginous region of the condyle is where the major growth of the condyle occurs. It can be further divided into two general layers—a *prechondroblastic* zone and a *chondroblastic* zone. The prechondroblastic zone lies immediately inferior to the articular layer and is continuous with the inner (osteogenic) portion of the periosteum.

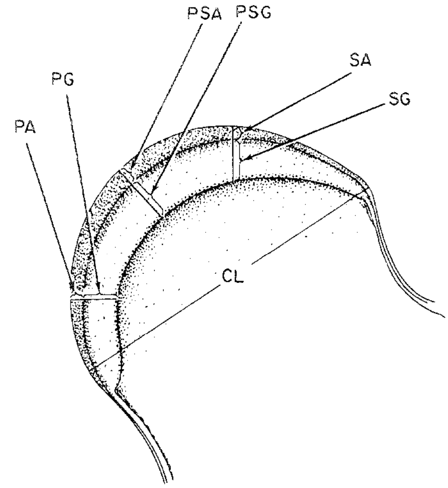

Fig. 2. Regions measured in the determination of cartilage thickness and condylar length. *PA*, Posterior articular cartilage; *PG*, posterior growth cartilage; *PSA*, posterosuperior articular cartilage; *PSG*, posterosuperior growth cartilage; *SA*, superior articular cartilage; *SG*, superior growth cartilage; *CL*, condylar length.

It is the major site of chondrocytic proliferation. The chondroblastic zone contains the maturing chondrocytes which eventually hypertrophy and form the structure necessary for osteogenesis along the endosteal surface of the condyle.

Condylar measurements. The method used in quantifying the histologic sections is similar to that described previously by Carlson and co-workers.[4] Three midline sections, stained with hematoxylin and eosin, were selected for study. The histologic sections were magnified (×10) and microprojected (×4.5) onto a flat surface from a distance of 9 feet. Tracings were made of the structures in the temporomandibular joint region, emphasizing the articular tissue and the prechondroblastic-chondroblastic (growth) cartilaginous layer within the mandibular condyle. No attempt was made to delineate the prechondroblastic zone from the chondroblastic zone, since the gradual nature of their transformation made it difficult to identify a single boundary between these two regions. The thickness of the layers was measured perpendicular to the articular surface at the posterior, posterosuperior, and superior regions (Fig. 2) along the circumference of the condyle.[4] Finally, the length of the mandibular condyle was measured on lateral head films perpendicular to the posterior border of the ramus in order to determine whether or not alterations in over-all condylar size occurred during treatment (Fig. 2).

Each of the three midline sections was traced and measured. The measurements were averaged for statistical evaluation, and the means and standard deviations were determined in order to compare the experimental and control groups. Linear regressions were computed for each region of the condyle in the experimental animals to determine the association between the thickness of the condylar cartilage and duration of treatment.

The error of the method for this procedure was determined in a previous study.[4] A two-tailed t test failed to demonstrate any significant differences between the means of the original and retraced samples for any of the seven measurements considered.

Table I. Measurements of the length of the mandibular condyle and thickness of the articular layer and prechondroblastic-chondroblastic layers of the condylar cartilage in control and experimental rhesus monkeys

		Treatment intervals (weeks)						
	Control (N = 14)	*2 (N = 2)*	*4 (N = 2)*	*6 (N = 2)*	*8 (N = 1)*	*10 (N = 2)*	*12 (N = 3)*	*24 (N = 1)*
Condylar length (mm.)	7.0 ± 0.9	6.8 (0.5)	6.8 (0.5)	6.8 (0.5)	7.0 (0)	7.0 (0)	6.8 (0.5)	7.0 (0)
Articular tissue (μm)								
Posterior	100.0 ± 20.7	141.1 (43.5)	93.1 (46.5)	116.3 (46.5)	170.5 (0)	98.5 (20.2)	129.8 (21.4)	65.8 (0)
Postero-superior	73.9 ± 13.4	104.7 (11.7)	81.4 (23.2)	91.1 (3.9)	104.7 (0)	79.5 (11.6)	92.4 (36.8)	62.1 (0)
Superior	61.9 ± 15.8	62.6 (2.8)	65.8 (23.0)	89.1 (10.2)	81.4 (0)	60.1 (4.0)	73.2 (17.9)	93.0 (0)
Prechondroblastic-chondroblastic cartilage (μm)								
Posterior	219.9 ± 81.8	734.1 (26.3)	527.2 (139.6)	620.2 (364.3)	372.1 (0)	244.2 (139.6)	311.4 (77.4)	209.3 (0)
Postero-superior	334.0 ± 76.5	351.8 (5.9)	713.2 (170.5)	407.0 (131.6)	356.5 (0)	248.1 (30.9)	348.3 (164.7)	162.1 (0)
Superior	138.1 ± 30.5	170.0 (2.5)	78.5 (5.8)	170.5 (71.4)	116.3 (0)	106.5 (58.2)	149.8 (124.0)	155.1 (0)

Means and standard deviations are reported for the control sample. Means and ranges (in parentheses) are reported for the experimental sample.

Results

The right temporomandibular joints of the untreated monkeys were examined and quantified to provide control data for the evaluation of temporomandibular joint adaptations following functional protrusion (Table I).

Control sample. The temporomandibular joint region of the juvenile rhesus monkey (Fig. 3) includes the mandibular condyle, the articular disc, the articular eminence, and, in lateral sagittal sections, the postglenoid spine. The latter structure is not generally observed in man.

As mentioned earlier, the cartilaginous covering of the mandibular condyle (Fig. 4) can be divided into two layers the articular tissue layer and the prechondroblastic-chondroblastic (growth) cartilage layer. The articular tissue varied in thickness along its circumference in the fourteen control animals but was thickest in the posterior region (100 μm), becoming progressively less thick through the posterosuperior (73.9 μm), and superior regions (61.9 μm).

The prechondroblastic and chondroblastic zones of the subarticular cartilage combined to form a relatively thick layer, indicating active cartilaginous growth. As evidenced by the thickness of the prechondroblastic zone alone and in combination with the chondroblastic zone, growth was most active in the posterosuperior region of the condyle in the juvenile monkeys. The cartilage in the posterosuperior region (334.9 μm) was approximately one and one half times as thick as that in the posterior region (219.9 μm) and almost two and one half times as thick as that in the superior region (138.1 μm).

