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Functional determinants of craniofacial size and shape

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Much of the orthodontic treatment undertaken throughout the world, and particularly in the United States, is aimed at correcting dentoalveolar and skeletal malrelationships. With the current level of fixed appliance refinement, we have become quite adept at achieving excellent occlusions. However we often do not consider one important fact when designing our treatment regime: the craniofacial complex maintains a state of homeostasis regardless of whether structural balance or imbalance exists. Abnormal skeletal or dentoalveolar configurations are counterbalanced by abnormal or atypical patterns of masticatory and perioral muscle function and by pressures of the other associated soft tissue. Therefore, any given overall form-function relationship is *stable*, even though each of its individual components may have an abnormal configuration or pattern of activity. This stability is demonstrated by the relative consistency of the overall skeletal and dentoalveolar relationships during the growth period; i.e., barring environmental insult or therapeutic intervention, the individual in late adolescence generally resembles himself as he appeared many years earlier.

The aim of most fixed banded therapy is the correction of skeletal and dentoalveolar malrelationships, with little or no attention paid to co-existing abnormal functional patterns. Many clinicians naively assume that these abnormal functional patterns will correct spontaneously if structural balance is obtained. However, in cases in which only one part of the form-function relationship is considered, regression of the skeletal and dentoalveolar configurations towards their original malrelationships usually occurs in both growing and non-growing patients following appliance removal.

The form-function relationship in the non-growing face

Over the last 11 years, a series of experiments dealing with various aspects of the relationship between structure and function have been conducted in our laboratory. That these two are interrelated is easily demonstrated in the non-growing individual by considering the relationship between the pterygomasseteric sling (masseter, temporalis and internal pterygoid muscles) and the morphology of the gonial angle (McNamara et al., 1978). Our experimental animal in the following studies is the adult female rhesus monkey (*Macaca mulatta*).

Adaptations following muscle lengthening

It is possible to produce a lengthening of the masticatory musculature without surgical intervention. In this study, cast ticonium onlays cemented to the maxillary arch were used to open the bite 15–18 mm incisally (Fig. 1), thus producing an increase in the length of the muscles of the pterygomasseteric sling.

Changes in muscle length were monitored radiographically using specially prepared 14 k

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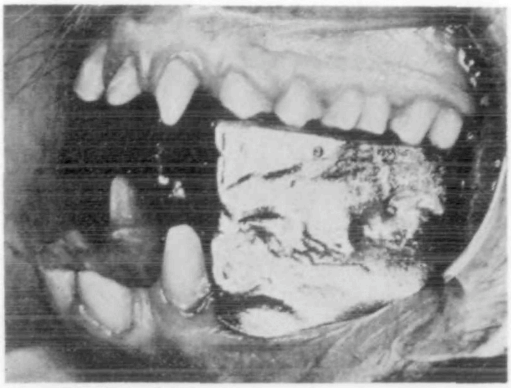

Figure 1 Intraoral view of the ticonium bite opening appliance cemented on the maxillary arch. The vertical dimension was opened 15 to 18 millimeters incisally.

gold barbed broaches (Muhl, 1974; Muhl and Grimm, 1974 Muhl et al., 1978) sections of which were placed near the inferior border of the masseter muscle. The movements of at least two implants on each side were monitored to determine alterations in muscle length. Serial cephalograms were traced and the locations of the implants were digitized to provide a quantitative method of assessing muscle adaptation. After implant placement the animals were monitored weekly until the implants appeared stable in successive cephalograms.

As one would expect, the stability of the muscle implants is not as reliable as that of bone implants. However, our control data demonstrated that over a 24-week interval, the pattern of movement tended to be random in nature and was limited to less than 1 mm (Fig. 2).

The first experimental group of six animals wore a bite opening appliance for from 4 to 48 weeks, according to a predetermined schedule. One animal was sacrificed at 4, 8, 12, and 48 weeks, and two animals at 24 weeks following placement of the appliance, so that histochemical, biochemical and contractile property analysis could be performed. Cephalometric finding only will be considered below.

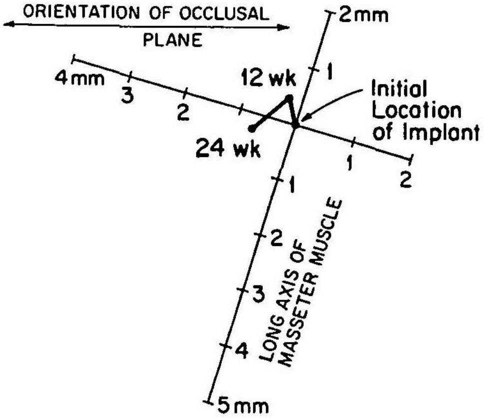

Figure 2 Graphic representation of the movement of the intramuscular implants in the control animals during a 24-week interval, demonstrating the average displacement of the anterior and posterior masseter implants bilaterally. The intersection point represents the original position of the muscle implant and all movements are calculated from that point.

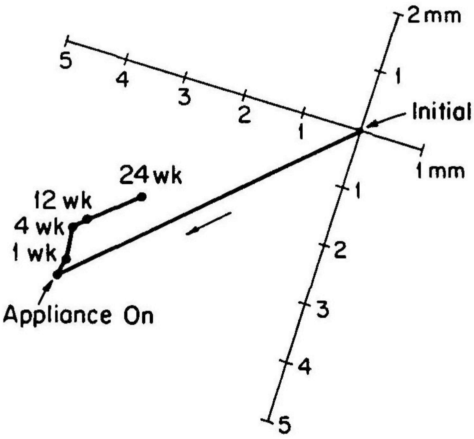

Figure 3 Graphic representation of the mean movement of the masseter implants in the animals in which bite opening appliances were placed. Note the gradual movement of the implants back toward the initial position.

The opening of the bite following the placement of the appliance resulted in an immediate downward and backward displacement of the muscle implants (Fig. 3). The mean movement of the implants bilaterally was 4 mm in both an inferior and posterior direction relative to the axis of the masseter muscle. Since it is a basic physiological principle that a stretched muscle will attempt to re-establish its original length, we anticipated that there would be a gradual migration of the muscle implants back toward their original position during the period the appliance was worn. In fact, this migration did occur but the movement observed was gradual. By 24 weeks after placement of the appliance, the muscle implants had moved approximately 30–40% back toward their original (pre-appliance) position.

In order to monitor adaptations occurring simultaneously in the region of muscle attachment, serial tracings were also made of the morphology of the mandible (Fig. 4), with particular emphasis on gonial remodelling. Although supposedly non-growing adult monkeys were used in this study, we observed a slight amount of normal remodelling along the posterior border of the mandible in some animals. A method of analysis was devised to cancel out, as much as possible, these small posterior growth increments. Only the anterior-inferior portion of the attachment of the pterygomasseteric sling was considered. The limits of the area studied were determined by the point at which the anterior perpendicular line and the line bisecting the gonial angle intersected the inferior border of the mandible (Fig. 4). The amount of bone deposition or resorption in successive tracings was measured by planimetery in mm^2. The control animals averaged 1–2 mm^2 of bone resorption during the 24-week experimental period.

Those animals in which the masseter and the other muscles of the pterygomasseteric sling were lengthened demonstrated a gradual increase in bone resorption, reaching an average among animals of 10 mm^2 at the end of the 24-week period (Fig. 5). The increasing amount of bone resorption at the gonial angle corresponded in time to the gradual migration of the muscle markers (presumably indicating the migration of the muscle along the periosteum) toward their original implant position.

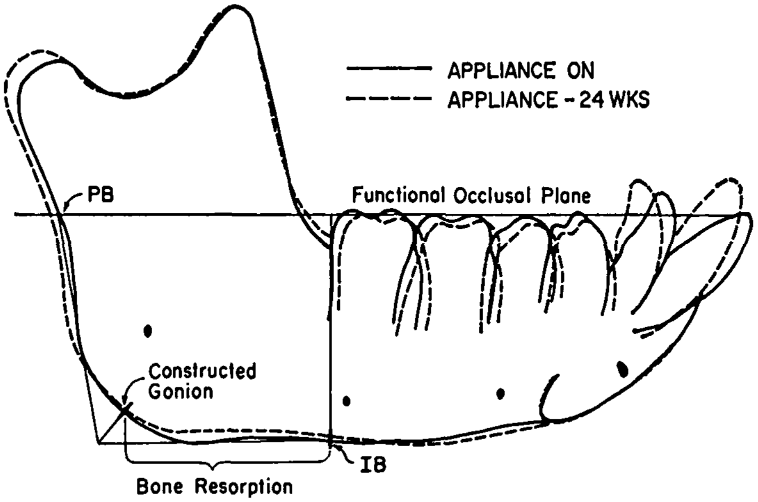

Figure 4 Method of calculating bone deposition and resorption in the gonial region. A line was drawn perpendicular to the functional occlusal plane through the distal contact point of the lower second molar and intersecting the inferior border of the mandible at point IB. Tangents to the gonial region were drawn from point IB and point PB (intersection of the functional occlusal plane and the posterior border of the mandible). The angle of their intersection was bisected and gonion was constructed. The area from gonion anteriorly to point IB was monitored by planimetry. Changes in contour were measured in square millimeters. In this illustration, bone resorption occurred along the inferior border of the gonial region following placement of a bite opening appliance.

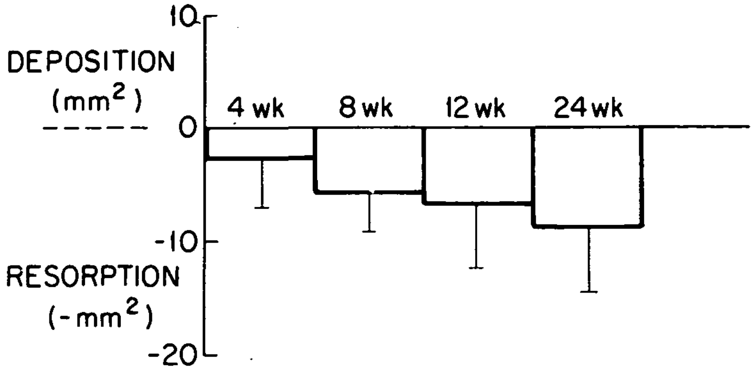

Figure 5 Resorption in the gonial region following the placement of the bite opening appliance. Resorption was measured by planimetry in square millimeters.

Adaptations following muscle shortening

In a second experimental group of five animals, a similar bite-opening appliance was placed for 24 weeks and then removed. One animal was sacrificed at intervals of 4, 8, 12, 24 and 48 weeks after appliance removal.

The results during the muscle lengthening phase during which time the appliance was worn, were similar to those observed in the first experimental group mentioned above (Fig. 6). However, when the appliance was removed and the vertical dimension of the face decreased, the muscle implants were displaced anteriorly and superiorly to a position which, on the average, indicated that the muscle had shortened beyond its original, pre-appliance length. During the subsequent 24-week period, during which no appliance was worn, a gradual lengthening of the muscle occurred. A gradual migration of the muscle markers was noted back toward and eventually beyond the original location of the markers.

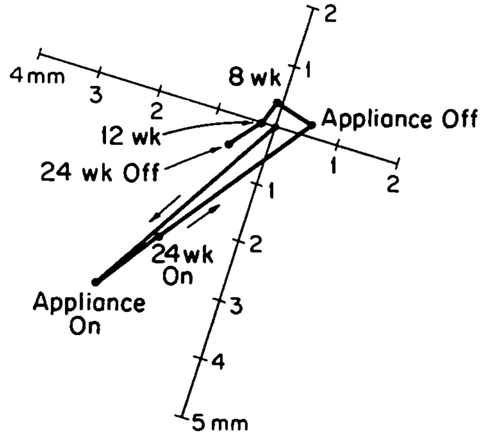

Figure 6 Graphic representation of the mean movement of the intramuscular implants in the second experimental group. Note the spontaneous shortening of the masseter muscle following placement of the appliance and spontaneous lengthening of the masseter muscle following appliance removal.

