CASE WESTERN RESERVE UNIVERSITY

GRADUATE STUDIES

We hereby approve the thesis of

Eric Mathers Ornella

candidate for the Master Of Science In Dentistry

degree.

Signed: Donald N. Enlow
(Chairman)
Roy B. Bellucci
Robert Cichy

Date April 20, 1984

RAMAL REMODELING IN THE PIG AS AFFECTED BY CONTINUOUS POSTERIOR TRACTION AND FUNCTIONAL HYPERPROPULSION OF THE MANDIBLE

by

ERIC MATHERS ORNELLA

Submitted in partial fulfillment of the requirements

for the Degree of Master of Science in Dentistry

Department of Orthodontics

School of Dentistry

CASE WESTERN RESERVE UNIVERSITY

May 1984

RAMAL REMODELING IN THE PIG AS AFFECTED BY CONTINUOUS POSTERIOR TRACTION AND FUNCTIONAL HYPERPROPULSION OF THE MANDIBLE

Abstract

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The purpose of this study was to investigate the effects of continuous posterior traction and functional hyperpropulsion of the mandible on growth and remodeling of the ramus. Three, five week old pigs were used as animal models. Pig 1 received a mandibular retrusive appliance. Pig 2 received a mandibular protrusive appliance. Pig 3 received no appliance and acted as a control. The protrusive appliance consisted of an anterior inclined plane bonded to the mandibular incisors, which upon jaw closure, elicited a 4 mm functional protrusion. A continuous posterior traction of 16 ounces per side was accomplished by bonding an acrylic splint on the mandibular anterior teeth, with a wire hook exiting each side of the mouth connected by springs to a chest harness. The experimental period lasted for 30 days.

On the 1st experimental day the animals were weighed, stainless steel implants were placed in the mandible at the symphysis and the posterior border of the ramus, and lateral head radiographs were exposed. Vital dyes were administered on the

2nd, 12th, 22nd, and 29th experimental days. The animals were sacrificed, weighed, and radiographed on the 30th experimental day. The mandibles of each animal were measured and compared for gross anatomic differences. The radiographs were superimposed and described. Histologic evaluation of serial ground sections was carried out.

The radiographic superimposition showed specific differences in the patterns of mandibular growth and remodeling in the three pigs. Pig 1 (retrusive appliance) displayed a decrease in bone deposition on the posterior border of the ramus and an increase of bone deposition at the mandibular symphysis. Pig 2 (protrusive appliance) showed an increase in vertical growth of the ramus along with a decrease in the amount of bone deposition on the posterior border of the ramus and a decrease in bone deposition on the inferior border of the mandible. There were specific differences in the configuration, distribution, and size of the ramal growth fields in the three pigs. Pig 2 (protrusive appliance) displayed a resorptive field that extended along the entire length of the anterior border of the ramus, but only to the level of the mandibular notch. This is in contrast to the resorptive field of Pig 1 (retrusive appliance), which extended far up the coronoid process. The lateral surface of the ramus of Pig 1 also exhibited a depository growth field extending from the base of the mandibular notch to the start of the ascending ramus. This

resulted in a ridge of bone not present on the lateral ramal surface of the other two animals. The depository growth field covering the inferior mandibular border of Pig 2 (protrusive appliance) resulted in the elimination of the antegonial notch which was found to be present in the other animals.

Direct measurement of the mandibles revealed that Pig 1 (retrusive appliance) had the shortest mandible; Pig 2 (protrusive appliance) had the longest mandible, the largest ramus height, and the smallest ramus width; and Pig 3 (control) had the widest ramus. Both appliances, in addition to their intended action, also demonstrated a bite opening effect.

The results of this study indicate that the mandibular ramus is quite responsive to continuous posterior traction and functional hyperpropulsion of the mandible. This responsiveness of the ramus to altered mandibular posture indicates that it may be an extremely important contributor to compensatory alteration of the mandible and could actually be the principal clinical target for many of the appliances used in orthodontics.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to the following individuals:

Dr. Donald H. Enlow, Professor and Chairman, Department of Orthodontics, Assistant Dean for Graduate Studies and Research, Thomas J. Hill Distinguished Professor, School of Dentistry, whose incredible knowledge of facial growth and development, and ability to teach have inspired my desire to learn.