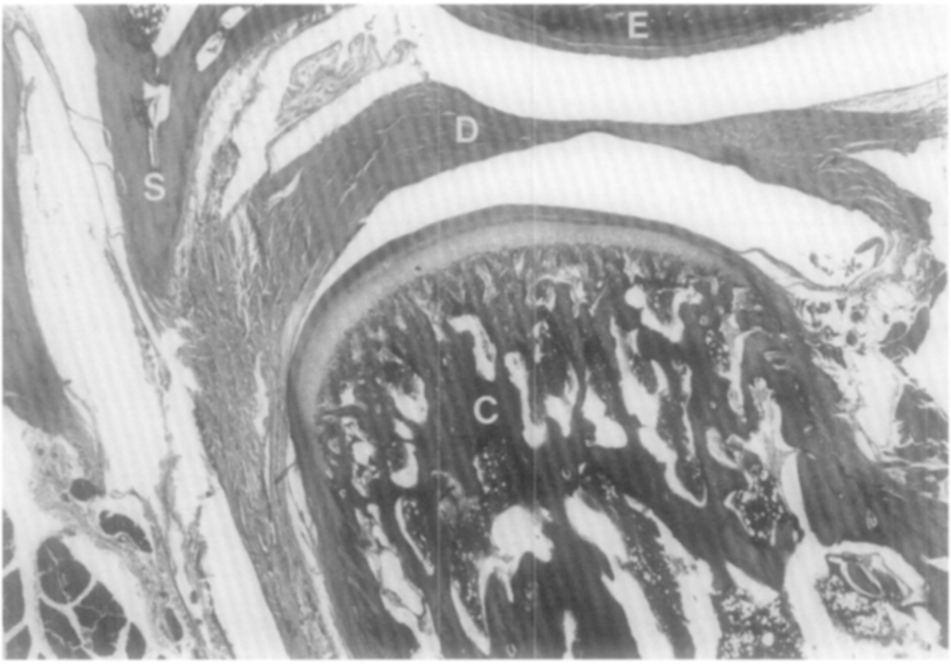

Fig. 3. Overview of the temporomandibular joint region in a control juvenile rhesus monkey *(Macaca mulatta). C,* Mandibular condyle; *D,* articular disc; *E,* articular eminence; *S,* posterior glenoid spine. (Sagittal section. Hematoxylin and eosin stain. Magnification, ×5.)

Experimental sample. Although some of the experimental monkeys exhibited an articular tissue layer which was slightly thicker than the controls (Table I), there was no apparent relationship between variation in thickness and treatment or duration of treatment.

Significant adaptive changes in the subarticular cartilage layer of the mandibular condyle were evident in every monkey. Considerable hyperplasia of the prechondroblastic-chondroblastic cartilage layer was particularly evident in the posterior region of the condyle from the initiation of the experiment through the twelfth week posttreatment. Changes in the bony morphology of the postglenoid spine were also evident in many experimental animals.

TWO-WEEK ANIMALS. Adaptive responses were observed in the mandibular condyle 2 weeks posttreatment (Fig. 5). The principal area of adaptation was along the posterior border of the condylar cartilage, where an increase in the thickness of the growth cartilage layer was observed. Adaptations were also noted along the posterior border of the ramus, as indicated by the increase in the size of the posteriorly directed bony trabeculae present in that region.

Resorption of bone occurred anteriorly under the attachment of the lateral pterygoid muscle, as normally occurs in growing animals. Since the over-all length of the condyle (Fig. 2) of the experimental animals did not differ from that of the controls, in spite of the increased posterior growth (Table I), one can infer that the rate of bone resorption anteriorly was higher than would have normally occurred without experimental intervention.

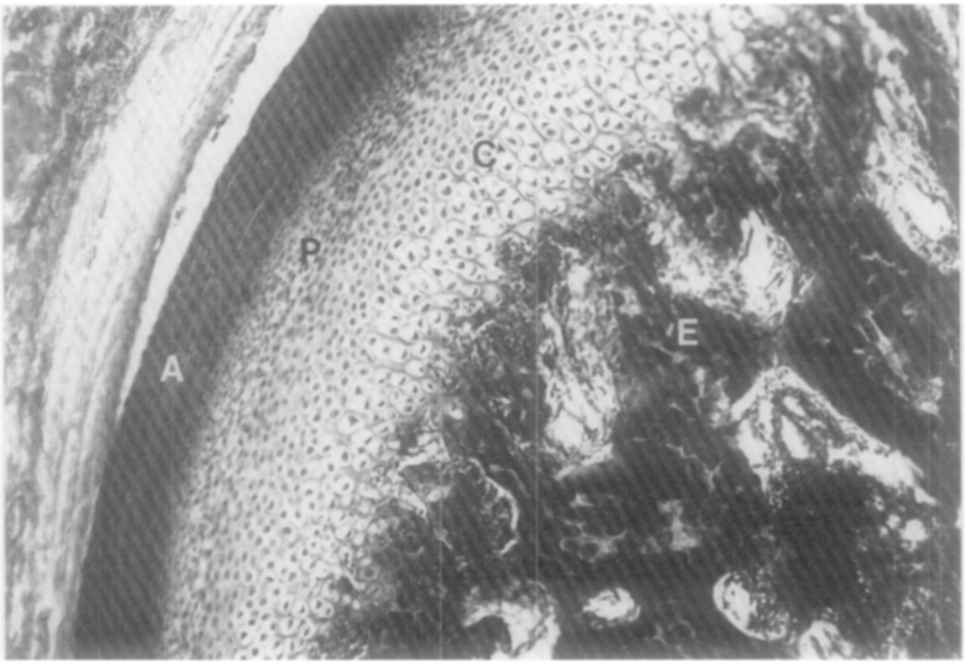

Fig. 4. Condylar cartilage from an untreated juvenile rhesus monkey. *A,* Articular zone; *P,* prechondroblastic (proliferative) zone; *C,* chondroblastic zone (zone of maturation and hypertrophy); *E,* region of endochondral bone formation. The posterior portion of the articular disc can also be observed adjacent to the articular tissue. (Sagittal section. Hematoxylin and eosin stain. Magnification, ×40.)

Extreme hyperplasia of the growth cartilage layer and hypertrophy of individual chondrocytes were noted in the posterior region of the mandibular condyle (Fig. 6). The mean thickness of prechondroblastic-chondroblastic layer in the posterior condylar region of monkeys with the functional protrusion appliance was 734.1 μm (Table I), approximately three and one half times the mean thickness of the same region in the control monkeys. No significant differences between the experimental and control groups were observed for the posterosuperior and superior regions of the condyle.

In addition to alterations in the condylar cartilage and posterior border of the ramus, deposition of new bone was observed along the anterior surface of the postglenoid spine (Fig. 7), a region that is normally resorptive.

FOUR-WEEK ANIMALS. A pattern of response similar to that observed in the 2-week animals was noted in the two, 4-week posttreatment animals, with adaptations occurring in the posterior condylar region, along the posterior border of the ramus, and along the anterior border of the postglenoid spine (Fig. 8). Resorption of bone was also observed under the attachment of the lateral pterygoid muscle anteriorly. The over-all condylar length in both 4-week animals was not significantly different from control values (Table I).