During the interval when the appliance was worn (as in the first experimental group) bone resorption in the gonial region was noted. However, this process was reversed during the interval following appliance removal; i.e., deposition, rather than resorption of bone occurred in the gonial region (Figs 7, 8).

This simple experiment in non-growing animals illustrates the continuing interplay between the hard and soft tissue components of the craniofacial region in maintaining homeostasis of the structural and functional components of the face. The reactive response of *shortening* following experimental lengthening of a muscle results in bone *resorption* while spontaneous *lengthening* of a muscle following the reactive shortening results in bone *deposition*.

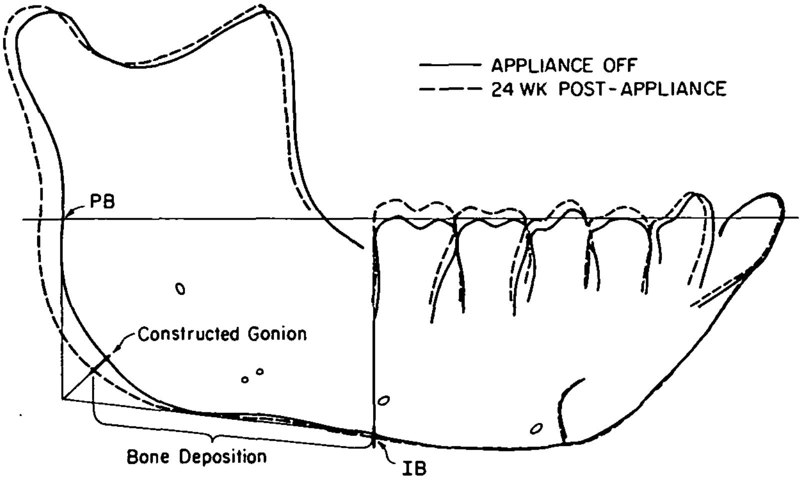

Figure 7 Adaptations occurring in the gonial region following appliance removal. Bone deposition occurred along both the inferior and posterior borders of the mandible.

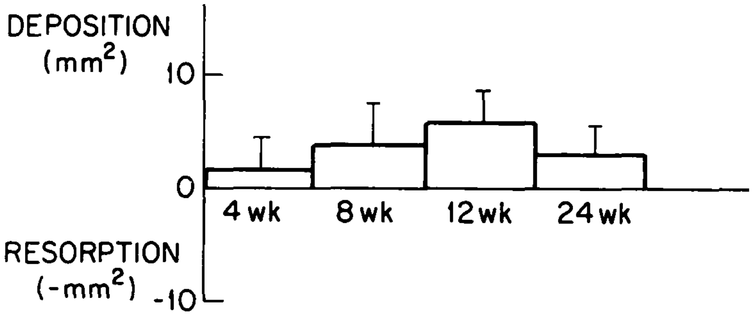

Figure 8 Bone deposition in the gonial region following appliance removal.

The relationship between form and function in the growing face

If such a clear relationship between structure and function can be shown in the adult, what are the implications of this interrelationship in the growth processes of the growing child? Since this question has been most often raised when considering the growth of the temporomandibular joint in the young individual, this region will be our focus of attention as an example of the form-function relationship in the growing face.

Various therapeutic appliances have been used for many years to promote not only dentoalveolar but skeletal and muscular balance in the young patient. (For a review of the literature on this topic, see McNamara, 1972.) Many conflicting reports exist in the literature on the effects of such functional appliances on the craniofacial complex of the growing individual. Such disagreement over results is due to the use of varying treatment appliances and analytical techniques, as well as to the problems inherent in studying any human sample.

Because of these difficulties, we have undertaken a continuing series of studies on the effect of altered function on the growth of the craniofacial complex of juvenile rhesus monkeys using experimental methods and procedures that are not possible on clinical patients.

Studies of functional protrusion

The first experimental model that we will discuss is not new and has been used by many investigators since its introduction by Carl Breitner (Breitner, 1930; Häupl and Psansky, 1939; Derichsweiler, 1958; Baume and Derichsweiler, 1961; Hiniker and Ramfjord, 1966; Joho, 1968; Stöckli and Willert, 1971), also in our laboratory for the last 11 years (Elgoyhen et al., 1972; McNamara, 1972, 1973a, 1976; McNamara et al., 1975; McNamara and Carlson, 1979).

In order to produce an altered postural position of the mandible, cast gold or ticonium onlays were cemented on the upper and lower dental arches. These castings usually produced a 4–5 mm anterior and 2–3 mm inferior displacement of the mandible during closure and resulted in a displacement of the mandibular condyle away from the structures in the glenoid fossa.

Electromyographic analysis

As in the experimental study in adult animals previously described, adaptations occurring in both the hard and soft tissue were monitored simultaneously. Our first experimental procedure was to record changes in the pattern of activity of the muscles of mastication. The muscles monitored included the anterior and posterior head of the temporalis muscle, the anterior portion of the superior head of the masseter muscle, the superior orbicularis oris muscle, the suprahyoid muscle group (including the anterior digastric, geniohyoid and mylohyoid), and the lateral pterygoid muscle.

As in man, the lateral pterygoid muscle in the monkey has two functionally and anatomically distinct heads. We determined that the inferior head of this muscle acts in a manner typically described for the lateral pterygoid, that is, a muscle which provides jaw opening and contralateral movement (McNamara, 1973b). In contrast, the superior head of the muscle acts as a jaw stabilizer during closure and, as will be demonstrated, is the muscle most obviously sensitive to changes in the anteroposterior position of the jaw.

Typical, slow-speed electromyographic recordings are shown in Figure 9. The anterior temporalis and posterior temporalis are often active in maintaining the postural position of the mandible, with the masseter or superior orbicularis oris and superior head of the lateral pterygoid muscle being intermittently

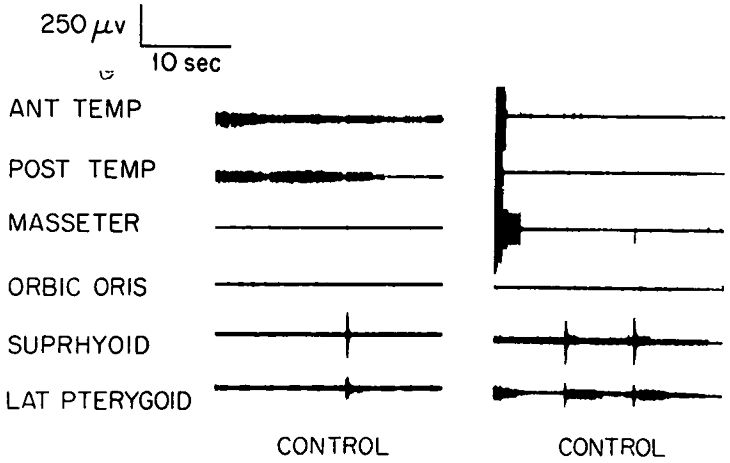

Figure 9 Overview of typical muscle activity during the control period. Postural activity can be observed in the anterior and posterior temporalis musculature, with little activity in the superior head of the lateral pterygoid muscle except in association with such phasic activities as swallowing.

active. As is typical of our experimental procedures, each animal was used as its own control. Three to five control records were taken on each animal before appliance placement so that the monkey could become accustomed to the procedure and so that reproducible control records could be gathered.

Initial placement of the appliance resulted in an increase in the overall activity of the muscles of mastication as the animal sought to find a new occlusal position (Fig. 10). However, during the interval immediately following appliance placement, there was no demonstrable change in the *pattern* of muscle activity, as is indicated by the fact that electromyographic recordings taken during this time could not be distinguished from those taken during the control period.

A distinct change in muscle activity occurred (Fig. 11) in one to seven days. This was characterized by a decrease in the activity of the posterior temporalis muscle, an increase in the activity of the masseter muscle and, most significantly, an increase in the function of the superior head of the lateral pterygoid muscle. This activity was different from that seen in control records in that the superior head did not fire only simultaneously with the jaw closing muscles, but also fired independently. This new functional pattern

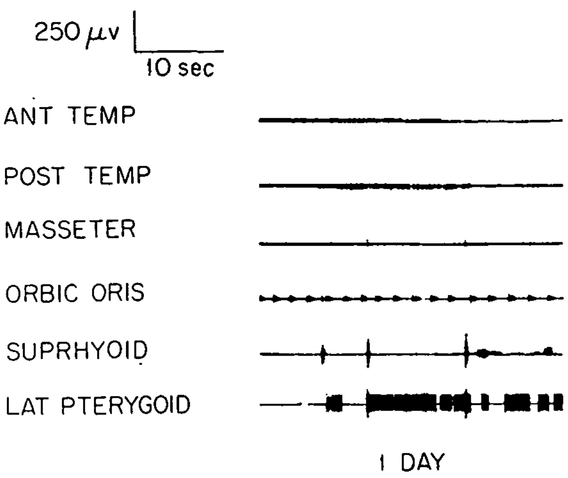

Figure 11 An increase in postural activity could be observed in the superior head of the lateral pterygoid muscle one day to one week following appliance placement.

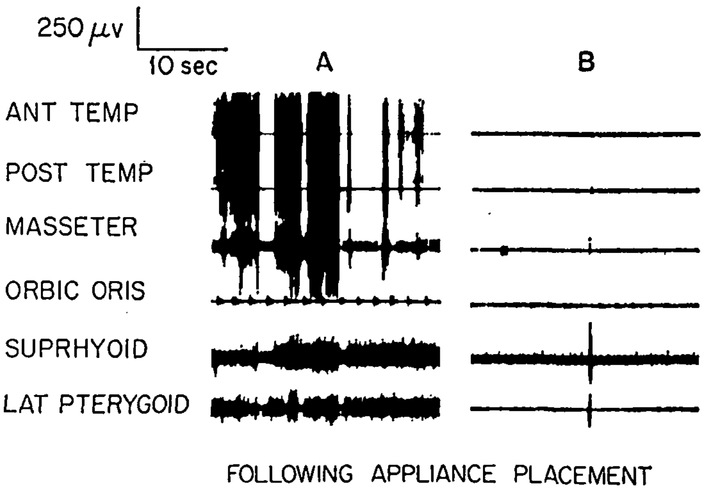

Figure 10 Overview of typical muscle activity immediately following appliance placement. A dramatic increase in the level of muscle activity and the presence of muscle splinting were often observed (A). However, at other times the animal held the jaws apart as indicated by the slight increase in the postural activity of the suprahyoid muscle group (B).

first appeared in association with such phasic activities as swallowing and then during such tonic functions as the maintenance of the mandibular postural position. In the lateral pterygoid this response reached its peak at four to eight weeks following appliance placement (Fig. 12). However, as the series of experiments progressed, a gradual return toward original levels and patterns of muscle activity occurred (Fig. 13). This represents a gradual increase of muscle function followed by a gradual decrease to control level values.

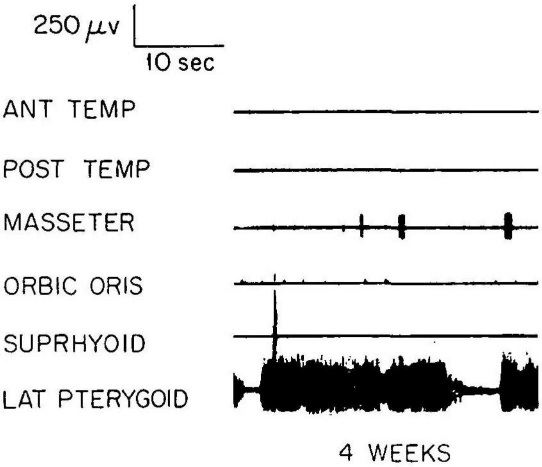

Figure 12 The level of postural activity of the superior head of the lateral pterygoid muscle reached a maximum at 4 to 8 weeks following appliance placement.

