Functional Adaptations in the Temporomandibular Joint

*James A. McNamara, Jr., D.D.S., Ph.D.**

In the practice of orthodontics, about 50 to 70 per cent of our patients have some degree of anteroposterior discrepancy in the maxillomandibular relationship. The most commonly occuring jaw discrepancy is "distoclusion" or the Angle Class II malocclusion. This type of malocclusion is characterized by a distal or posterior relation of the mandibular dental arch to the maxillary dental arch. The clinical condition can be caused by a protrusion or anterior positioning of the maxillary dental arch or of the whole nasomaxillary complex, by a retruded positioning of the mandibular dental arch or of the mandible itself, by imbalances in the cranial base and cranial floor regions, or by a combination of various factors including those mentioned above.

EXTRINSIC VS. INTRINSIC FORCES

The orthodontist is interested in correcting any maxillomandibular discrepancy with whatever therapeutic means are most appropriate functionally and esthetically for the individual patient. A protruded maxilla can be treated by using extraoral traction. Similarly, mandibular deficiencies are commonly treated by two types of therapeutic approaches: intermaxillary traction and functional jaw orthopedics. Both these procedures change the oral environment and influence the subsequent growth of the associated hard and soft tissues. However, the forces generated by these therapeutic approaches can be differentiated into two categories: forces *extrinsic* to the individual (elastic traction) and forces *intrinsic* to the individual (neuromuscular function). In this article we will consider the effect of induced extrinsic and intrinsic

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*Assistant Professor of Anatomy and Associate Research Scientist, Center for Human Growth and Development, University of Michigan, Ann Arbor, Michigan

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forces upon the growth and remodeling of the temporomandibular joint, a significant participant in the growth of the lower jaw. We will ask two questions: (1). Does functional adaptation occur in the temporomandibular joint as a result of an altered force or function? (2) If functional adaptation is induced, what are the underlying mechanisms leading to this adaptation?

Extrinsic Forces

As mentioned earlier, one approach to the correction of Class II malocclusion is the use of intermaxillary force. During the application of this type of force the mandible is displaced anteriorly, and mesial migration of the lower buccal segments usually occurs. There have been several experimental studies concerning the use of this type of extrinsic force in monkeys which have considered both changes within the dentition and within the mandibular condyle. In the study by Payne,[14] forces in the range of 20 to 30 gm produced significant migration of the lower molars in juvenile rhesus monkeys and also led to some remodeling changes in the temporomandibular articulation. However, Payne stated that the changes occurring in these articulations were not of a magnitude that would lead to the correction of a skeletal malocclusion. He found no evidence of change in the morphology of the condyle nor of increased growth in the condylar cartilage. The application of similar extrinsic forces in rats by Petrovic et al.[16] resulted in no significant increase in the proliferation of the cells of the condylar cartilage.

Adams et al.[1] placed cast gold splints over the maxillary and mandibular dentitions of young monkeys and then generated Class II forces of 75 to 150 gm. At the end of the experimental period, some changes were noted in the temporomandibular joint region. Condylar ossification appeared to be directed more posteriorly than normal and the shape of the condyle became less rounded. Adams et al. interpreted these findings as an alteration in the direction, but not necessarily in the amount of condylar growth. A Class II intermaxillary force applied to adult monkeys produced definite histologic changes along the articular eminence, but no increase in the amount or direction of condylar growth was evident.

These experimental studies have shown that whereas tooth migration can be induced by the use of Class II intermaxillary force, functional adaptation (i.e., alterations in the amount and direction of growth) of the temporomandibular joint does not readily occur. The forward displacement of the mandible by elastic traction does not *in itself* appear to result in significant growth and remodeling within the temporomandibular joint.

Intrinsic Forces

A second approach to the correction of a distal mandibular relationship is through the use of functional jaw orthopedics. There are a number of therapeutic appliances which are designed to change the function of the orofacial musculature. Skeletal adaptation is assumed to result from intrinsic craniofacial tissue remodeling responses, rather than from direct changes produced by extrinsic mechanotherapy.