The prechondroblastic-chondroblastic cartilage was significantly hypertrophic in the posterior condylar region, with a thickness three times that seen in normal monkeys (Fig. 9 and Table I). Unlike the 2-week animals, by 4 weeks the posterosuperior region of

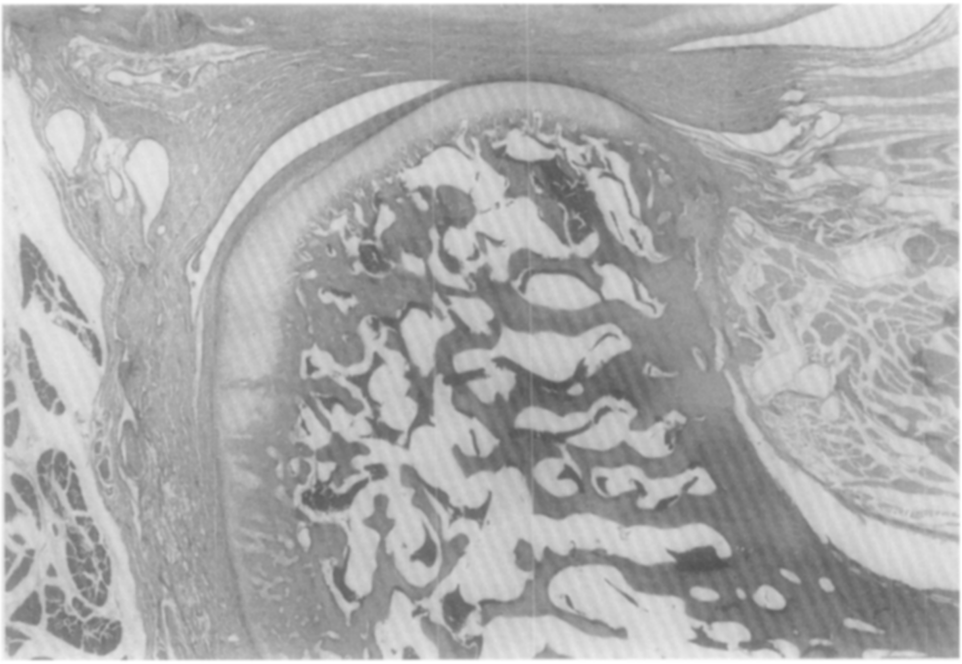

Fig. 5. The temporomandibular joint region of a 2-week experimental animal. Note the increased thickness of the condylar cartilage and the proliferation of bone along the posterior border of the ramus. (Sagittal section. Hematoxylin and eosin stain. Magnification, ×5.)

the condyle was also thicker, exhibiting a 50 percent increase in growth cartilage thickness. The superior region of the condyle remained unaffected.

Six-week animals. The maximum response observed in any animal in the experiment was in one of the 6-week animals (Figs. 10 and 11). In contrast to the normal 200 μm thickness of the posterior growth cartilage, this animal (No. 539) demonstrated an over-all thickness of the subarticular condylar cartilage of 800 μm at 6 weeks. A proportional increase was also observed in the posterosuperior region, but the superior region was not affected (Table I). In this animal, a natural bone marker may be evident. Rapidly forming new bone often has a different staining characteristic than mature bone. As demonstrated in Fig. 12, it is possible to see a line (indicated by the arrows) which may represent the beginnings of an area of new, unremodeled bone which has been deposited secondarily in the area of the condyle, thus providing graphic evidence of the extent of condylar growth during the 6-week period.

The other animal killed at 6 weeks responded in a manner similar to that to the first animal, although the magnitude of the cartilaginous response was less (Table I).

EIGHT TO 24-WEEK ANIMALS. While the growth cartilage continued to exhibit adaptive changes to the altered mandibular position beyond the 6-week interval, the degree of response became progressively less pronounced. The thickness of the growth cartilage in the posterosuperior region was within control values at 8 weeks. In the posterior region, however, an increased thickness of the growth cartilage remained evident through the twelfth week (Table I and Fig. 13).

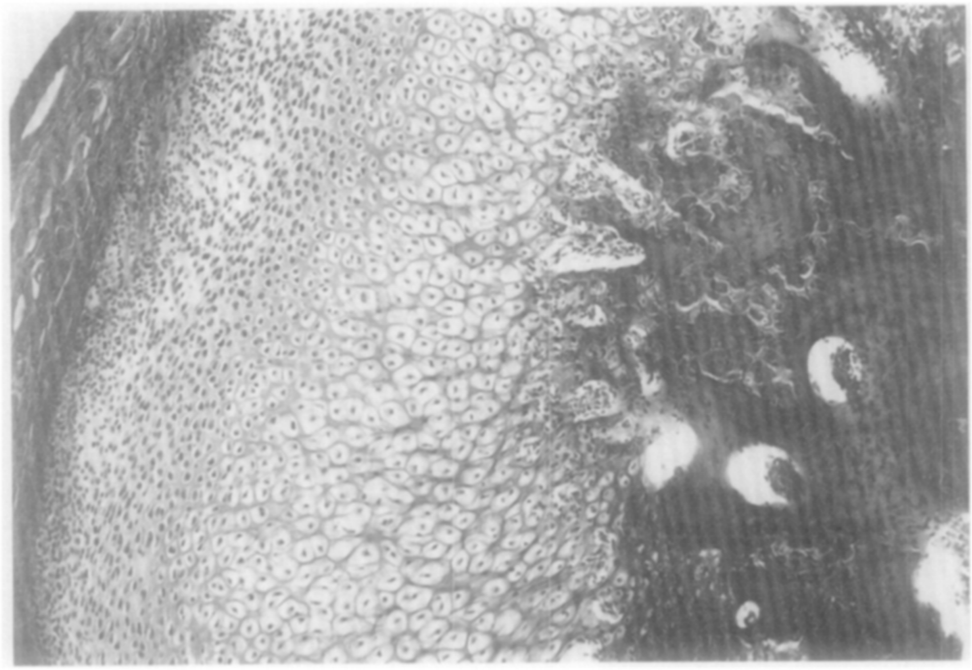

Fig. 6. The condylar cartilage in a 2-week experimental animal. Note the increased proliferation of the cells in the prechondroblastic and chondroblastic zones. (Sagittal section. Hematoxylin and eosin stain. Magnification, ×40.)

By 24 weeks, the thickness of the growth cartilage and the morphology of the condyle as a whole in the experimental sample were indistinguishable from that in the controls. However, more detailed observation revealed an apparent increase in the number of cells in the prechondroblastic layer of the condylar cartilage (Fig. 14).

Summary

Adaptive response of the prechondroblastic-chondroblastic cartilage layer of the specific regions of the condyle was evident within 2 weeks following cementation of the functional protrusion appliance. This adaptive response was most pronounced in the posterior region of the condyle, although there was also a significant increase in the thickness of the prechondroblastic-chondroblastic layer in the posterosuperior region as well. The superior condylar region was not significantly affected by the functional protrusion appliance.