Dr. Rolf G. Behrents, Assistant Professor and Director of the Orthodontic Clinic, for injecting a note of calm when worry got the best of me during this thesis.

Dr. Robert Cederquist, Assistant Professor of Orthodontics, for his valuable technical assistance.

Dr. Nancy Kleinman, whose patience, willingness to help, and skill with the animals allowed me to conduct this investigation.

Dr. Elias Katsavrias, fellow classmate, whose assistance on this thesis went above and beyond anything I could have expected.

Drs. Canepa, Katsavrias, Pinkard and Wu, whose friendship made the last two years so much more enjoyable and memorable.

The late Dr. Milton Rabine, whose confidence and support played a major role in my attending this orthodontic program.

Ms. Linda Nicholl, for her excellent skill in typing this thesis.

DEDICATED

TO

Mr. and Mrs. Albert Ornella, my parents, whose unconditional love and support have made everything possible.

Julia and Devin Ornella, my wife and son, whose loving and caring make life wonderful.

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INTRODUCTION

One of the most difficult situations facing any orthodontist is that of trying to correct a malocclusion resulting from a skeletal imbalance. Two of the more common skeletal imbalances involve the mandible; prognathia and retrognathia. If the clinician could stimulate or restrict mandibular growth at specific sites, then, theoretically many malocclusions due to skeletal imbalance could be corrected.

Many factors have been shown or theorized to be involved in the control of growth. Some of these factors are genetic influences, biomechanical forces, neurotrophism, the piezo factor, and the activity of inductor substances. No single factor though has been shown to be directly responsible for the control of growth. It has been recognized that control of growth is multifactorial. There is a chain of regulatory components that exist for each specific control pathway. It is important to recognize how a factor participates in the chain, whether as a first messenger, trigger, or a subordinate.

Traditionally, the site considered to be the most significant in terms of controlling growth of the mandible has been the condyle. It is now becoming realized that the entire ramus not just the condyle, is directly involved in the growth and adaptive requirements of the mandible. Thus, it is important to understand

how the ramus is involved in mandibular compensations if we hope to alter existing conditions predictably and favorably.

Many of the current appliances used for the purpose of controlling mandibular growth have the entire ramus (which includes the condyle) as a principal target. Extraoral forces have been in use for years in the attempt to correct skeletal imbalances of the mandible. As early as 1803, Fox and Cellier used extraoral forces in the manipulation of maxillomandibular skeletal problems. Currently, the chin cup is used to try to restrain and redirect mandibular growth. Studies (Janzen and Bluher, 1965; Petrovic et al., 1975; Graber, 1975) have shown that use of the chin cup with orthopedic forces can alter the growth of the mandible resulting in decreased ramal height, a closed gonial angle, and decreased cellular division in the condylar cartilage.

Over the years there has been much interest surrounding the possibility of using hyperpropulsive forces to stimulate mandibular growth. As early as 1902 hyperpropulsors were being used by Robin in children with mandibular micrognathia. At present there exists quite a number of "functional" appliances which are claimed to stimulate mandibular growth by holding the mandible of a growing child in a protrusive position. Experimental studies (McNamara, 1972; Petrovic et al., 1975; Woodside et al., 1983) have shown that a significant alteration in mandibular growth can

be produced by hyperpropulsing the mandible. Some of the changes observed experimentally have been increased proliferation of the condylar cartilage, increased mandibular length, an increased mandibular angle, and increased condylar remodeling.

While it has been demonstrated that the growth of the mandible can be altered, little attempt has been made to look at the actual patterns of remodeling produced in the entire ramus as a result of postural alteration, which could have a pronounced effect upon mandibular morphology. Thus, we must ask:

1. Do mandibular postural alterations produce changes in ramal remodeling patterns?
2. If so, do these changes differ with the type of postural alteration applied?
3. How is the overall morphology of the mandible affected if different ramal remodeling patterns are produced?
4. How do such alterations affect positional relationships of the mandible with the basicranium and maxillary complex?