While there seems to be a general agreement that dentoalveolar changes and alterations in maxillary growth can be achieved through the use of functional appliances, there is much disagreement as to the effects of functional jaw orthopedics on mandibular growth. A review of the literature in this area[10] reveals numerous clinical studies which have produced widely varying results. Some of these discrepancies have resulted from (1) the use of different diagnostic criteria and measuring techniques; (2) the erroneous assumption that all functional appliances have the same mechanism of action (e.g., the Activator[3] vs. Frankel's Functional Regulator); and (3) the wide variation in patient motivation and cooperation during clinical studies.

PREVIOUS EXPERIMENTAL STUDIES

Recognizing the shortcomings of clinical studies, researchers have turned to well controlled experiments to study the relationship of altered function to mandibular growth. The close interaction between form and function has been extensively studied in a series of primate experiments, in which various devices were fabricated to prompt the development of an altered functional position of the lower jaw (Fig. 1*A*). Craniofacial adaptations associated with the use of these devices have been studied either cephalometrically or histologically by a number of investigators.[4-7, 9, 10, 12, 13, 18] In most instances, the dentitional alterations achieved in these studies could be characterized by a change from a normal molar relationship (Class I) to a relative forward relationship of the lower molars (Class III) (Fig. 1*B*). This response is similar in many respects to the correction of a Class II malocclusion to a normal Class I molar relationship. Various skeletal and dental changes have been observed in both the mandible and maxilla, as well as in other parts of the skull of the monkey.

Do structural adaptations occur in the temporomandibular joint as a result of altered function? As in the human studies, conflicting results were reported from some of the earlier nonhuman primate experiments. Hiniker and Ramfjord[9] found that the temporomandibular joint was extremely stable and resistant to changes in occlusal relationship. They stated that the amount of adaptation observed in the temporomandibular joint was insignificant in affecting or changing skeletal relations. Similarly, Colico[6] found both pathologic and metaplastic changes in the temporomandibular joint after anterior displacement of the mandible. In contrast, Breitner,[5] Baume and Derichsweiler,[4] and Stockli and Willert[18] reported that the condylar cartilage

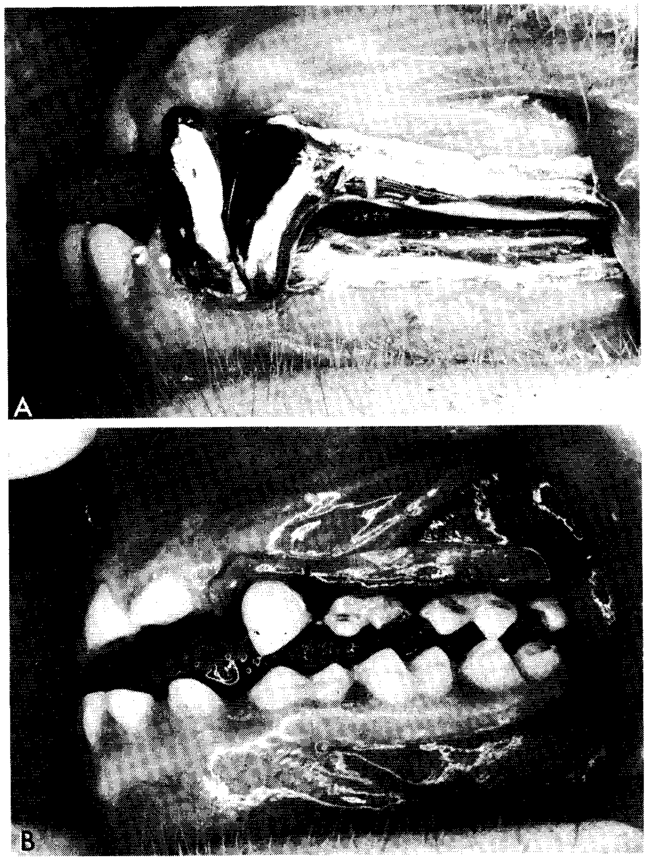

Figure 1. *A*, Cemented maxillary and mandibular overlays, typical of appliances used in our experiments. *B*, Intraoral view of a juvenile animal after the appliances have been removed at the end of the experimental period. Note the Class III molar and cuspid relationship. Compensatory drifting of the incisors masks some of the alterations anteriorly.

was capable of exhibiting compensatory tissue responses following experimental alteration of the mandibular functional position. It is interesting to note that the first two studies mentioned (Colico, Hiniker and Ramfjord) utilized *nongrowing* animals, and that the differences in and magnitude of the response of the temporomandibular joint may be due in part to the variation in the age of the animals used in the studies. Thus the maturational level of the individual seems to be one factor influencing the ability of the temporomandibular joint to adapt to altered function.