The specific extent and duration of the adaptive response of the growth cartilage to protrusive function is summarized graphically and statistically in a least-squares linear regression analysis (Fig. 15). Regression analysis demonstrated a clear association between the thickness of the prechondroblastic-chondroblastic cartilage layer in both the posterosuperior region ($r = -0.59$, $P < 0.05$) and the posterior region ($r = -0.75$, $P < 0.005$) over the entire 24-week experimental period. This association was most apparent within the first 12 weeks of the experiment, as indicated both by the raw data and by the correlation between thickness and experimental interval following exclusion of the

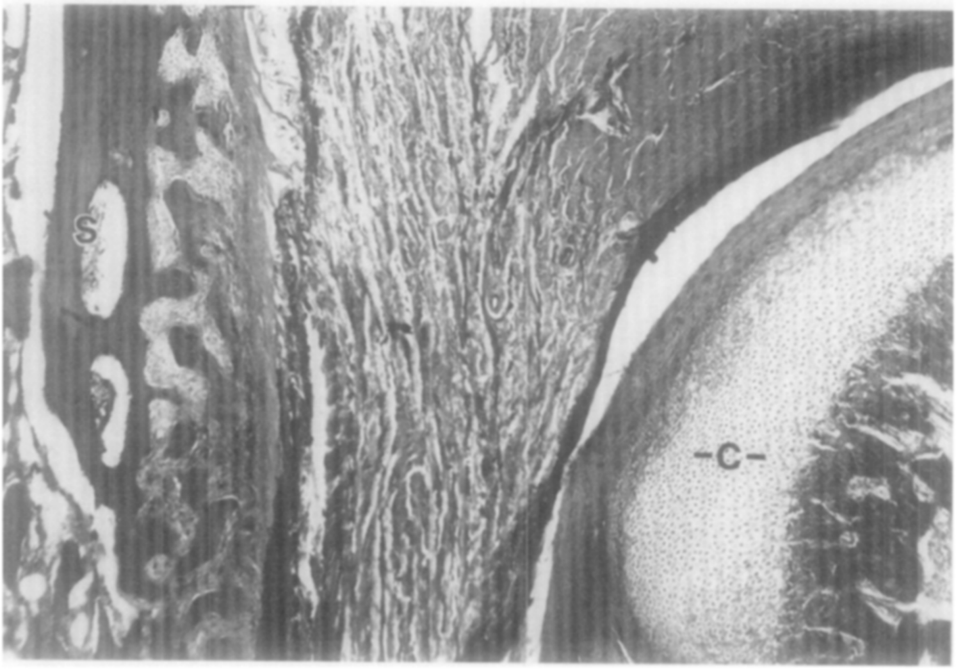

Fig. 7. Adaptations along the anterior border of the postglenoid spine *(S)* in a 2-week experimental animal. Note the increased proliferation of new bone in this region, as well as the increase in the thickness of the condylar cartilage *(C)*. (Sagittal section. Hematoxylin and eosin stain. Magnification, ×25.)

single data point in the 24-week category in the posterior condylar region ($r = -0.81$, $P < 0.001$).

Discussion

The cartilage of the mandibular condyle is unlike most other cartilages of the body. Embryologically, it is not a derivative of the primary cartilaginous skeleton but, like the articular cartilage of the clavicle and the cartilages of the coronoid process and the mental region of the mandible, is secondary in origin.[7, 8, 25, 26, 36] Biochemically, it is distinct from the other growth cartilages of both the craniofacial region and the appendicular skeleton.[1] Morphologically, its various layers appear to be continuous with the two major layers of the periosteum along the neck of the condyle,[4, 37] with the articular layer corresponding to the outer fibrous periosteum, and the prechondroblastic-chondroblastic layer corresponding with the inner osteogenic layer of the periosteum.[9] These observations have led to the conclusion that the cells of the prechondroblastic zone and the preosteoblasts of the remainder of the periosteum of the mandible are homologous.[29] Thus, since it is generally believed that mechanical forces are capable of both stimulating and inhibiting periosteal osteogenesis,[24] it is not illogical to expect that alterations in mandibular function which result in an altered biomechanical or biophysical environment in the temporomandibular joint region ultimately lead to an adaptive response in the cells of the condylar cartilage.

The results of this study provide quantitative data indicating that the morphology of

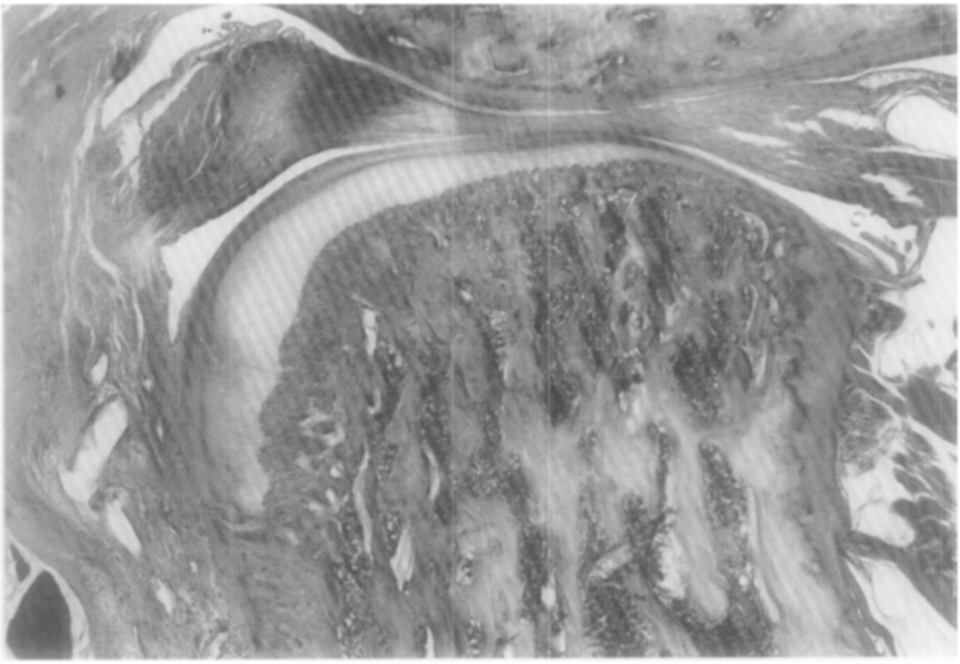

Fig. 8. The temporomandibular joint region of a 4-week experimental animal. Note the increased proliferation of the condylar cartilage, especially in the posterior and posterosuperior regions. (Sagittal section. Hematoxylin and eosin stain. Magnification, ×5.)