REVIEW OF THE LITERATURE

Overview of Mandibular Growth

Classically, the major emphasis for growth of the mandible has been centered around the condyle. The mandibular condyle has been thought of as a "master center" which controls the rate, amount, and direction of mandibular growth. This theory attributes mandibular displacement to the growth potential located in the condylar cartilage. The condylar chondroblasts were thought to contain the genetic program for determining mandibular growth, size, and shape.

Rushton (1944), believed that "it is the function of the condylar growth center to promote continual displacement of bone upon which subperiosteal additions and remodeling can be exercised." Sicher (1947), felt that mandibular growth was the result of growth of the condylar cartilage and associated osseous tissue replacement. Scott (1959), stated that the mandible grows in a downward and forward direction from its articulation in the glenoid fossa due to a thrust created by proliferation of the condylar cartilage toward its contact.

Although the classical theory of mandibular growth was accepted as dogma for many years, people began questioning whether it might be too simplistic an explanation for a process that was beginning to be shown to be quite complex. According to Moss

(1964), van der Klauuw suggested a functional analysis of craniofacial growth in the late 1940's. Moss (1960, 1964, 1968, 1969, 1971), has taken this idea and refined a theory of mandibular growth based on functional analysis. He considers every function to be carried out by a functional cranial component which consists of two parts:

1. a functional matrix which actually caries out the function and,

2. a skeletal unit whose role it is to protect and/or support its specific functional matrix.

Moss (1964), states:

> That all growth changes in the size, shape and spatial position and, indeed, the very maintenance in being, of all skeletal units are always secondary to temporally primary changes in their specific functional matrices.

Thus, the genetic determinants of the growth process are not in the bone itself, but are in the functional matrices surrounding the bone. Moss designates two basic types of functional matrix:

1. Periosteal matrices (muscle, teeth, glands, etc.) that act to alter the size and shape of skeletal units by osseous deposition and resorption and,

2. Capsular matrices (spaces, brain, orbit, etc.) which, upon their expansion, are responsible for translative growth.

Moss (1960), rejects the concept of the condyle as being the "master center" and states that the growth of the condylar cartilage is a compensatory event resulting from mandibular translation brought about by the growth of the so-called "functional matrices".

Enlow and Harris (1964), studied remodeling in the human mandible during the growth period. They showed that relocation, regional growth fields, and the "V" principle occur throughout the mandible. The regional growth fields of either resorption or deposition exist on both the periosteal and endosteal surfaces of a bone. The soft tissue matrix surrounding the bone contains the genetic and functional determinants of growth. Thus, in Enlow's (1975) opinion, the growth field in the soft tissue membranes act to stimulate remodeling, which functions to:

1. progressively enlarge each whole bone;
2. sequentially relocate each of the component parts of the whole bone to allow for overall enlargement;
3. shape the bone to accomodate its various functions in accordance with the physiologic actions exerted on that bone;
4. carry out regional structural adjustments so that a functional fitting of all the separate bones to each other and to their soft tissues is achieved.

Another part of the overall growth process is displacement. Primary displacement occurs when a bone is carried away from its articular contact by the expanding soft tissues while simultaneously enlarging to maintain that contact. Secondary displacement occurs when a bone's movement relates to enlargement of other bones (Enlow, 1975).

The mandibular condyle is considered by Enlow (1975), to be a special growth site but not a "master center". He feels that it does not directly regulate the growth of the mandible as a

whole, but it does represent a "regional field of growth adapted to the localized morphogenic circumstances in its own area." The condylar cartilage cells are considered to be genetically coded to divide. The rate and direction of condylar growth is thought to be influenced by extra condylar agents including intrinsic and extrinsic biomechanical forces and physiologic inductors (Enlow, 1982). Increased compression on the condylar cartilage is believed to inhibit the rate of cell division and growth while decreased amounts of pressure are considered to stimulate cell division and growth.

Enlow (1982), states that the ramus plays a direct and major role in adaptive, interrelated growth of the mandible. In his view, it is responsible for the anteroposterior position of the lower arch, placing the arch in occlusal contact with the maxilla, and vertical dimension of the mandible. The masticatory muscles attach to the ramus, which in turn must be able to accomodate their growth and size.