INTEGRATED EXPERIMENTAL STUDIES

Many investigators have assumed that the experimentally produced adaptations in the skeletal elements of the craniofacial complex

were due to altered demands of the associated musculature. Yet the "functional nature" of the orofacial adaptation has not been adequately defined. Most of the previous investigations have employed one study technique in the analysis of craniofacial disproportions, but only recently have various investigations been carried out which approached the problem of function and the effects of function from a multiple-technique point of view.

For the last several years, our laboratory has conducted studies involving various types of experimental alteration of craniofacial growth.[7, 10-13] Of particular interest to us have been studies of functional mandibular protrusion resulting from alterations in patterns of muscle activity. Thirty-five rhesus monkeys (Macaca mulatta) of various age levels have been used as experimental animals in our protrusive experiments. In our initial study,[7] a statistically significant increase in both the rate and extent of growth in the mandibular condyle was recorded after functional protrusion was created for a five month period. Structural adaptations were noted in the temporomandibular region of the six juvenile monkeys used in this study. In a subsequent cephalometric, electromyographic, and histologic study,[10, 12] certain correlations existed between the occurrence and disappearance of altered muscle function and the re-establishment of skeletal balance.

Neuromuscular Adaptations

What is the relationship between altered muscle function and skeletal adaptation? First, alterations within the neuromuscular system, particularly changes in the electromyographic activity of specific orofacial muscles, were considered. The superior head of the lateral pterygoid muscle[11] appeared to assume an active role in the determination of anteroposterior mandibular position. The lateral pterygoid muscle gradually increased in activity after appliance cementation, with muscular discharges evident in functional movements and during the maintenance of the mandibular postural position (Fig. 2). The frequency of tonic discharges increased in successive recordings, usually reaching a maximum at four to eight weeks. After this time there was a gradual reduction in the frequency and duration of this altered lateral pterygoid activity. In many animals, a "normal" pattern of muscle function reappeared at 12 to 24 weeks after appliance cementation.

Skeletal Adaptations

At the end of the experimental period, it appeared as though most of the animals had skeletally adapted to the experimentally induced changes. Cephalometrically, the mandibular condyles had regained their original anatomic orientation in the glenoid fossa of the temporal bone. In general, the specific nature of the skeletal adaptation could be directly related to the maturational level of the animal. In the mandi-

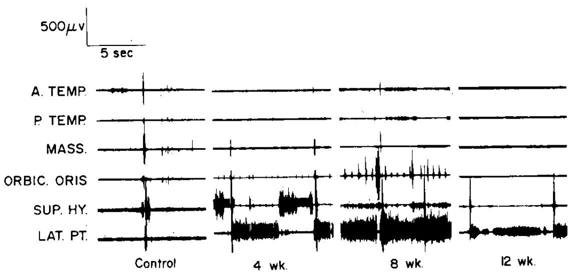

Figure 2. Overview of typical muscle activity during the experimental period. In the control records the superior head of the lateral pterygoid functioned during such movements as chewing, clenching, and swallowing, but not alone during the maintenance of the mandibular postural position. After appliance cementation the lateral pterygoid gradually increased in activity not only during functional movements but also during postural maintenance. This activity was usually maximal by eight weeks and then reduced by the end of the experimental period.

bles of adolescent and adult animals, compensatory tooth movement was usually observed, while in the younger animals alterations in the *amount* and/or the *direction* of condylar growth were evident. No significant alteration in condylar growth was noted in the mature animals during the time period studied, although these findings do not preclude the possibility of adaptation occurring over longer periods of time.