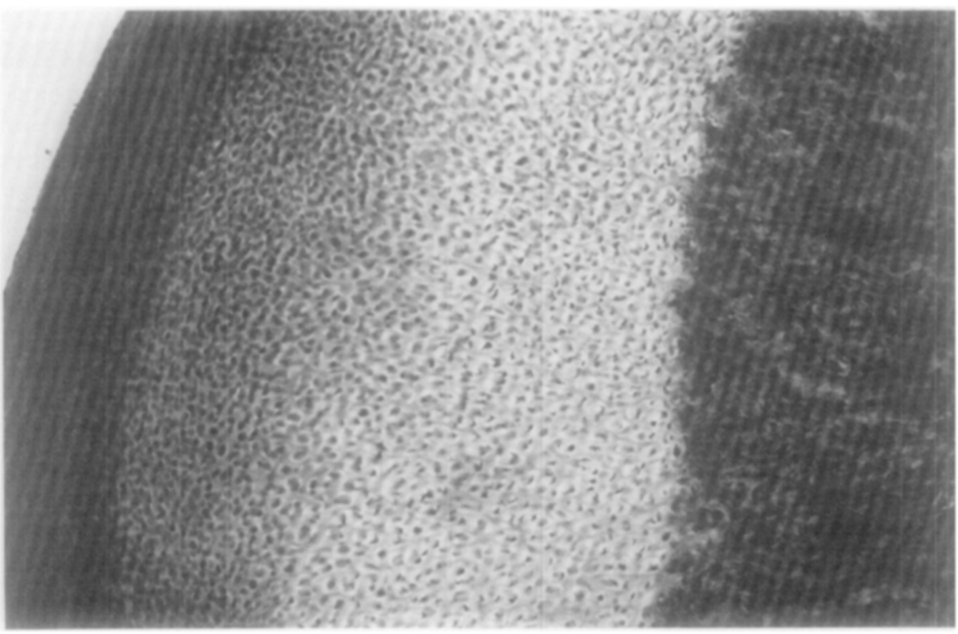

Fig. 9. The condylar cartilage from a 4-week experimental animal. (Sagittal section. Hematoxylin and eosin stain. Magnification, ×40.)

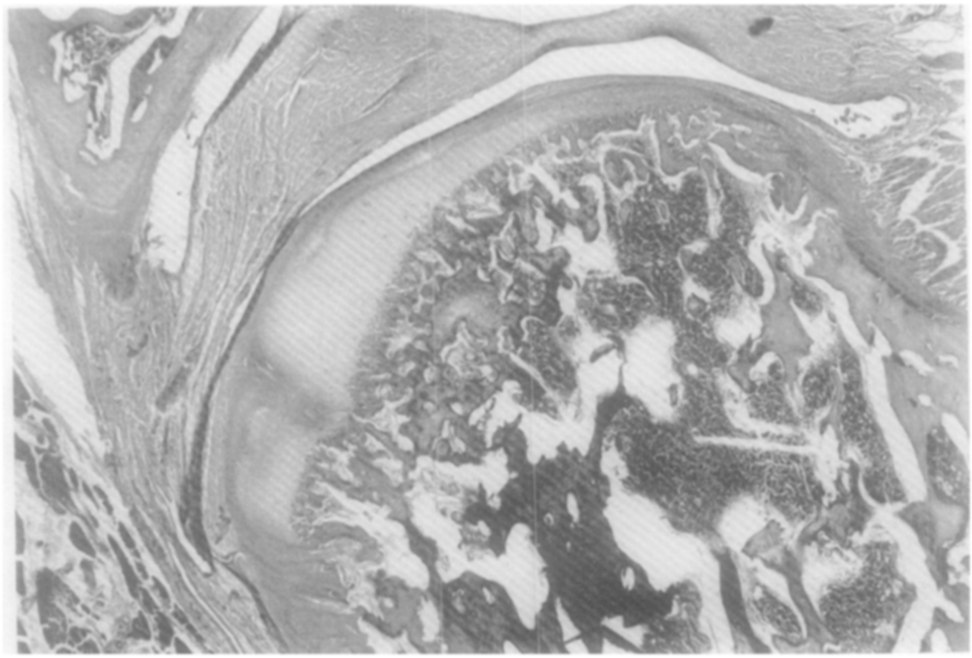

Fig. 10. The temporomandibular joint region in a 6-week experimental animal (No. 539). Note the increased proliferation of the condylar cartilage posteriorly as well as the concomitant increase in bone deposition inferior to the condylar cartilage. (Sagittal section. Hematoxylin and eosin stain. Magnification, ×5.)

the growth cartilage (prechondroblastic-chondroblastic layers) of the mandibular condyle can be predictably influenced by alteration of the biomechanical and biophysical environment of the temporomandibular joint. Functional protrusion of the mandible in growing rhesus monkeys led to an immediate adaptation within the growth cartilage resulting in a thickening of the prechondroblastic-chondroblastic layer, as well as an increase in bone deposition along the posterior border of the ramus immediately below the condylar cartilage.

The adaptive changes were not uniform throughout the condylar cartilage but were primarily localized in the posterior region. Furthermore, the adaptations were clearly time-dependent. There was a dramatic increase in the thickness of the prechondroblastic-chondroblastic layer in the posterior region of the condyle during the first 6 weeks following placement of the protrusive appliance. After this time there was a gradual diminution of the response of the cartilage until, by the twenty-fourth week, the thickness of the prechondroblastic-chondroblastic layer among the experimental sample could not be distinguished from that of the control animals.

The time-dependent component of this adaptive response can be interpreted in two ways. First, the increase in the thickness of the condylar cartilage could be a transient phenomenon, resulting in no permanent increase in the length of the mandible as a whole or change in the size and position of the mandible relative to the rest of the craniofacial complex. Second, the localized increase in the thickness of the cartilage could indicate an

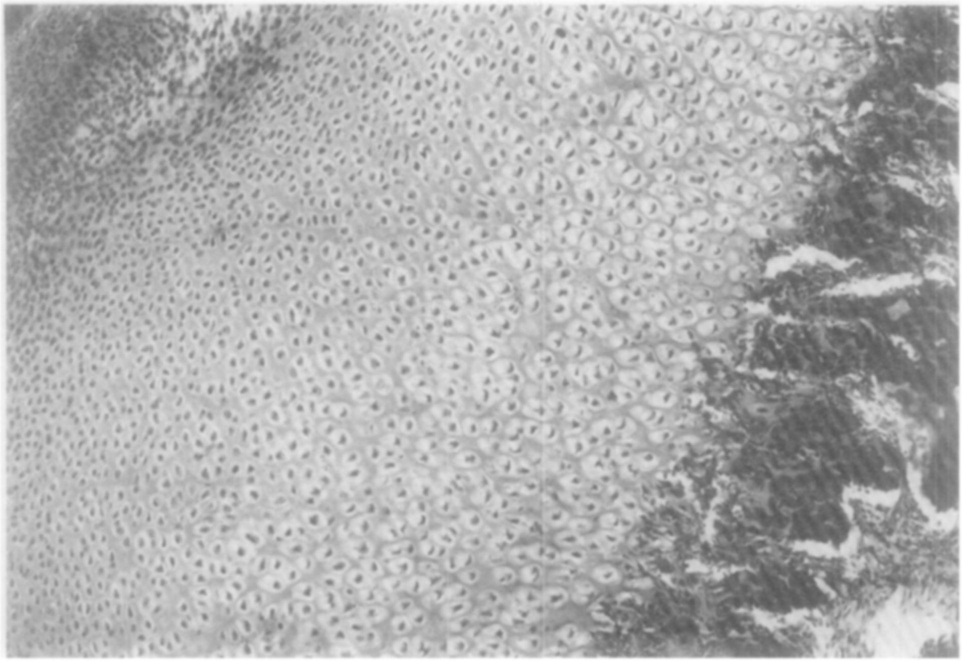

Fig. 11. The condylar cartilage in a 6-week experimental animal (No. 539). Note the extreme increase in the thickness of both the prechondroblastic and chondroblastic zones in comparison to a control (Fig. 3). (Sagittal section. Hematoxylin and eosin stain. Magnification, ×40.)

increase in both the rate and amount of proliferation of chondrocytes in the prechondroblastic-chondroblastic layer, leading to an over-all increase in the size of the mandible.