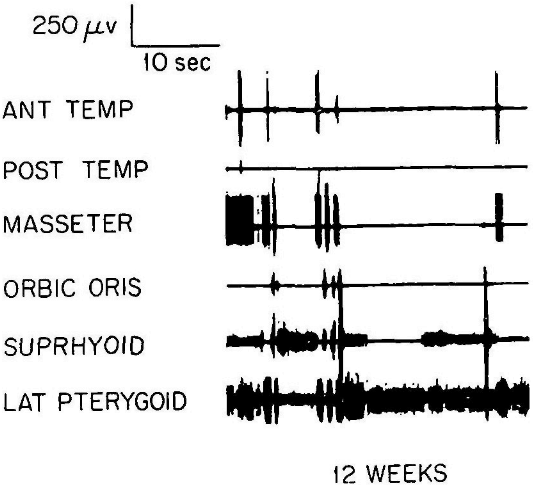

Figure 13 A gradual reduction in the level of lateral pterygoid activity was observed 12 to 24 weeks following appliance placement.

Cephalometric analysis

At the end of the experimental period, which varied from 12 to 96 weeks, the appliance was removed and a Class III molar relationship could be observed (Fig. 14). Among the many

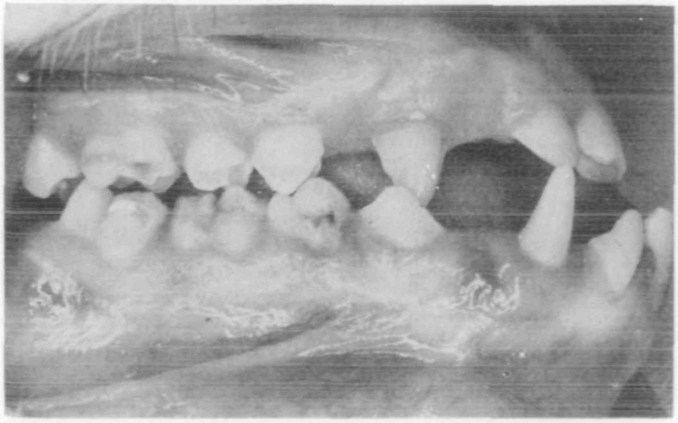

Figure 14 Intraoral photograph of the occlusion following appliance removal. Note the Class III relationship of the canines and posterior teeth.

possible adaptations that may lead to a Class III molar relationship in this experimental design are restriction of maxillary skeletal growth, the inhibition of the downward and forward migration of the maxillary dentition, mesial migration of the mandibular dentition and increased mandibular skeletal growth. Adaptations could have occurred in other regions as well, particularly in the cranial base.

In order to monitor skeletal changes observed cephalometrically, metallic implants were placed before the beginning of the experimental period, in various regions of the craniofacial complex including the mandible (McNamara and Graber, 1975), the maxilla, the frontal bone and the cranial base region (the latter through an incision through the soft palate and the posterior pharyngeal wall,

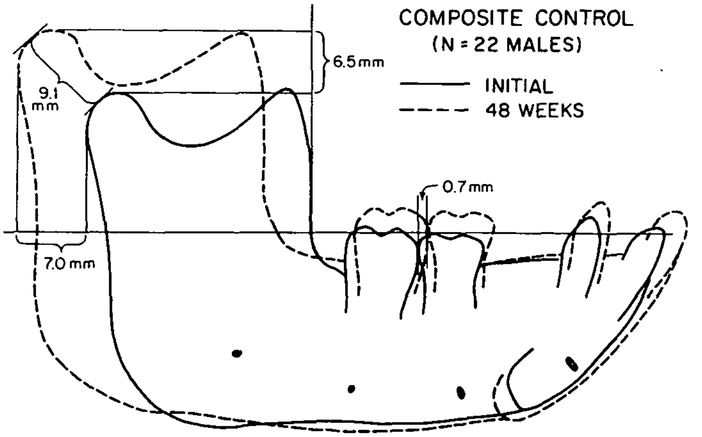

Figure 15 Tracings of a control animal (superimposed on mandibular implants) which is representative of the 22 male control animals used in this study (values extrapolated from McNamara and Graber, 1976).

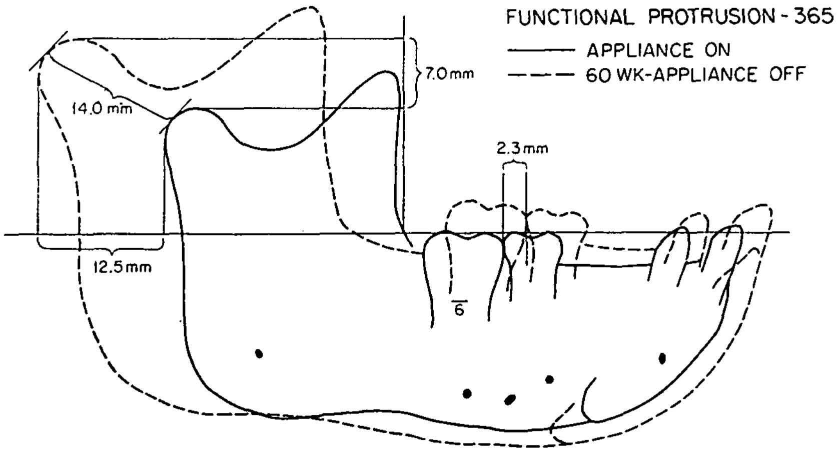

Figure 16 Mandibular tracings of an experimental animal which wore a series of functional protrusion appliances for a 60-week period. Note the increase in condylar growth posteriorly and posterosuperiorly when compared with control values (Figure 15). Also note the slight increase in the mesial migration of the posterior dentition.

McNamara et al., 1976). The radiographs were then enlarged precisely three times on translite film in order to monitor skeletal and dentoalveolar adaptations which might be masked by tracing errors. Composite tracings were made which allowed for the quantification of skeletal and dentoalveolar adaptations in both the anteroposterior and vertical dimensions relative to the functional occlusal plane.

Several statements can be made regarding the cephalometric analysis. First, the clinical observation of a Class III dental relationship could not be explained by adaptations in any single craniofacial structure or region; rather, it was a result of both pronounced and subtle adaptations throughout the structures of the craniofacial complex. This was in contrast to similar studies of functional protrusion in *adult* rhesus monkeys in which the adaptations observed were primarily dentoalveolar in nature (Hiniker and Ramfjord, 1966; Ramfjord and Enlow, 1971; McNamara, 1972, 1973a).

The adaptations occurring in mandibular structures are of specific relevance to the topic of this paper. Discussion of the findings will be limited to those concerning the mesial migration of the lower dentition and the alterations in the growth of the temporomandibular joint. Our previous studies of normal mandibular growth in the juvenile rhesus monkey (McNamara, 1972;McNamara and Graber, 1975) indicate that the average anterior movement of the lower first molar is approximately 1 mm during a 48-week period. Similarly, there is an upward and backward displacement of the mandibular condyle, as was shown in a sample of 22 male juvenile monkeys used as controls (Fig. 15). The mandibular condyle in the control animals grew superiorly by an average of 6.5 mm, posterosuperiorly 9.1 mm, and posteriorly 7.0 mm.

Significant adaptations occurred in the mandibles of those animals who wore functional protrusion appliances. One such animal, which received two sets of appliances during an experimental period of 60 weeks, demonstrated an alteration in both the amount and direction of mandibular condyle growth (Fig. 16), which was typical of the animals in this study. While the amount of superior growth was within control values, the amount of growth of the condyle posterosuperiorly was 14.0 mm, which was a 40% increase over control values. The 10.6 mm posterior growth was almost 65% above control values. It should also be noted that the mandibular dentition moved anteriorly slightly more than 2 mm during the 60-week experimental period.

Control data were available on many of the experimental animals preceding the placement of the appliance. For example, serial records were obtained for 51 weeks on the animal whose mandible is shown in Figure 17. During this pre-appliance interval, the condyle was displaced posterosuperiorly 9.0 mm and posteriorly 6.4 mm. During a subsequent 48-week experimental period, this animal demonstrated a 45% increase in the amount of posterosuperior growth of the condyle and more than a 50% increase in the amount of condylar growth posteriorly. The amount of growth of the mandibular condyle superiorly was slightly above control values. This animal also demonstrated an increased amount of forward movement of the lower dentition (2.9 mm) during the experimental period.

In our initial study of functional protrusion (Elgoyhen et al., 1972), monthly increments in condylar growth were measured. The largest increment occurred during the second month, a time interval which corresponded to the highest level of muscle activity seen in the electromyographic records. The increments gradually decreased to control levels as the patterns of muscle function began to resemble those recorded before the onset of the experiment. Thus the electromyographic and cephalometric data show a close correlation in time between the appearance and disappearance of altered muscle function and associated skeletal and dentoalveolar adaptations.

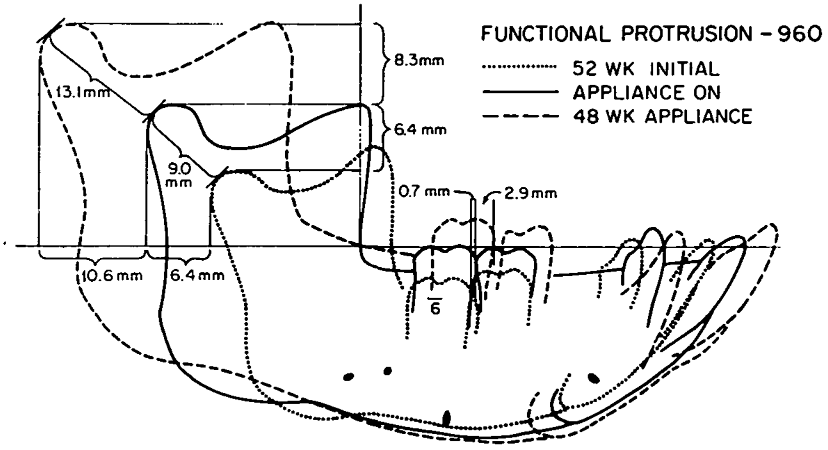

Figure 17 Mandibular tracings of an experimental animal which, after a control period of 52 weeks, wore a series of protrusive appliances for a 48-week period. The growth increments monitored during the control period were similar to the average values for the controls (Fig. 15). Note the increase in posterior and posterosuperior growth during the experimental period.

Histological analysis

The next step in our investigation was to evaluate histologically temporomandibular joint adaptations to protrusive function. The experiments were repeated and the animals were sacrificed at intervals of 2, 4, 6, 8, 10, 12 and 24 weeks following appliance placement. A total of 14 animals were used in this experiment, with an additional 14 animals as controls. The adaptations in the temporomandibular joint were quantified through the use of planimetry and direct measurements were also made of condylar cartilage thickness in the superior, posterosuperior and posterior regions (Carlson et al., 1978).

Control animals The temporomandibular joint region in a typical juvenile rhesus monkey consists of the mandibular condyle with its associated condylar cartilage, the articular disc, the articular eminence, the glenoid fossa, the posterior glenoid spine (a structure found in monkeys but not in man) and the external auditory meatus (Fig. 18).

The cartilage covering the mandibular condyle (Fig. 18) consists of two layers, the articular tissue layer and the growth cartilage layer. This latter layer can be subdivided into prechondroblastic and chondroblastic zones (e.g., Petrovic et al., 1975). These two zones form a relatively thick layer of cartilage, the thickness of which averaged approximately 335 μm posterosuperiorly, 220 μm posteriorly and 138 μm superiorly in the 14 control animals.