Musculoskeletal Interaction

As skeletal adaptations occurred, regardless of their specific nature, the need for compensatory muscle function (e.g., lateral pterygoid activity) was reduced. The *timing* of the appearance and disappearance of altered functional patterns was related to the rate and extent of skeletal and dentoalveolar adaptation. In our initial protrusive study,[7] monthly condylar growth increments were measured, and significant increases in the extent of growth within the mandibular condyle were noted. However, the rate of growth varied according to the time interval after appliance cementation. The increased growth rates of the experimental animals tended to occur during the first three months, with a peak occurring in the second month. At four months, however, the growth rate of the experimental animals was not significantly different from that of the controls. It is important to note that the maximal rate of condylar growth in these animals was during the second month. Maximal adaptive neuromuscular activity appeared just prior to or during this time (Fig. 2). A decreased rate of adaptive skeletal growth can be assumed to indicate that structural balance had been almost entirely restored by the fourth month. The activity of the superior head of the lateral pterygoid was reduced by this time as well (Fig. 2). Thus there seemed to be a correlation in time between the appearance and disappearance of altered neuromuscular function and the occurrence of skeletal and dentoalveolar adaptations.

A similar comparison can be made with histologic finding of temporomandibular joint adaptation. Stockli and Willert,[18] in a study of protrusive function in young monkeys, observed certain structural adaptations within the head of the condyle at specific time intervals. Increased proliferation of condylar cartilage and increased endochondral ossification were observed at approximately one and two months, respectively. However, no evidence of alterations in tissue response was reported at either the four month interval or at any succeeding intervals. Stockli and Willert hypothesized that all the experimental animals passed through the same sequence of tissue response, but all evidence of adaptation was ultimately removed by normally occurring internal remodeling processes.

Preliminary results from our histologic and autoradiograpic study of seven monkeys sacrificed at two week intervals after appliance cementation seem to support Stockli and Willert's finding (Fig. 3). Evidence of increased proliferation of the cells of the condylar cartilage was evident as early as two weeks after the change in the oral environment was induced. The proliferation of the condylar cartilage reached a maximum at six weeks and then gradually became reduced during succeeding time intervals. These findings again correlate chronologically with the skeletal growth rates noted in our initial studies, and with the appearance and disappearance of the altered function of the lateral pterygoid muscle.

We have postulated a general sequence of adaptation to the occlusal overlay which prompted all oral function to occur in a foward position. First, the exteroceptive and proprioceptive stimuli from the orofacial area are altered by the introduction of an appliance. Existent patterns of muscle activity are interrupted and subsequently reorganized, causing a change in the maxillomandibular functional relationship (Fig. 4*A*). This change in functional pattern alters the orofacial environment in such a way that structural adaptations eventually result, and anatomic balance is eventually restored. As this occurs, neuromuscular compensation correspondingly declines, and functionally more efficient patterns of muscle activity develop (Fig. 4*B*).

The results of the above studies seem to indicate that the temporomandibular joint can structurally adapt to changes in altered neuromuscular function, and that a change in muscle function is an essential factor in producing structural adaptations. There is a temporal correlation between the appearance and disappearance of altered muscle function and the associated skeletal adaptations. The specific nature and location of the skeletal and dentoalveolar adaptations vary according to the age of the experimental animal.