Related radioautographic and cephalometric studies indicate that the latter interpretation is correct. In an analysis of a subsample of the monkeys used in the present study who were injected with tritiated thymidine prior to death,[22] not only was an increase in the number of dividing cells in the condylar cartilage noted, but there was also an increase in the number of preosteoblasts and osteoblasts in the endosteum. Furthermore, the type and distribution of labeled cells in the experimental animals relative to controls make it clear that the increase in cartilage proliferation is followed closely by an increase in both endochondral bone formation along the endosteal surface of the condyle and periosteal deposition along the posterior condylar neck and anterior postglenoid process. Since radiographic analysis of the experimental group in this study failed to indicate any gross distortion or enlargement of the condyle, the increased bone resorption along the anterior surface of the condyle and condylar neck must have occurred concomitantly with increased bone deposition along the posterior surface. The cephalometric analysis of similar animals in our initial study of this experimental model[10] demonstrated a significant over-all increase in the length of the mandible, both in absolute terms and with respect to the maxilla.

The adaptive response of the prechondroblastic-chondroblastic layer can also be evaluated as it relates to differences of the functional activity of the muscles of mastica-

Fig. 12. The mandibular condyle in a 6-week experimental animal (No. 539). The differences in the staining characteristics of mature and new rapidly forming bone may be observed in this section *(arrows)*. (Sagittal section. Hematoxylin and eosin stain. Magnification, ×25.)

tion. In previous electromyographic analyses of monkeys with functional protrusion appliances,[16-18, 21] we found that the animals tended to reposition the mandible more forward prior to closure in order to avoid appliance interference and occlusal trauma. Associated with the change in position of the mandible, the superior head of the lateral pterygoid muscle gradually increased in activity, with discharges evident during both functional movements and maintenance of postural position. The frequency of tonic discharges increased in successive recordings, usually reaching a maximum at 4 to 8 weeks. These contractions most likely caused the anterior positioning and stabilization of the articular disc and head of the condyle along the articular eminence. The gradual disappearance of modified neuronmuscular patterns at about 8 weeks may be directly or indirectly correlated to the gradual skeletal adaptations that resulted from the experimental procedures. Specifically, it appears that as skeletal adaptations occur (that is, the mandibular condyle becomes re-established structurally within the glenoid fossa), the need for compensatory muscle function is reduced. Thus, there seems to be a correlation in time between the appearance and disappearance of altered neuromuscular function, the activity of the prechondroblastic-chondroblastic layer of the condyle, and the extent of skeletal adaptation. This series of experiments demonstrates the close relationship between form and function in the craniofacial region of the growing individual.

Preliminary studies of intermaxillary traction and of intermaxillary fixation in growing animals[21] indicate that the activity of the lateral pterygoid muscle *per se* may not be

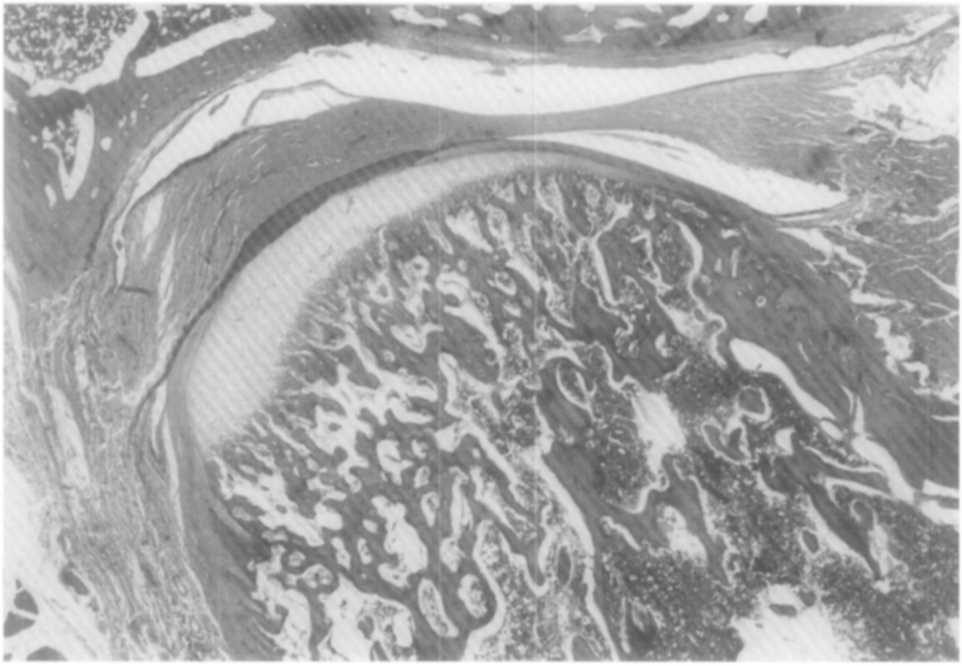

Fig. 13. Temporomandibular joint region in a 12-week experimental animal. A slight amount of increased proliferation along the posterior border of the condyle is still evident in this animal. (Sagittal section. Hematoxylin and eosin stain. Magnification, ×5.)

necessary to produce an adaptive response in the temporomandibular joint region. These ongoing experiments indicate that the critical factor may be the alteration in the biomechanical or biophysical environment of the joint produced by either muscular or nonmuscular (for example, intermaxillary traction) forces which initiates the adaptive response in the temporomandibular region.

One question cannot be answered by the present study: Can the ultimate length of the mandible be increased beyond what would have been expected without experimental intervention? However, a recent study by Petrovic and Stutzmann,[32] in which hyperpropulsor devices were used on rats during their growth period has shown that there was a statistically significant increase in the over-all length of the mandibles of the experimental animals when compared to untreated controls after both groups had reached adulthood. Since the results of Petrovic and co-workers' previous experiments have been similar to those of our monkey studies in the past, we expect that similar long-term studies in primates would yield similar results.