Experimental animals Three animals were sacrificed two weeks after appliance placement. In this short period, significant adaptations could be seen along the posterior and posterosuperior region of the temporomandibular joint, with the thickness of the cartilage increasing posteriorly an average of 3.5 times (734 μm) above control level values in these three animals (Fig. 19). Increased deposition of new bone was also evident along the posterior border of the ramus and the anterior border of the posterior glenoid spine. Similar adaptations were observed in the animals sacrificed at four weeks.

The largest response was observed in one of the animals sacrificed at six weeks (Fig. 20). This animal exhibited a fourfold increase (approximately 800 μm) in the posterior thickness of the condylar cartilage. The

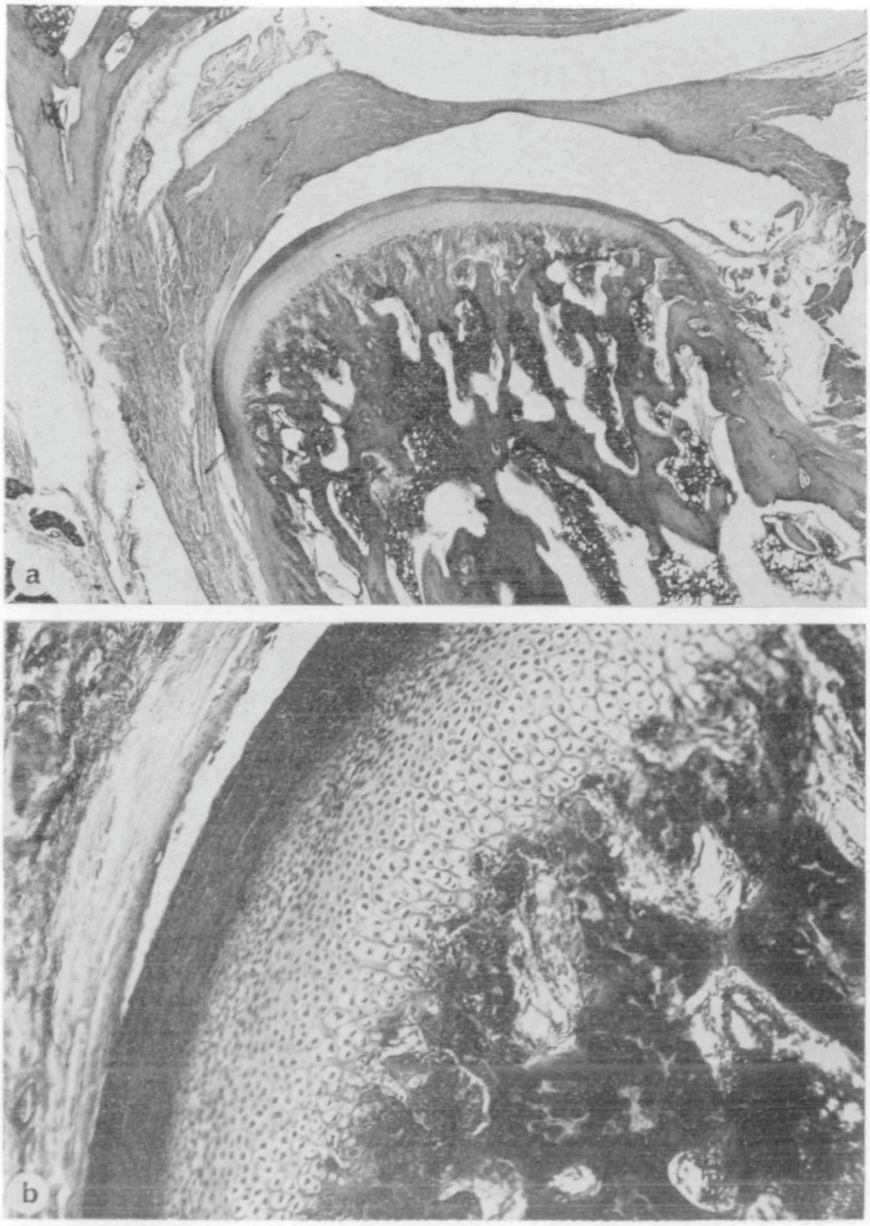

Figure 18 (a) Overview of the temporomandibular joint region from a typical control animal. This and all subsequent histological sections were stained with hematoxylin and eosin. (×8.4). (b) Higher power view of the condylar cartilage in a typical control animal (×28).

occurrence of rapidly-forming new bone was also observed in this area. This increase in the rate of bone formation was verified by an increase in osteoblastic activity observed autoradiographically (McNamara, and Carlson, unpublished data).

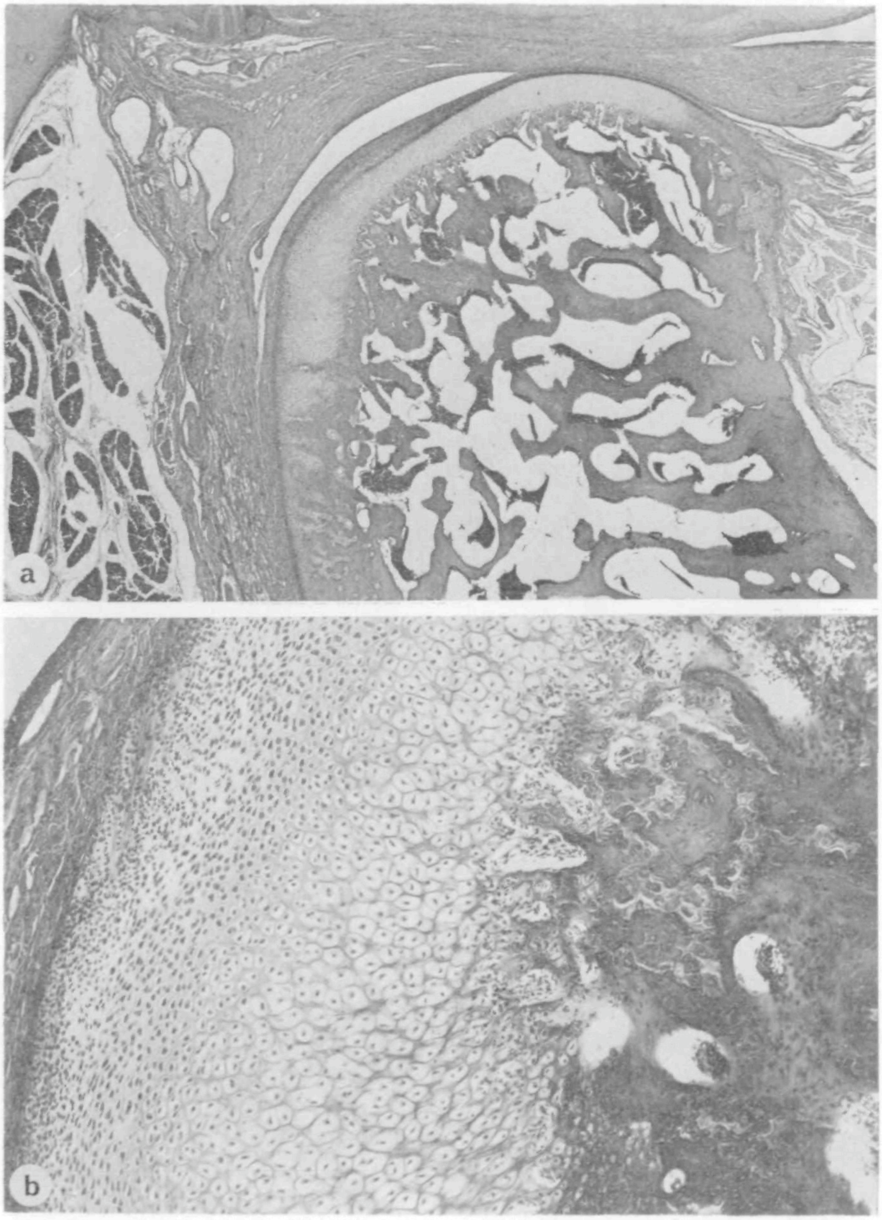

Figure 19 (a) Temporomandibular joint region of a two-week experimental animal. Note the proliferation of tissue, particularly in the posterior portion of the condylar cartilage and along the posterior border of the ramus. (×8.4). (b) Proliferation of cartilage along the posterior border of the condyle. Note the increase in both the size and number of chondrocytes. (×28).

Our electromyographic and cephalometric studies have indicated that maximum adaptation occurs during the second month of the experimental period, during which time much of the structural adaptation at the temporomandibular joint is also taking place.

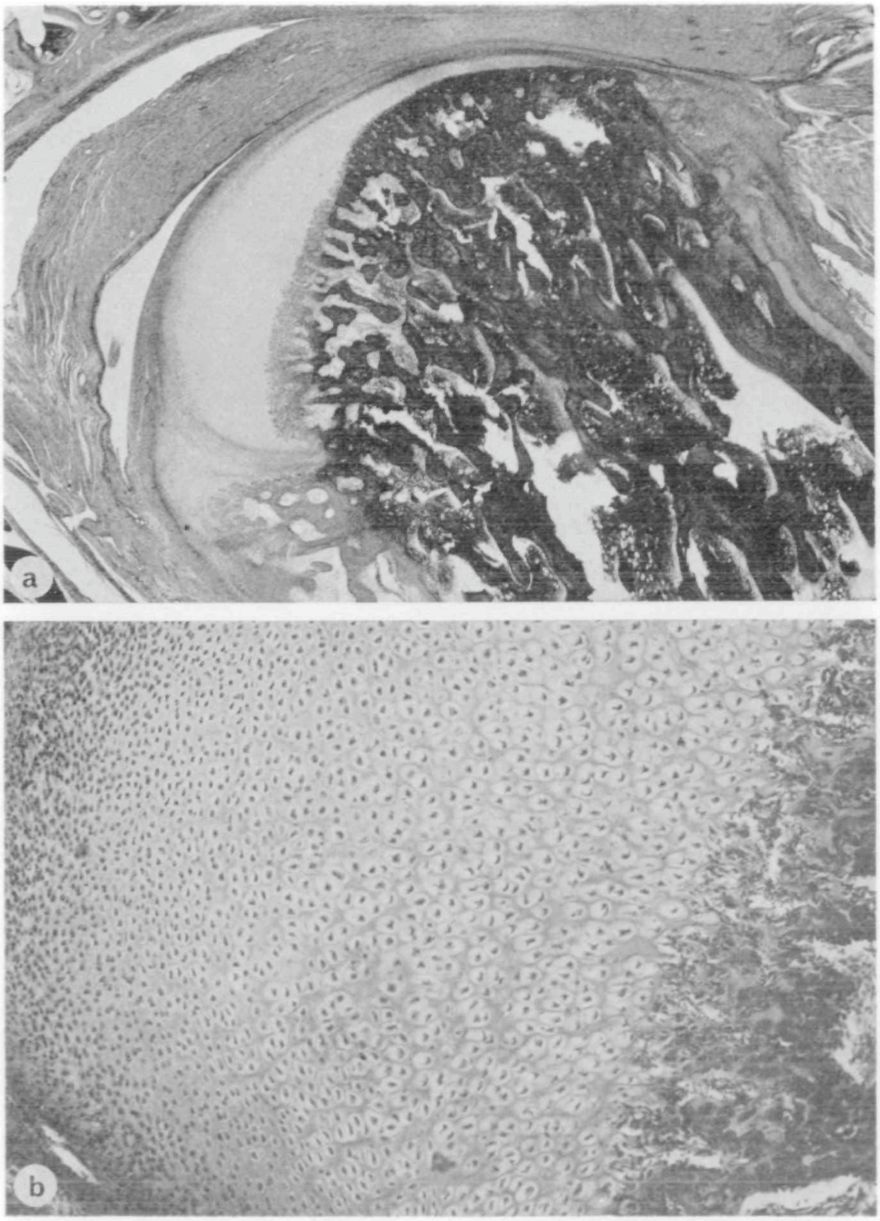

Figure 20 (a) The temporomandibular joint region of a six-week experimental animal. Note the increase in the thickness of the condylar cartilage, particularly along the posterior aspect of the condyle. (×8.4). (b) Higher power view of the posterior portion of the condylar cartilage. Compare the size and number of cells to that of the control animal in Figure 18b. (×28).