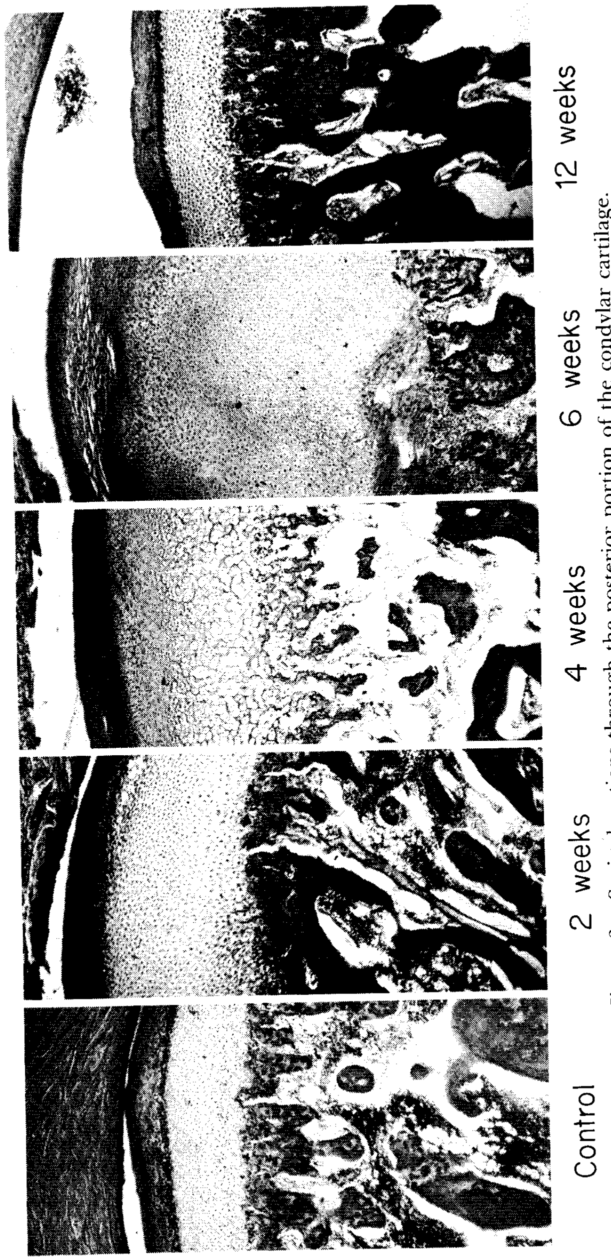

Figure 3. Sagittal sections through the posterior portion of the condylar cartilage. The thickness of the condylar cartilage in the control section is representative of seven nontreated animals. Increased cartilage proliferation is evident at two weeks with maximal cellular proliferation occurring at six weeks. By 12 weeks, the proliferation of the condylar cartilage is much less evident and most bony remodeling has been completed (Hematoxylin and eosin, 25×).

POST-TREATMENT ADAPTATIONS

The most frequently asked questions regarding the results of these experimental studies have been: "What happens when the appliances are removed? Is the experimental adaptation maintained, or does relapse or rebound occur?" Of the 35 animals in our protrusive studies, the appliances were removed in eight animals (six young and two mature), and these animals were allowed to continue their normal activities without *any type* of retention appliance. These monkeys have been followed cephalometrically and electromyographically for three months to two years after appliance removal.[13]

Neuromuscular Adaptations

As we saw previously, an alteration in the oral environment (in this instance, the removal of the cast gold overlay) resulted in adaptations in neuromuscular function. By removing the appliances, a new skeletal imbalance was created, and again we saw alterations in the activity of certain orofacial muscles, particularly in the lateral pterygoid. These al-

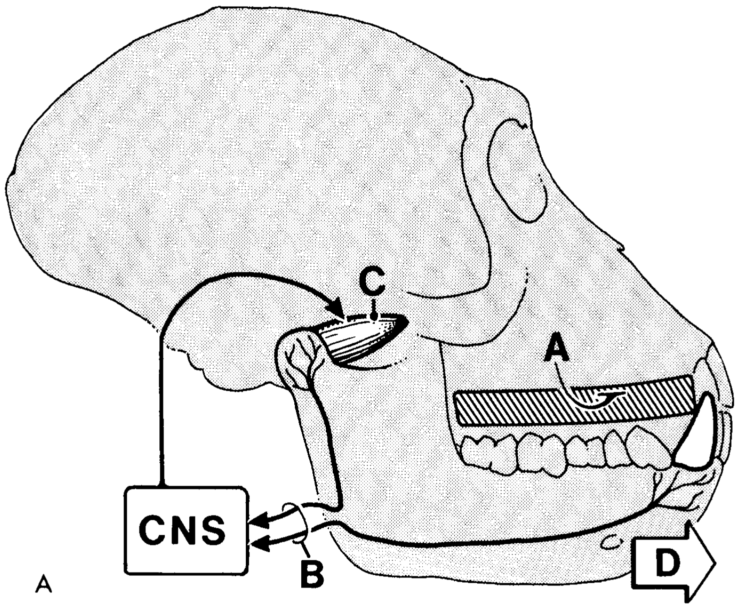

Figure 4. *A*, Sequence of musculoskeletal adaptations. (*A*), Placement of the appliance. (*B*), Alterations in exteroceptive and proprioceptive stimuli as represented by receptors in the dentition and the temporomandibular joint, are transmitted to the central nervous system (*CNS*). (*C*), This change in sensory stimuli eventually results in a complex pattern of altered neuromuscular function represented schematically by contraction of the superior head of the lateral pterygoid muscle. (*D*), This results in a forward function position of the mandible.