SUMMARY AND CONCLUSIONS

Twenty-eight juvenile rhesus monkeys *(Macaca mulatta)* were used in an experimental study of temporomandibular joint adaptations to protrusive function. Cast maxillary and mandibular onlays which prompted the mandible to function in an anterior and inferior position were placed in fourteen animals, with additional animals used as con-

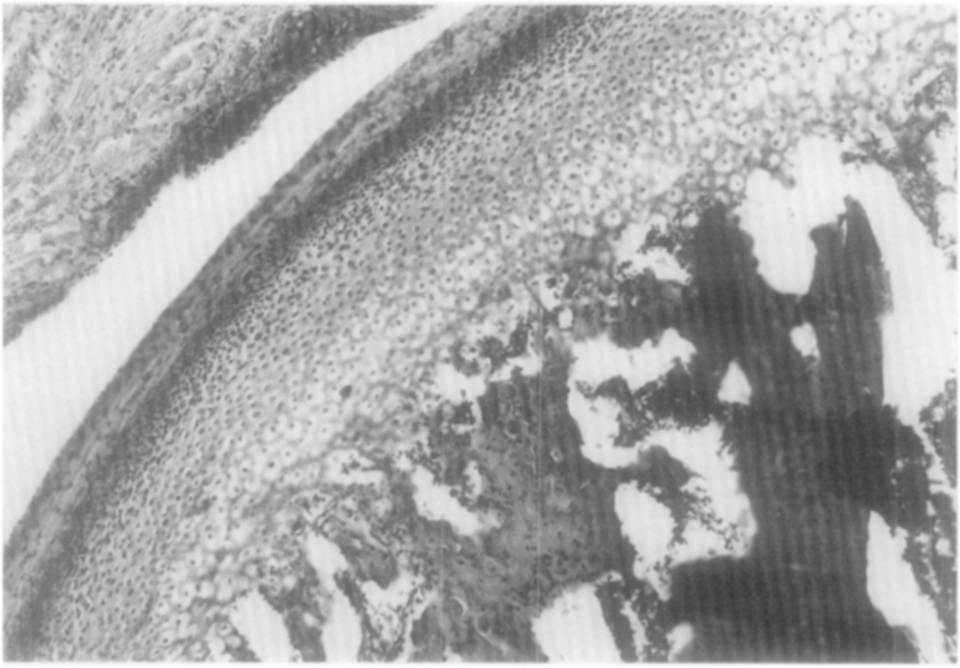

Fig. 14. The temporomandibular joint region of the 24-week experimental animal. Although the over-all thickness of the condylar cartilage is not different from that of the control animals, there is an apparent increase in the number of cells in the prechondroblastic zone. This observation has been verified by radioautographic analysis.[13] (Sagittal section. Hematoxylin and eosin stain. Magnification, ×40.)

trols. The experimental animals were killed at various intervals from 2 to 24 weeks following appliance placement. Adaptation in the temporomandibular joint region was analyzed qualitatively and quantitatively using sagittal histologic sections.

Adaptive responses were observed in the prechondroblastic-chondroblastic (growth) layer of the condylar cartilage within 2 weeks following cementation of the appliance. They reached a maximum at 4 to 6 weeks and then gradually diminished in intensity after that time. The adaptive response was first observed along the posterior border of the mandibular condyle, with adaptations later occurring in the posterosuperior region. No alteration in the growth of the superior region of the condyle was observed. Regression analysis demonstrated a clear association between the thickness of the prechondroblastic-chondroblastic layer of the condylar cartilage and the interval following appliance placement.

This study demonstrates that significant adaptive responses can occur in the mandibular condyle of the juvenile rhesus monkey following alteration in the functional position of the mandible. Since the cartilage of the mandible condyle appears to be homologous to periosteum and not to the cartilages of the cranial base and long-bone epiphyses, one can hypothesize that the cartilage of the mandibular condyle is highly responsive to changes in the biomechanical and biophysical environment of the temporomandibular joint region during growth. The results of the study support this hypothesis.

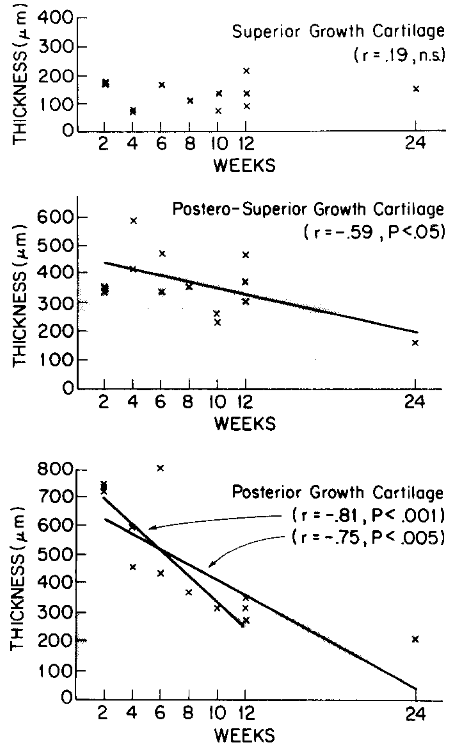

Fig. 15. Least-squares regression analysis of adaptive responses in the thickness of the three regions of the prechondroblastic-chondroblastic cartilage of the condyle relative to treatment duration. Data points for each experimental animal are indicated by an *X*. Stippled area indicates the range of condylar thickness to the first standard deviation in normal juvenile rhesus monkeys.[2]

We would like to acknowledge the technical assistance of Ms. M. Christine McBride and Ms. Jody Ungerleider. Illustrations are by Mr. William C. Brudon.

REFERENCES

1. Baume, L. J., and Derichsweiler, H.: Is the condylar growth center responsive to orthodontic therapy? An experimental study in *Macaca mulatta,* Oral Surg. **14:**347-362, 1961.
2. Breitner, C.: Experimentelle Veranderung der mesiodistalen Beziehungen der oberen und unteren Zahnreihen, Z. Stomatol, **28:**343-356, 1930.
3. Brigham, G. P., Sealetta, L. J., Johnston, L. E., Jr., and Occhino, J. C.: Antegenic differences among condylar, epiphyseal, and nasal septal cartilage. *In* McNamara, J. A., Jr. (editor): Biology of occlusal development, Monograph No. 7, Craniofacial Growth Series, Ann Arbor, 1977, Center for Human Growth and Development, The University of Michigan.
4. Carlson, D., McNamara, J. A., Jr., and Jaul, D. H.: Histological analysis of the growth of the mandibular condyle in the rhesus monkey *(M. mulatta),* Am. J. Anat. **151:**103-118, 1978.
5. Charlier, J.-P., Petrovic, A., and Herrmann-Stutzmann, J.: Effects of mandibular hyperpropulsion on the prechondroblastic zone of young rat condyle, Am. J. Orthod. **55:**71-74, 1969.
6. Colico, G. L.: Le modificazoni dell'A.T.M. del *Macacus rhesus* a seguito di apparecchi fissi, Rass. Int. Stomatol. Prat. **9:**41-45, Suppl. 4, 1958.
7. Durkin, J. F.: Secondary cartilage: A misnomer? Am. J. Orthod. **62:**15-41, 1972.
8. Durkin, J. F., Heeley, J. D., and Irving, J. F.: The cartilage of the mandibular condyle, Oral Sci. Rev. **2:**29-99, 1973.