We, therefore, expected that, with the decrease in muscle activity and the re-establishment of the structural integrity of the temporomandibular joint, less condylar cartilage proliferation would be observed. In fact, this was the case. For example, only a

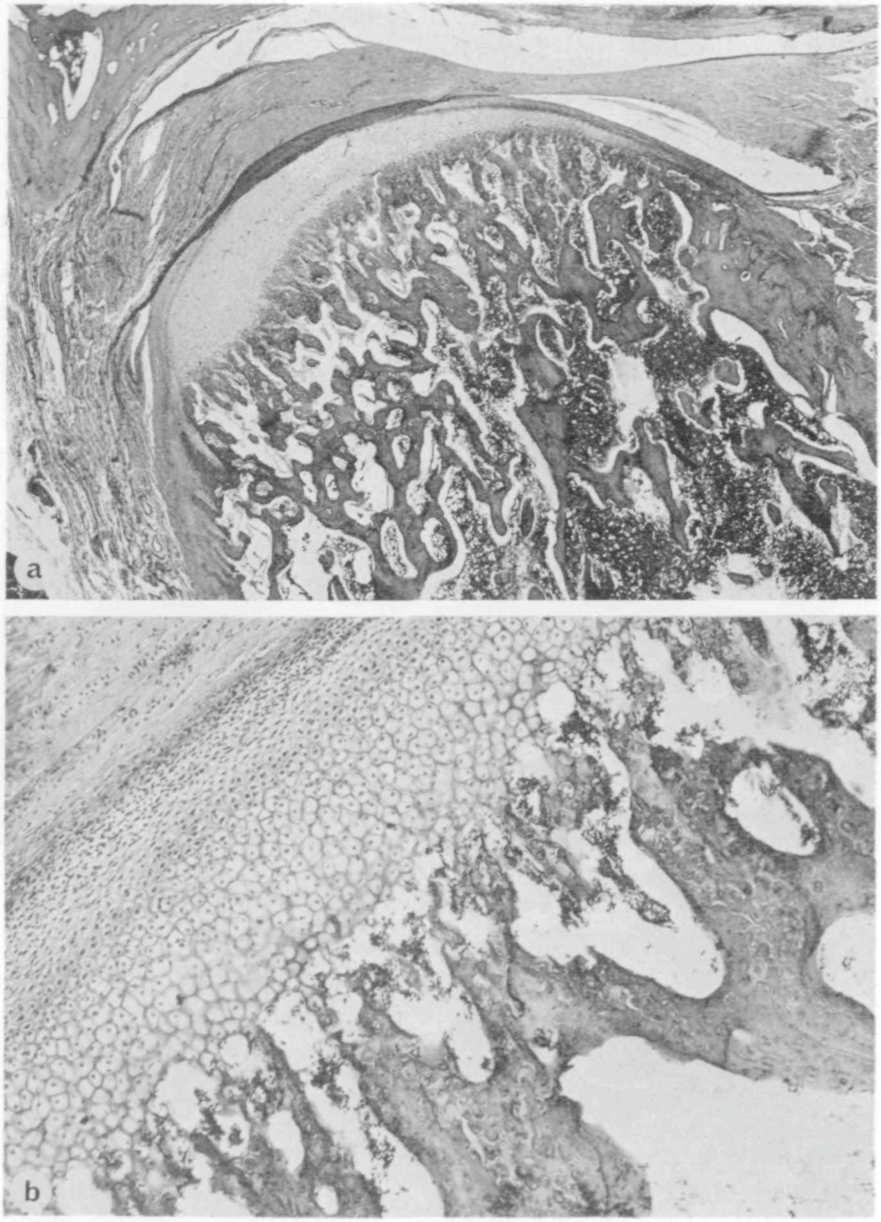

Figure 21 (a) The temporomandibular joint region of a 12-week experimental animal. Some continuing cartilage proliferation is observed in this animal. (×5.6). (b) The temporomanibular joint region of the 24-week animal. (×28).

moderate amount of proliferation was seen in the animals sacrificed at 12 weeks (Fig. 21a). By 24 weeks (Fig. 21b) the condyle could not be differentiated histologically from those of the controls. However, increased mitotic activity in the prechondroblastic layer of the condylar cartilage could still be observed autoradiographically at 24 weeks.

In midline sagittal sections, we measured by planimetry the area of the condylar cartilage and the thickness of the cartilaginous layers. We determined a least squares regression analysis of the adaptive responses in the thickness of the three regions of the prechondroblastic-chondroblastic cartilage of the condyle relative to treatment duration (Fig. 22). As expected, no significant increase in thickness was observed superiorly. However, growth in thickness at the postero-superior region and, even more dramatically, along the cartilage posteriorly was observed.

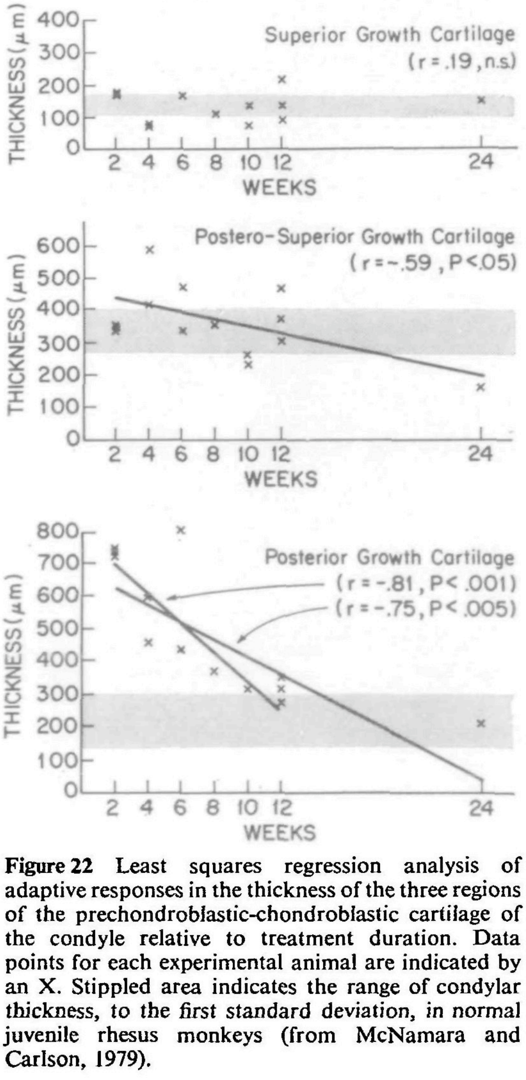

Figure 22 Least squares regression analysis of adaptive responses in the thickness of the three regions of the prechondroblastic-chondroblastic cartilage of the condyle relative to treatment duration. Data points for each experimental animal are indicated by an X. Stippled area indicates the range of condylar thickness, to the first standard deviation, in normal juvenile rhesus monkeys (from McNamara and Carlson, 1979).

Summary

We have developed two diagrams (Figs 23a and b) to summarize the adaptive responses observed in our functional protrusion experiments. The placement of the appliance results in an immediate change in the stimuli to the receptors in the orofacial region, particularly those in the tongue, gingiva, palate, dentition and temporomandibular joint region (Fig. 23a). This alteration in stimuli is transmitted to the central nervous system which, perhaps through the lateral reticular formation, mediates changes in muscle activity, as indicated by a decrease in the activity of the posterior temporalis muscle, an increase in the activity of the masseter muscle and, most significantly, an increase in the function of the lateral pterygoid muscle. This alteration in muscle function leads to a forward positioning of the jaw. These muscular changes are very *rapid* and can be measured in terms of minutes, hours and days.

Structural adaptations are more *gradual* in nature (Fig. 23b). As noted earlier, structural adaptations occur throughout the craniofacial region, as indicated in this diagram by a forward movement of the dentition and increased growth at the temporomandibular joint region. As structural balance is restored during the weeks and months following appliance placement, the need for altered muscle activity is lessened, and there is a gradual return to more typical muscle patterns. This experimental model provides a clear illustration of the relationship between form and function in the growing individual.

Studies of intermaxillary traction

In order to determine the role of 'function' in the growth of the temporomandibular joint, another series of experiments was undertaken in association with Dr Lee W. Graber, in which extrinsic (non-muscular) forces were applied to move the mandible anteriorly. Coiled springs producing a force of 200 g per side were attached to maxillary and

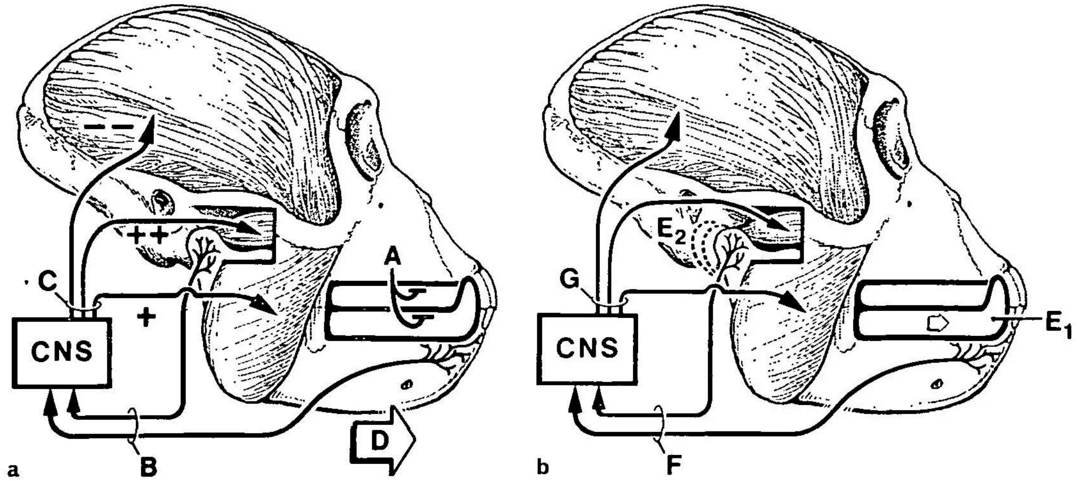

Figure 23 Overview of neuromuscular and skeletal adaptations occurring during the functional protrusion experiments. The insertion of the appliance (A) results in a change in the sensory stimuli to various oral facial receptors. This information is relayed (B) to the central nervous system (CNS) which mediates changes in the level of activity (C) of various craniofacial muscles. This change in activity leads to the forward displacement of the mandible (D) in both phasic and tonic activities. The above neuromuscular responses are rapid in nature. Skeletal adaptations are more gradual. Structural harmony can be re-established by a combination of mechanisms including dentoalveolar movement (E_1) or increased condylar growth (E_2). The exact nature of the skeletal adaptations depend upon the age of the animal. Such adaptations again alter the sensor stimuli which is transmitted (F) to the central nervous system. The need for neuromuscular adaptations is reduced (G) so that normal structural and functional balance is once again attained.

mandibular splints to produce a forward movement of the jaw (Fig. 24).

These experiments followed the same protocol as that of the functional protrusion experiments. Five short-term animals were studied histologically and three long-term animals were followed electromyographically and cephalometrically.