(*Figure 4 continues on following page.*)

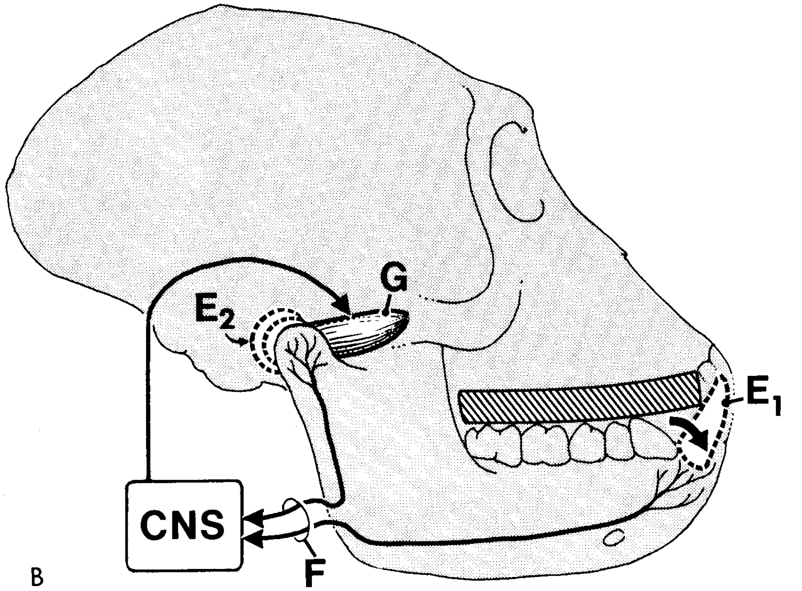

Figure 4 (*Continued*).

B, The nature of the skeletal adaptations depends upon the maturation level of the animal. (E_1), One of the dentitional adaptations observed in the mature animals. (E_2), One of the skeletal changes occurring in the younger animals. (*F*), Alterations in oral sensory stimuli again occur resulting in (*G*), a decline in corresponding neuromuscular compensations and the development of more efficient muscle patterns. (*From* McNamara, J. A., Jr.: Neuromuscular and skeletal adaptations to altered function in the orofacial region. Am. J. Orthodont. *64*:578–606, 1973, with permission.)

terations were most prominent during the first few months of the post-treatment period, and resembled to some extent the electromyographic patterns observed during the earlier experimental period. The changes in muscle pattern gradually disappeared during the post-treatment interval.

Skeletal Adaptations

The skeletal adaptations observed during the post-treatment period can best be described by first considering the maturational level of the animal.

*1. **Mature Animals.*** As mentioned earlier, the most significant skeletal adaptations in the adolescent and adult animals during the experimental period occurred in the dentoalveolar areas. During the post-treatment period the animals returned to their original occlusal relationships, again by dentoalveolar adaptation, with little significant change in maxillary or mandibular skeletal growth.

*2. **Young Animals.*** The changes during the post-treatment period in the young animals varied from total retention to total rebound. Of the six experimental animals, two maintained a Class III molar relationship, two returned to the original Class I molar relationship (at least on one side), and two lost about half of the experimentally induced change. Although adaptive changes occurred throughout the craniofacial complex, only mandibular adaptations are considered in this report.

As described previously, changes in condylar growth during the experimental period in the young animals were characterized by alterations in both the *amount* and *direction* of growth of the mandibular condyle. After the appliances were removed changes were again noted in the growth of the mandibular condyle. The amount of condylar growth was reduced during the post-treatment period and the direction of growth was altered vertically. For example, one juvenile animal was monitored during a 15 month experimental period (during which three successive appliances were used) followed by a 14 month post-treatment period (Fig. 5). There was a decrease in the amount of growth at the posterosuperior border of the condyle during the post-treatment period (13 mm experimental, 9 mm post-treatment. An even greater difference was evident in the anteroposterior component of condylar growth (12 mm experimental, 7 mm post-treatment). The amount of vertical growth during both periods was the same (7 mm). In another animal, there was a 2 mm reduction in growth during the post-treatment when measured at condylion, but the expression of this change was 5 mm when measured in an anteroposterior dimension.