9. Duterloo, H. S., and Jansen, H. W. B.: Chondrogenesis and osteogenesis in the mandibular condylar blastema, Trans. Eur. Orthod. Soc., pp. 109-118, 1969.
10. Elgoyhen, J. C., Moyers, R. E., McNamara, J. A., Jr., and Riolo, M. L.: Craniofacial adaptation to protrusive function in young rhesus monkeys, AM. J. ORTHOD. **62:**469-480, 1972.
11. Hall, B. K.: Developmental and cellular skeletal biology, New York, 1978, Academic Press, Inc.
12. Haupl, K., and Psansky, R.: Experimentelle Untersuchungen über Gelenktransformation bei Verwendung der Methoden der Funktionskieferorthopaedie, Dtsch. Zahn, Mund, Kieferheild, **6:**439-448, 1939.
13. Hiniker, J. J., and Ramfjord, S. P.: Anterior displacement of the mandible in adult rhesus monkeys, J. Prosthet. Dent. **16:**503-512, 1966.
14. Hurme, V. O., and Van Wagenen, G.: Basic data on the emergence of permanent teeth in the rhesus monkey *(M. mulatta),* Proc. Am. Phil. Soc. **105:**105-116, 1961.
15. Kanouse, M. C., Ramfjord, S. P., and Nasjleti, C. E.: Condylar growth in rhesus monkeys, J. Dent. Res. **48:**1171-1176, 1969.
16. McNamara, J. A., Jr.: Neuromuscular and skeletal adaptations to altered orofacial function, Monograph No. 1, Craniofacial Growth Series, Ann Arbor, 1972, Center for Human Growth and Development, The University of Michigan.
17. McNamara, J. A., Jr.: Neuromuscular and skeletal adaptations to altered function in the orofacial regions, AM. J. ORTHOD. **64:**578-606, 1973.
18. McNamara, J. A., Jr.: Functional adaptability of the temporomandibular joint, Dent. Clin. North Am. **19:**459-471, 1975.
19. McNamara, J. A., Jr.: The role of muscle and bone interaction in craniofacial growth. *In* McNamara, J. A. (editor): Control mechanisms in craniofacial growth, Monograph No. 3, Craniofacial Growth Series, Ann Arbor, 1975, Center for Human Growth and Development, The University of Michigan, Ann Arbor, 1975.
20. McNamara, J. A., Jr.: Experimentelle Untersuchungen des Unterkieferwachstums, Informat. Orthod. Kieferorthopad. **7:**219-243, 1976.
21. McNamara, J. A., Jr.: Functional determinants of craniofacial size and shape, Eur. Orthodont. J. (In press.)
22. McNamara, J. A., Jr., and Carlson, D. S.: Unpublished data.
23. McNamara, J. A., Jr., Connelly, T. G., and McBride, M. C.: Histological studies of temporomandibular joint adaptations. *In* McNamara, J. A., Jr. (editor): Determinants of mandibular form and growth, Monograph No. 4, Craniofacial Growth Series, Ann Arbor, 1975, Center for Human Growth and Development, The University of Michigan.
24. Meikle, M. C.: *In vivo* transplantation of the mandibular joint of the rat; an autoradiographic investigation into cellular changes at the condyle, Arch. Oral Biol. **18:**1011-1020, 1973.
25. Moffett, B. C.: The prenatal development of the human temporomandibular joint, Carnegie Inst. Contrib. Embryol. **36:**19-28, 1955.
26. Moffett, B. C.: The morphogenesis of the temporomandibular joint, AM. J. ORTHOD. **52:**401-415, 1966.
27. Oudet, C., and Petrovic, A. G.: Variations in the number of sarcomeres in series in the lateral pterygoid muscle as a function of the longitudinal deviation of the mandibular position produced by the postural hyperpropulsor. *In* Carlson, D. S., and McNamara, J. A., Jr.: Muscle adaptation in the craniofacial region, Monograph No. 8, Craniofacial Growth Series, Ann Arbor, 1978, Center for Human Growth and Development, The University of Michigan.
28. Petrovic, A.: Recherches sur les mecanismes histophysiologique de la croissance osseuse cranio-faciale, Ann. Biol. **9:**303-311, 1970.
29. Petrovic, A.: Mechanisms and regulation of mandibular condylar growth, Acta. Morphol. Neerl. Scand. **10:**25-34, 1972.
30. Petrovic, A., Oudet, C., and Gasson, N.: Variations du nombre de sarcomeres en serie dans le muscle pterygoidien externe en fonction de la propulsion et de la retropulsion mandibulaire du jeune rat, J. Physiol. (Paris) **67:**213, 1973.
31. Petrovic, A., Oudet, C., and Gasson, N.: Effets des appareils de propulsion et de retropropulsion mandibulaire sur le nombre des sarcomeres en serie du muscle pterygoidien externe et sur la croissance du cartilage condylien du jeune rat, Orthod. Fr. **44:**191, 1973.
32. Petrovic, A. G., and Stutzmann, J.: Effect of periodic forward repositioning of the rat mandible on the condylar cartilage growth rate. *In* Carlson, D. S. (editor): Craniofacial biology, Monograph No. 10, Craniofacial Growth Series, Ann Arbor, Center for Human Growth and Development, The University of Michigan. (In press.)

33. Petrovic, A., Stutzman, J., and Oudet, C.: Control processes in the postnatal growth of the mandibular condylar cartilage. *In* McNamara, J. A., Jr. (editor): Determinants of mandibular form and growth, Monograph No. 4, Craniofacial Growth Series, Ann Arbor, 1975, Center for Human Growth and Development, The University of Michigan.
34. Ramfjord, S. P., Walden, J. M., and Enlow, R. D.: Unilateral junction and the temporomandibular joint in rhesus monkeys, Oral Surg. **32**:236-247, 1971.
35. Stockli, P. W., and Willert, H. G.: Tissue reactions in the temporomandibular joint resulting from anterior displacement of the mandible of the monkey, AM. J. ORTHOD. **60**:142-155, 1971.
36. Symons, N. B. B.: A histochemical study of the secondary cartilage of the mandibular condyle in the rat, Arch. Oral Biol. **10**:579-584, 1965.
37. Wright, D. M., and Moffett, B. C., Jr.: The postnatal development of the human temporomandibular joint, Am. J. Anat. **141**:235-250, 1974.
38. Zimmerman, H. I.: The normal growth and remodeling of the temporomandibular joint of *Macaca mulatta*, M. S. Thesis, University of Washington, Seattle, 1971.