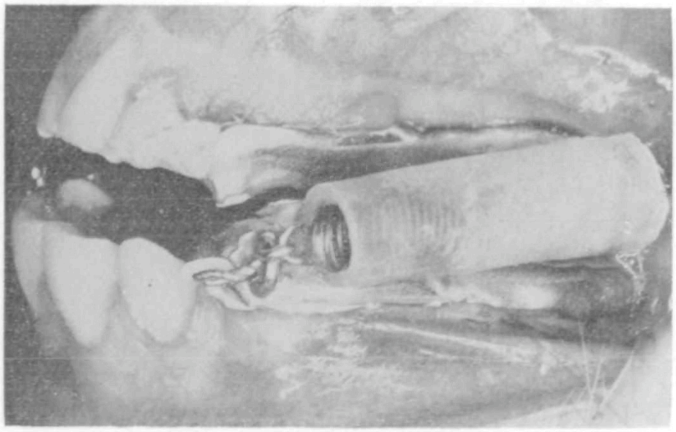

Figure 24 Intraoral view of intermaxillary traction appliance. A spring is attached to the anterior portion of the maxillary appliance and the posterior portion of the mandibular appliance, creating a force of 200 grams per side.

Electromyographic analysis

In contrast to the functional protrusion experiment, no uniform neuromuscular response could be determined. For example, the posterior temporalis muscle became either hypoactive or hyperactive. Hyperactivity was observed in the masseter and suprahyoid muscles of certain animals. Lateral pterygoid activity was altered in each animal, but only occasionally was the hyperactivity typical of that seen in the functional protrusion experiments. During the 48-week experimental period, patterns of muscle activity typical of that observed during the control period were observed. But, even at the end of the 48-week interval, some alteration in muscle pattern was still evident, indicating that musculoskeletal balance had not yet been achieved.

Cephalometric analysis

Since intermaxillary traction is most often used clinically to produce dentoalveolar adaptations, we expected to see a tremendous amount of dentoalveolar movement occurring in these animals. And indeed, such was the case. However, in spite of this increase in the amount of mesial tooth movement, an alteration in the rate of condylar growth could be observed. Two of the three long-term animals demonstrated a 50% increase in the amount of condylar growth over control values (Fig. 25), although the direction of condylar growth was not redirected as posteriorly as was observed in the functional protrusion experiments. Condylar growth in the third animal, although greater than control values, was not as marked. It should be noted, however, that this animal showed the greatest amount of dentoalveolar adaptation.

Histological analysis

In order to examine the tissue responses in the mandibular condyle, the short-term animals were sacrificed at 2, 4, 6, 8, 12, and 24 weeks after appliance placement. Increased proliferation of the condylar cartilage could be observed at two weeks (Fig. 26), as well as at subsequent time intervals. In contrast to the

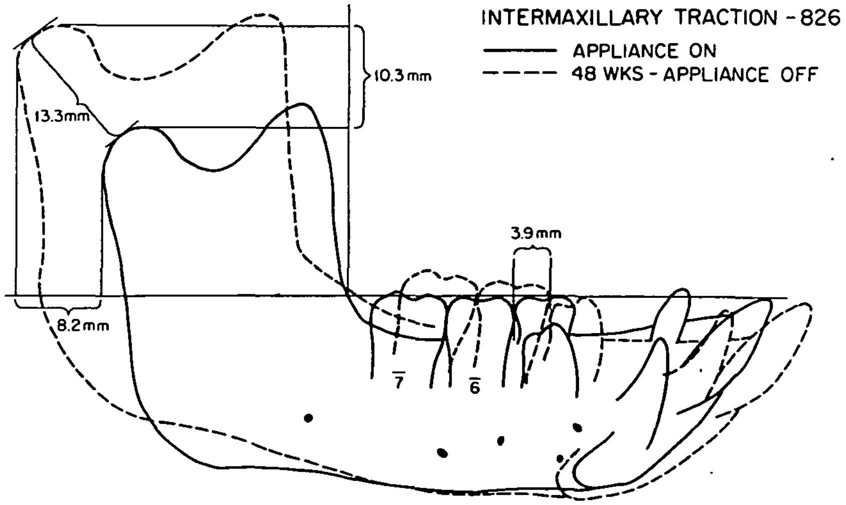

Figure 25 Adaptations in the mandible following 48 weeks of intermaxillary traction. Note the increase in condylar growth in all directions, when compared to control values (Fig. 15). Note also the increase in mesial migration of the posterior dentition.

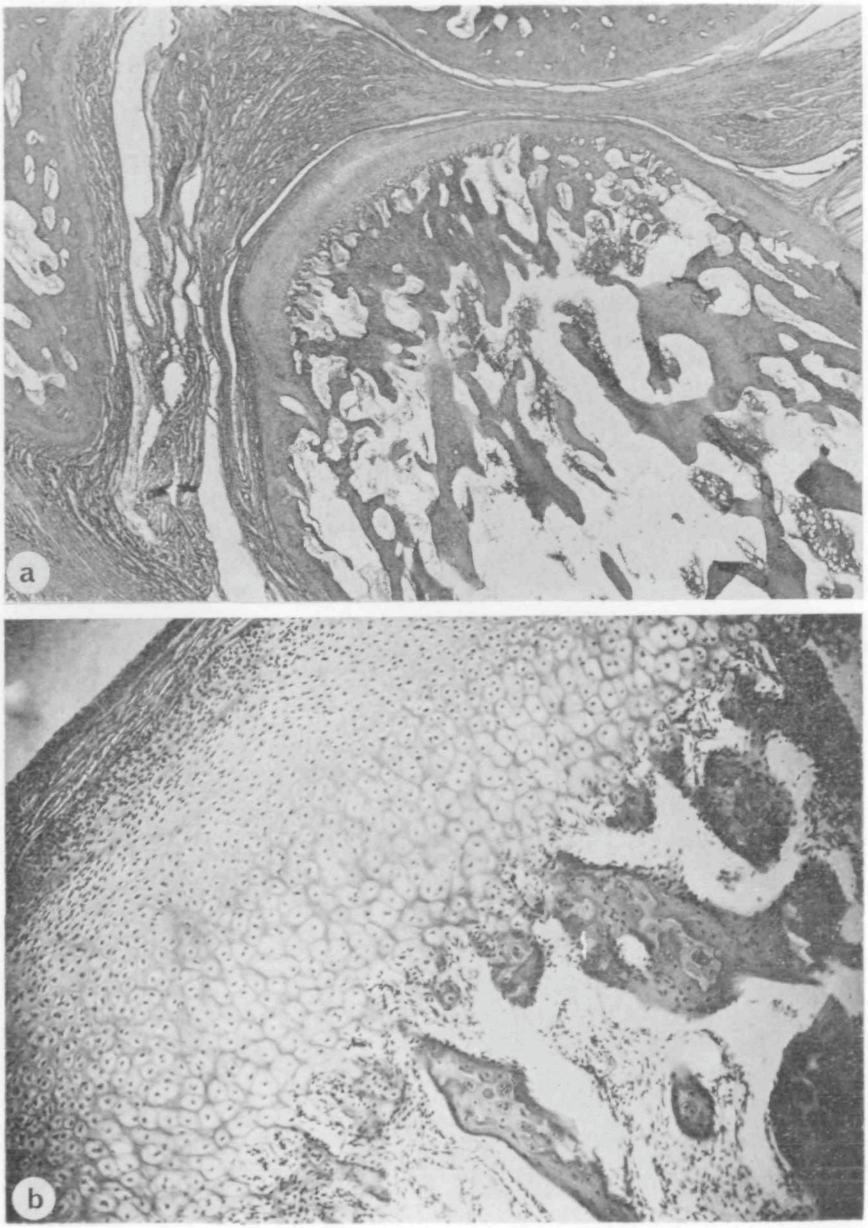

Figure 26 A temporomandibular joint region of the two-week intermaxillary traction animal. (a) Low power view demonstrates increased proliferation of the condylar cartilage, particularly in the posterosuperior region. (×8.4). (b) High power view of condylar cartilage in the same animal. Note the increase in the size and number of cells when compared to a control specimen (Figure 18b).

functional protrusion experiments, increased cartilage proliferation was also observed as late as 12 weeks following appliance placement (Fig. 27).

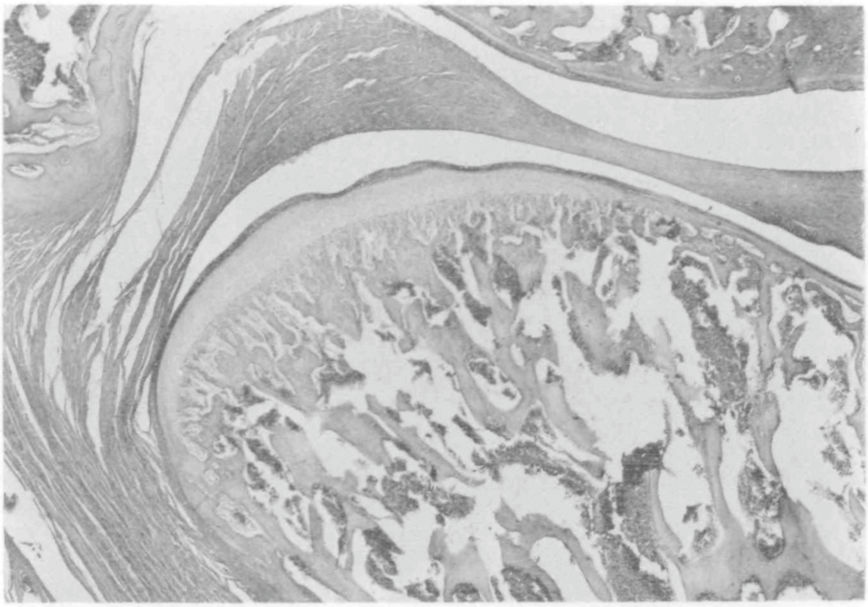

Figure 27 Temporomandibular joint region of a 12-week intermaxillary traction animal. (×8.4).

Summary

Figure 28 illustrates the sequence of responses we think occurs in this experimental model. The placement of the intermaxillary traction appliance results directly in the forward positioning of the jaw, due to the contraction of the coiled springs (A–Fig. 28). This forced forward positioning results in an alteration in the stimuli to the various receptors of the orofacial region. This response triggers an alteration in neuromuscular function characterized by a decrease (or increase) in the activity of the posterior temporalis muscle, an increase in masseter muscle activity, and a variable response from the lateral pterygoid muscle. The pattern of muscular response is not as predictable as in the functional protrusion experiments, perhaps because of the lack of a fixed postural positioning of the mandible (B–Fig. 28). We have seen that structural adaptations gradually occur and that, although there is a gradual decrease in compensatory muscle activity, this activity never quite returns to control level values.

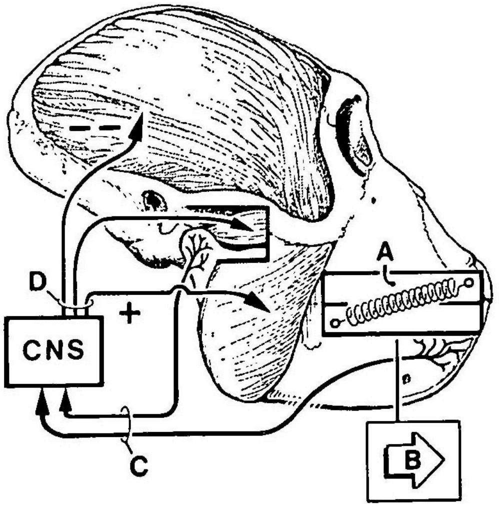

Figure 28 Schematic representation of adaptations following initiation of intermaxillary traction. Placement of appliance (A) results in the forward movement of the mandible (B). The change in spatial relationships alters the nature of the stimuli to the various receptors of the orofacial region. This information is transmitted (C) to the central nervous system (CNS). The central nervous system then initiates changes in neuromuscular function, the nature of these changes varying with the individual animal.