Alterations in maxillary growth and differential movement of the dentition also accounted for some of the post-treatment changes. The migration and interdigitation of the upper and lower dentition was a major factor in determining the maintenance or lack of mantenance of an experimentally induced result.

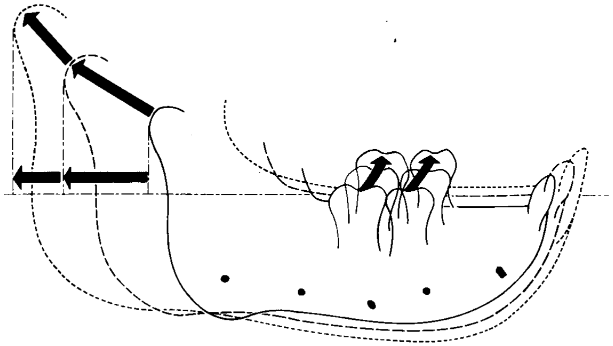

Figure 5. Growth of the mandible in a young animal during a 15 month experimental period followed by a 14 month post-treatment period. Note that the greater amount of condylar growth occurred during the experimental period. After appliance removal the amount of condylar growth was reduced and the direction of condylar growth became more vertically oriented. This animal has maintained a full tooth Class III molar relationship three years after appliance removal.

Musculoskeletal Interaction

The results of these studies indicate that when an appliance is removed at the end of an experimental period, a new "experimental" situation is created in which the oral environment is altered, new neuromuscular adaptive patterns are established, and skeletal adaptations occur. Alterations in both the amount and direction of condylar growth in the young animals are evident during the post-treatment phase. The *amount* of condylar growth during the post-treatment period is less than the experimental period and the expression of this growth in an anteroposterior *direction* of condylar growth is even more reduced, approaching values observed during the control period. The amount of post-treatment change in the structures of the craniofacial region is based to a large extent on the functional stability of the skeletal relationship resulting when the appliance is removed. The more functionally stable the result, the less post-treatment changes occur.

One other statement must be made regarding the long-term implications of the experimental studies. These studies have not been of sufficient duration to answer the question of whether or not mandibular growth can be increased above that normally occurring without treatment. The experimental studies have shown that the growth of the mandibular condyle can be increased on a short term basis (one to three years in monkeys, equivalent to three to nine years in man). Further experimentation is necessary to understand the long-term implications of these adaptations in craniofacial growth.

THE ROLE OF MUSCLE FUNCTION IN CONDYLAR GROWTH

The previously mentioned studies of extrinsic and intrinsic forces indicate that a forward displacement of the mandible by elastic traction is not usually sufficient in itself to cause significant adaptive changes in the temporomandibular joint of growing individuals. Rather these adaptations in condylar growth occur concomitantly with alterations in muscle function, particularly of the lateral pterygoid muscle.

Recent studies by Petrovic and Stutzmann[15] confirm the relationship between the function of the lateral pterygoid muscle and the growth of the temporomandibular joint. The resection of the lateral pterygoid muscle from the mandibular condyle in growing rats caused a decrease in condylar growth. Without the presence of the lateral pterygoid muscle the chondroblasts in the condylar cartilage tended to become osteoblasts. Petrovic and Stutzmann stated that the presence of the lateral pterygoid muscle seemed necessary to the attainment and maintenance of chondroblastic differentiation in the condylar cartilage. The unilateral resection of the lateral pterygoid muscle was followed by a reduction in cell multiplication in the adjacent condyle.

Further investigations of extrinsic and intrinsic alterations in function have been carried out by Petrovic and associates.[16] These studies have demonstrated that an orthopedic appliance can significantly affect the growth rate of the condylar cartilage in rats. In the first group of animals a functional anterior protrusion was created (similar to the monkey studies cited earlier) in which the rat was forced to bite in a forward position. Petrovic reported that this passive device, which required changes in muscle activity, resulted in measurable alterations within the lateral pterygoid muscle. Histologic examination revealed that the muscle fibers of the lateral pterygoid exhibited obvious hypertrophy and that the number of serially arranged sarcomeres of this muscle was reduced. Through the use of autoradiography the investigators also charted changes in the skeletal elements, noting increased proliferation of the cells within the prechondroblastic layer of the condylar cartilage.

When the forward displacement of the mandible was caused by forces *extrinsic* to the animal (intermaxillary elastics), the temporomandibular joint region of the treated animals did not differ significantly from the control animals. There was no hypertrophy of the lateral pterygoid, no alteration in sarcomere number, and no significant increase in the proliferation of the condylar cartilage. There seemed to be little if any effect of the intermaxillary traction on the growth of the mandibular condyle.

In a third study retrusive forces were applied to the mandible through the use of a chin cap. The thickness of the condylar cartilage and the number of radioactively labeled cells decreased during the experimental period. There were also alterations in the lateral pterygoid muscle, with an increase in the number of serial sarcomeres noted.

Petrovic et al.[16] hypothesized that a prolonged contraction of the lateral pterygoid muscle produced acceleration of condylar growth while a reduction in contraction produced a slowing down in the growth of the condylar cartilage, thus again establishing at least indirectly a relationship between muscle function and bone or cartilaginous growth. Many questions still remain unanswered regarding the specifics of this relationship, particularly as to the control mechanisms acting at the muscle-bone interface.

CLINICAL IMPLICATIONS

How do the findings in rats and monkeys apply to specific therapeutic approaches used on human patients? The result of the experimental studies have shown clearly that structural adaptations can be induced in the temporomandibular joints of young, growing animals as a response to altered function. Caution must of course be exercised in translating these findings directly to the clinical treatment in man.

These experiments were conducted in a controlled situation, in an environment not usually attainable in clinical studies. Such variables as patient motivation and cooperation were eliminated by the experimental design. In addition, study methods were used (e.g., needle electromyography, histology, implant cephalometrics) which are not commonly available in clinical studies.

The above mentioned experimental studies are often used to prove or disprove the effect of the activator,[3] one of the most popular functional appliances in use today, on mandibular growth. However, it appears to the author that the mechanism of action of the activator appliance is not adequately tested by these experiments. In the treatment of Class II malocclusions, the mandible is *held* mechanically downward and forward in a teeth-apart position by the activator. In contrast, the cast overlays used in our experiments cause a neuromuscular alteration in the functional position of the mandible. These overlays are worn on a full-time basis, leading to an altered yet less variable oral environment than that which would result from the intermittent wear of a removable appliance.

There is no universal agreement as to the specific mechanism of action of the activator. Andresen and Haupl[3] have postulated that the frequency of muscle activity is increased through activator wear by contractions caused by proprioceptive stretch reflexes. Schwartz[17] suggests that the orthopedic force produced is due at least in part to isometric muscle contractions against the bulk of the appliances. Harvold[8] has stated that the increased muscle activity results from increased tonus in the stretched postural muscles, and that frequency of jaw movement is less significant. Ahlgren[2] has postulated that activators give rise to both continuous and intermittent muscle forces. It appears to the author that none of the explanations of the mechanism of action of the activator resembles the mechanism of action of the appliances used in the experimental studies, and thus, these experimental studies do not prove or disprove the effects of the activator on mandibular growth. The functional appliance currently in use which most closely resembles the experimental situation appears to be Frankel's Functional Regulator, in which the mandibular position is prompted anteriorly by the appliance. Our clinical armamentarium may not yet include the appliance which will cause functional adaptations to occur in the temporomandibular joint in man analogous to those seen in our experimental animals.

CONCLUSION

In conclusion, experimental studies have shown that the temporomandibular joint is not an immutable structure, but rather is an articulation capable of functional adaptation. These structural adaptations within the mandibular condyle are usually related to (1) changes in neuromuscular activity, particularly to the function of the lateral pterygoid muscle; and (2) the level of maturation of the individual. The challenge to the clinician remains to take advantage of this knowledge of temporomandibular joint adaptability and employ it in the design and use of appliances that alter mandibular growth in man.

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Department of Anatomy
University of Michigan
4811 Medical Science II
Ann Arbor, Michigan 48104