Studies of intermaxillary fixation

Preliminary findings from a third series of experiments will now be presented, in which the movement of the temporomandibular joint is eliminated through the use of intermaxillary fixation. An intraoral appliance (Cobel-Geard et al., 1978) consisting of maxillary and mandibular intraoral castings which were connected with an interlocking system and stabilized with a nut and bolt fastener (Fig. 29) were cemented in juvenile rhesus monkeys after the removal of the upper and lower incisors to facilitate feeding. The appliances were then bolted together to provide positive positioning of the lower jaw in one occlusal relation.

To date we have histological data on only three short-term animals, two sacrificed at 6 weeks and one sacrificed at 28 weeks following appliance placement. However, the condylar responses to this lack of temporomandibular joint movement are so dramatic that they are relevant to the discussion of the role of function in the growth of the temporomandibular joint.

Histological analysis of the temporomandibular joint region of the two animals sacrificed after six weeks of intermaxillary fixation indicated that the condylar cartilage had significantly decreased in thickness (Fig. 30a). The prechondroblastic and chondroblastic layers could usually be distinguished although, in some posterior regions, the identification of distinct condylar cartilage layers was not possible (Fig. 30b). The most dramatic changes occurred in the chondroblastic zone, which demonstrated a decrease in the number of cell layers (3–4 layers in the fixation animals in comparison with 15–20 layers in the controls) and reduction or absence of intracellular matrix around each chondrocyte.

The thickness of the growth cartilage was significantly greater in the 28 week animal. However, in certain regions, particularly in the posterior and posterosuperior regions, the cartilaginous matrix appeared to be undergoing calcification.

Summary

The preliminary conclusion drawn from this experiment is that the lack of movement of the mandible which occurred after the cementation of the fixation appliance had an immediate and profound effect on the morphology of the condylar cartilage. A decrease in function resulted in both qualitative and quantitative changes in the condylar cartilage.

Regulation of condylar growth

The experimental models of functional protrusion, intermaxillary traction and inter-

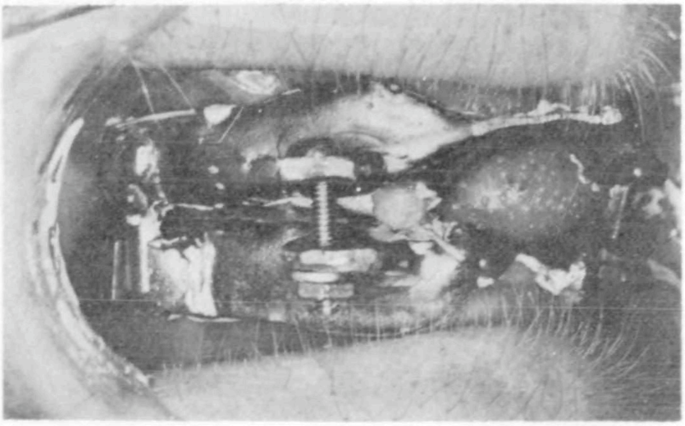

Figure 29 Intraoral view of intermaxillary fixation device (after Cobel-Geard et al., 1978).

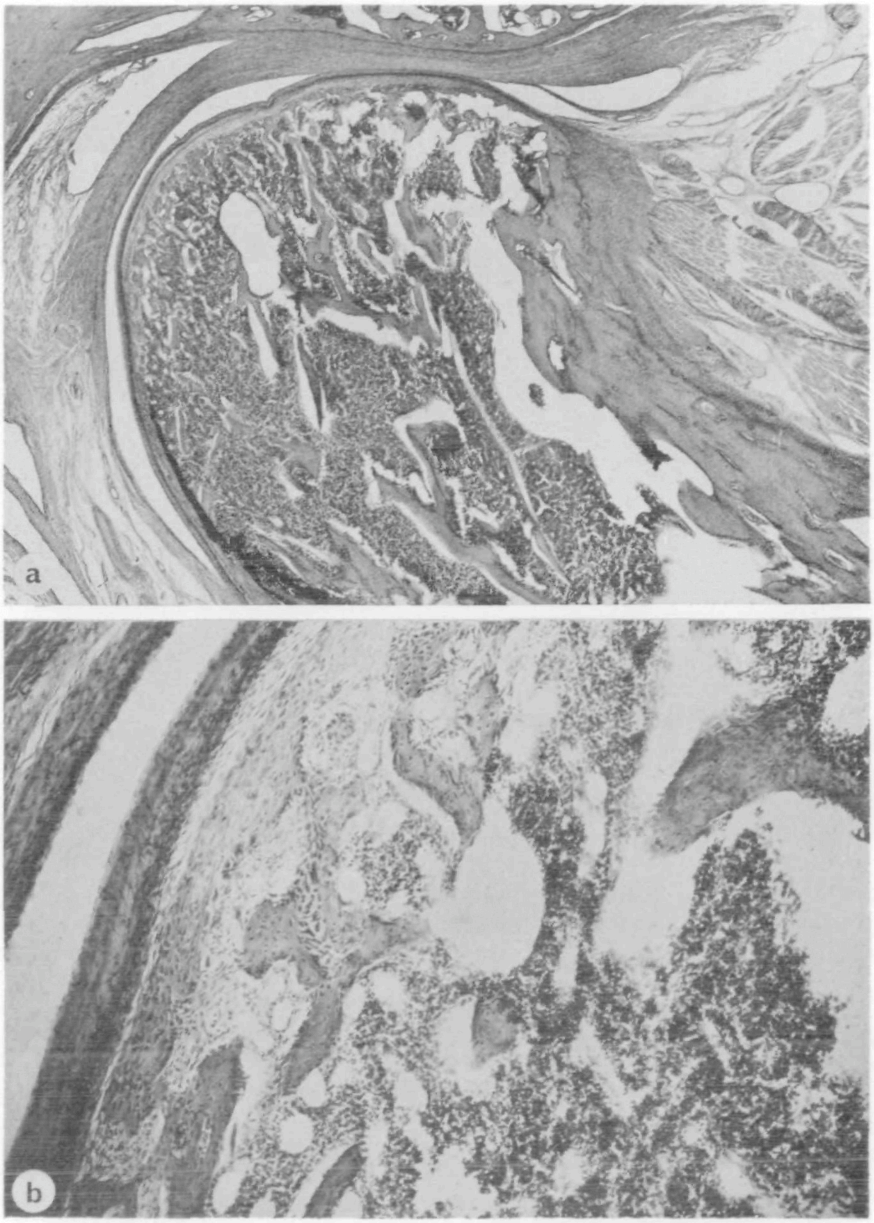

Figure 30 (a) Temporomandibular joint region of a six-week intermaxillary fixation animal. Note the decrease in the thickness of the condylar cartilage. (×8.4). (b) Condylar cartilage in same animal. Note the almost total absence of chondrocytes in the posterior region of the condyle. Compare this section to that from a control animal (Figure 18b). (×28).

maxillary fixation provide dramatic evidence that the growth of the temporomandibular joint in the *growing* individual can be altered by changing the functional environment. This is not surprising when the embryology of the temporomandibular joint is considered.

Embryology and phylogeny of the mandibular condyle

Most of the articulations in the body are originally formed from the primary cartilaginous skeleton. Numerous clinical and experimental studies have shown that primary cartilages are extremely resistant to changes in pressure and tension and provide the skeleton with a mechanism of growth under compressive forces (e.g., Strobino et al., 1952; Blount and Zieir, 1952).

In contrast to most other bones of the body, the mandibular articulation of the mandible is not derived from the primary cartilage of the first branchial arch (Meckel's cartilage), but is secondary in nature (Moffett, 1966; Petrovic, 1972), and perhaps is closer to the periosteum in its response to pressure and tension. Immunological studies by Brigham and co-workers (1977) have shown distinct differences between the cartilage of the mandibular condyle and other cartilages of the craniofacial and appendicular skeletons.

Intrinsic regulation of condylar growth

Perhaps the best understanding of the regulation of the growth of the mandibular condyle has been provided by Alexandre Petrovic, Jeanne Stutzmann and their co-workers in Strasbourg, France. For the last fifteen years their laboratory has been involved in numerous studies of the growth of the mandibular condyle in the rat (e.g., Charlier et al., 1969; Petrovic, 1970, 1972; Petrovic et al., 1973, 1975; Petrovic and Stutzmann, 1977; Oudet and Petrovic, 1978), many of which are similar to our studies in the monkey.

A recent paper by Stutzmann and Petrovic (1979) which deserves particular attention reports a study in which Stutzmann and Petrovic carried out an extensive investigation of condylar growth in organ culture by sectioning the mandibular condyle at specific divisions of condylar differentiation. They documented a negative feedback mechanism between the thickness of the layer of functional chondroblasts and the mitotic activity in the prechondroblastic layer. My interpretation of their working hypothesis and how it applies to changes in the functional environment is as follows (Fig. 31a):—

Any change in the biomechanical environment causes the cells in the inner chondroblastic layer to increase in thickness and number. This increase has two effects. First, the change in the biomechanical environment leads to an increase in the amount of endochondral bone formation and, second,

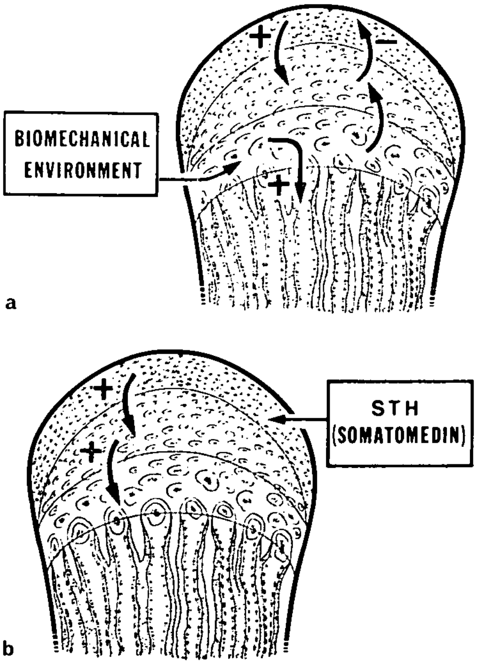

Figure 31 Mechanisms regulating condylar growth, as postulated by Stutzmann and Petrovic (1979). (a) Biomechanical control—A change in the biomechanical environment (e.g., displacement of the condyle away from the glenoid fossa) results in an increase in the size of the hypertrophic zone of the chondroblastic layer of the condylar cartilage. This results in an increase in secondary bone deposition and a decrease in the number of functional chondroblasts. This decrease in functional chondroblasts results in a proliferation of the prechondroblasts and a restoration of the functional chondroblastic layer. (b) Hormonal control – somatotrophic (growth) hormone (STH) through its intermediary somatomedin has a direct effect on the proliferation of the prechondroblastic layer of the condylar cartilage.

it leads to a gradual depletion of the chondroblasts in the functional layer. Functioning under the control of some type of negative feedback system, this decrease in the number of functional chondroblasts prompts an increase in the mitotic activity of the prechondroblastic layer. This increase in the prechondroblastic layer results in the restoration of the thickness of the functional chondroblastic layer, thus re-establishing structural balance in the condylar cartilage.

Stutzmann and Petrovic also demonstrate another mechanism for affecting the rate of condylar growth; namely the influence of hormones (Fig. 31b). They note that an agent such as somatotrophic hormone (STH) or its intermediary somatomedin may act directly on the mitotic compartment rather than in the functional or hypertrophic zones of the chondroblasts. The Stutzmann-Petrovic model provides two independent mechanisms by which condylar growth can be altered. Our histologic and radiographic experiments in monkeys to date support the hypotheses presented by Stutzmann and Petrovic (1979).

Analyses of three experimental models, incorporating the Stutzmann-Petrovic hypothesis

Functional protrusion The placement of the appliance results in an altered muscle pattern, which ultimately results in a forward positioning of the mandible. This forward positioning of the mandible changes the biomechanical and biophysical environment of the temporomandibular joint. This alteration in biomechanical environment is perhaps mediated by changes in pressure and tension gradients in the joint capsule, ligaments and other associated soft tissue. This change in environment initially produces an increase in thickness of the hypertrophic layer of chondroblasts, which subsequently leads to an increase in the rate of bone deposition in the zone of endochondral bone formation and a decrease in the thickness of the functional chondroblastic layer. This decrease in the thickness of the functional chondroblastic layer is relayed to the prechondroblastic layer (mitotic compartment) through a negative feedback system, which results in an increase in the mitotic activity of this region. As the amount of displacement is gradually reduced through condylar remodeling, the degree of condylar response again returns to control values.

Intermaxillary traction The placement of the intermaxillary traction device with the coiled spring perhaps, in itself, causes the displacement of the condyle, thus leading to the alteration of the biomechanical environment. A sequence of condylar responses similar to the functional protrusion model is observed until the integrity of the temporomandibular joint is once again re-established. The direct role of muscle contraction in mediating the response in the mandibular condyle does not appear to be an important factor in this model

Intermaxillary fixation The Stutzmann-Petrovic hypothesis can also be applied to the intermaxillary fixation experiments. The permanent closure of the jaws in a fixed position results in an alteration of the biomechanical environment of the joint, but in this instance in the opposite manner. The lack of function, through some mechanism yet unknown, causes the gradual change of chondroblasts into osteoblasts in an environment in which there is no movement. This relationship between the chondroblasts and osteoblasts of the condylar cartilage has been previously described by Petrovic and coworkers (1975). A similar response of the angular and condylar cartilages of the rat mandible to changes in the functional environment has also been shown by the study of Duterloo and Wolters (1971).

Post-treatment adaptations

The Stutzmann-Petrovic hypothesis may also help us understand some of the condylar responses which occur after the appliances are removed. Any time an appliance is removed from an experimental animal, a structural and functional imbalance is produced and a new experiment begins. In the analysis of our post-treatment animals we have found that the nature of the response depends, in great part, upon the stability of the occlusion at the time of appliance removal. The neuromuscular and skeletal adaptations occurring during the post-treatment period may be quite variable. For example, Figure 32 is a tracing of a control animal during two sequential 38-week intervals. Compare this tracing with that (Fig. 33) of an animal in which a functional protrusion appliance was

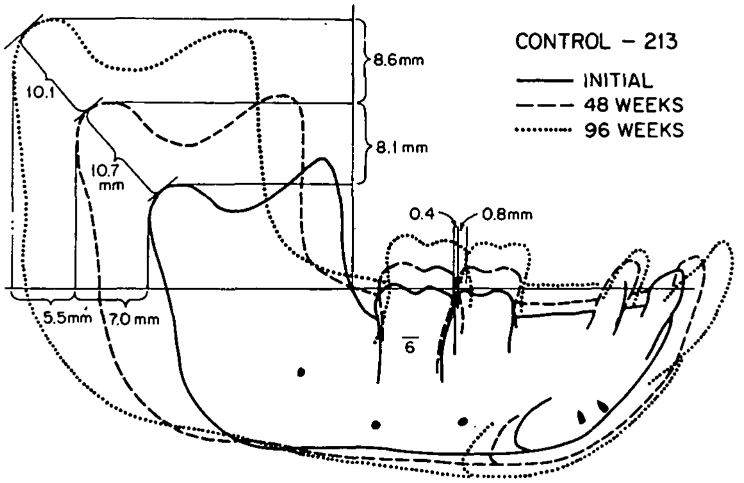

Figure 32 Mandibular growth of a control animal during two sequential 48-week periods.

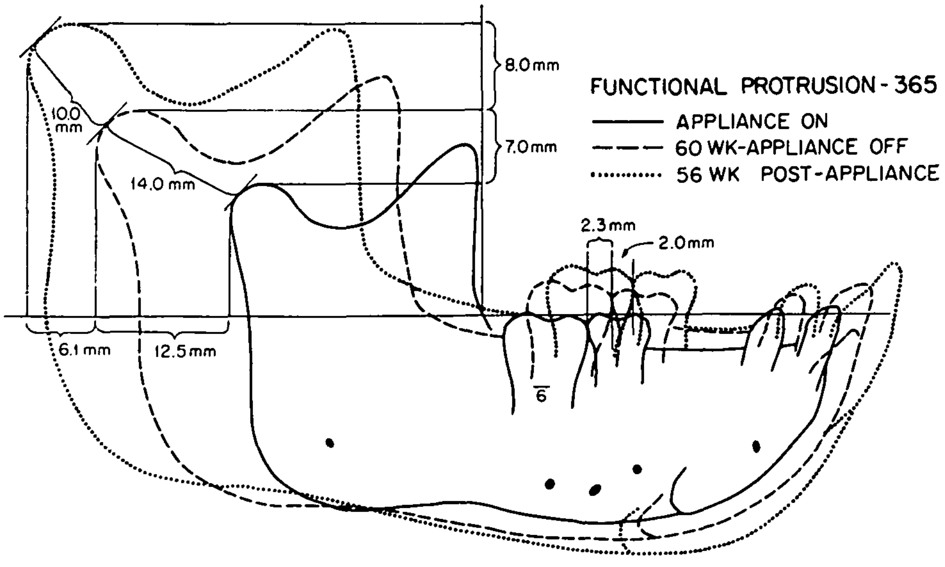

Figure 33 Post-treatment adaptations in a functional protrusion animal. Note the relatively larger amount of condylar growth during the experimental period. Growth during the post-appliance period was similar to that observed in control animals.

placed for 60 weeks and then removed for 56 weeks. Note the alterations in the amount and direction of condylar growth during the treatment and post-treatment periods. Similarly, in Figure 34, note the differences in response when intermaxillary traction devices were placed for a 48-week period and then removed for an additional 48-week period. At first inspection the growth of these animals seems quite varied. Yet this alteration in the amount and direction of condylar growth is probably in response to the biomechanical environment present in the temporomandibular joint region, and may be merely a reflection of an intrinsic control mechanism which regulates the growth of the mandibular condyle.

Stimulation of manibular growth

This discussion leads us to the obvious question of 'Can mandibular growth be stimulated?' I think this question, although repeatedly asked, is not phrased correctly, since it appears that at least one aspect of the growth of condylar cartilage is regulated by an intrinsic feedback mechanism. Our concepts of variations in normal growth, the increased growth produced by experimental or therapeutic intervention, and the decreased growth produced by intermaxillary fixation (or perhaps retrusive forces on the condyle), are merely illustrations of a *spectrum* of growth potential which is influenced by the biomechanical environment in which the joint exists (Fig. 35). The growth of the temporomandibular joint, at least in part, is always stimulated. Perhaps a better question would be, 'Knowing that an intrinsic regulating mechanism exists in the temporomandibular joint, how can I best utilize this knowledge in planning the ideal treatment for my patients?'

Summary and conclusions

There is an intimate relationship between the functional and structural components of the craniofacial region. Any intervention in this region, whether through experimental or

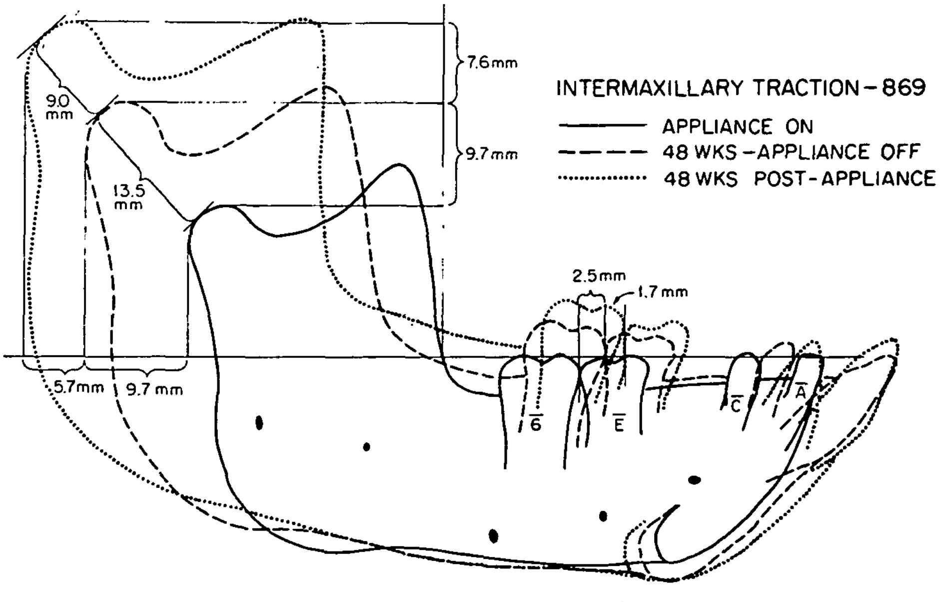

Figure 34 Post-treatment adaptations in an inter-maxillary traction animal. The amount of growth occurring during the 48 weeks that the animal was wearing the appliance was substantially greater than that occurring after the appliance was removed.

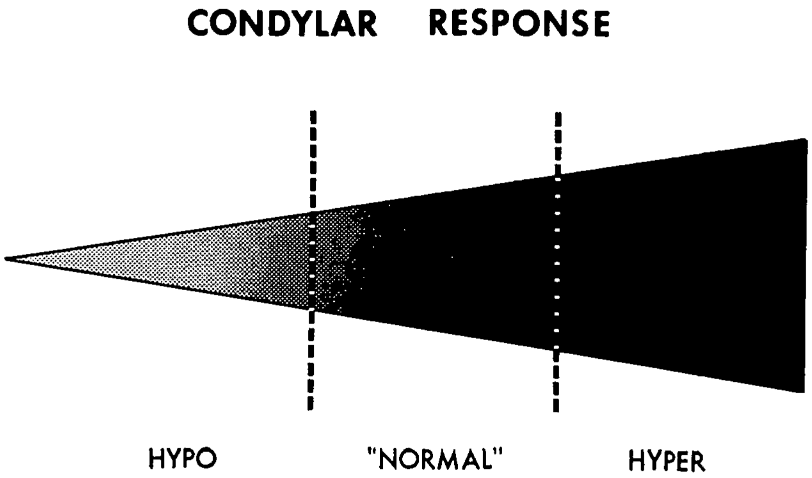

Figure 35 A diagramatic representation of condylar response to altered function.

therapeutic means, results in an alteration in the existing balance between the various hard and soft tissue components of the craniofacial region. Functional adaptations tend to occur very rapidly but are always gradually followed by structural adaptations, the nature of which depends upon the age of the individual.

If we carry this philosophy to the diagnosis and clinical treatment of patients, we must always be aware that any existing malocclusion is in a state of balance regardless of the nature of the individual components. In planning the ideal therapeutic regime, the goals of treatment should include the achievement of long-term stability, which can be obtained only if the resultant skeletal and dentoalveolar configuration exists in harmony with the associated musculature and other soft tissues following treatment. If this goal is achieved, the concept of 'relapse' as used in orthodontics can be limited primarily to alterations in tooth position. Theoretically there should be no need to retain mechanically a structural relationship which has been achieved concomitant with the elimination of compensatory muscle function. Only by taking into account functional as well as structural imbalances can we provide the best treatment for our orthodontic patients.

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