Enlow (1975), has outlined the four basic functions that the continuing sequence of remodeling changes occurring in the ramus provide:

1. The entire ramus is progressively relocated posteriorly by combinations of resorption and deposition on its various surfaces;

2. The essential function of this relocation is to provide for the posterior growth and elongation of the contiguous corpus. The lengthening of the corpus requires a direct remodeling conversion from ramus into corpus;

3. The ramus lengthens vertically to accomodate the vertical growth of the nasomaxillary complex and tooth eruption;

4. The ramus undergoes progressive remodeling changes in order to position the mandibular corpus in juxtaposition with the maxillary corpus.

Thus, remodeling of the ramus would be responsible for opening or closing of the gonial angle thereby resulting in a more vertical or horizontal growth pattern of the mandible.

According to Enlow, the condyle is only one part of the ramus which contains many other regional growth sites. To him the ramus is a compensatory structure that provides adaptation to the particular structural and developmental conditions that exist. Thus, if the views of Enlow are to be believed, the ramus must be considered as playing an extremely significant role in overall mandibular growth and its control.

Clinical and Experimental Investigations

Over the years many experimental investigations have been performed on various animal models for the purpose of studying mandibular growth. The earliest such studies looked at how the mandible grew under relatively normal circumstances.

Hunter (1778), fed pigs madder, a type of vital dye, and discovered that the mandible increased in size by apposition at the posterior ramal border. He also found that the jaw remodeled by resorption at the anterior border of the ramus. Humphry

(1871), confirmed Hunter's findings in the pig by the use of wire implants placed around the ramus.

In 1941, Brodie studied human serial roentgenograms. He concluded that the condyle contributed to an increase in height of the ramus and forward growth of the mandible.

In 1955, Robinson and Sarnat, using 8 week old pigs as a model, placed metallic implants in the ramus and body of the mandible. These implants yielded a stable base upon which to superimpose radiographs for the purpose of studying growth. They confirmed the findings of Hunter, and in addition, stated that apposition of bone took place at the inferior border of the mandible. They stated that the ramus was responsible for 80% of the anterior-posterior body length of the mandible due to the fact that there is twice as much bone apposition on the posterior ramal border as there is bone resorption from the anterior ramal border. The condyle was seen as being responsible for 80% of the vertical height of the mandible.

Bjork (1955, 1963) used metallic implants and radiographs to study mandibular growth in humans. He found a great individual variability in mandibular growth.

Over the years many investigators have attempted to understand more about mandibular growth by testing Wolff's law of bone transformation, which states that a bone's morphology becomes progressively structured to accomodate the sum of all the changing

mechanical forces exerted on it during growth and development. Thus, mechanical forces have been applied in various animal models to try and determine what effects they will have on mandibular growth.

The greatest emphasis has been placed on trying to stimulate mandibular growth. As early as 1902, Robin was placing intraoral appliances to protrude the mandible of children suffering from severe mandibular micrognathia. Since that time, many different appliances have been developed to protrude the mandible in the hope of stimulating growth, e.g., Activator, Functional Regulator, Herbst. Only in the last 25 years have there been experimental studies designed to investigate the results of such mandibular hyperpropulsion. Elgoyhen et al. (1972) and McNamara (1973a), in juvenile rhesus monkeys, used intraoral gold castings to protrude the mandible. They observed changes in the growth pattern of the condylar head. The extent of the growth was increased and the direction of growth became more horizontal. Elgoyhen et al. (1972) noted an increased deposition of bone at the posterior ramal border after four weeks of protrusion, whereas McNamara (1973a) noted no increase in the rate of bone deposition along the posterior border of the ramus after a 13 week experimental period. McNamara also observed alterations at the angle of the ramus and condyle to the occlusal plane. The angle to the occlusal plane did not decrease as in the controls. He concluded

that there was no single adaptive process that could be identified as the only cause of any alteration in maxillomandibular relations. Each resulting relationship was the result of specific adaptations throughout the craniofacial complex.

Petrovic et al. (1975) placed postural hyperpropulsors in rats. After four weeks they found that cell divisions of the condylar, coronal, and angular cartilages were increased. The mandibular length was measured directly by calipers between the posterior condylar border and the mental foramen. In the four week experimental rats, this length was found to be increased over that of the controls. The mandibular angle (a line drawn through the middle of the condyle to a line tangent to the inferior border of the mandible) was found to be increased by three degrees. This increase was due to increased apposition of periosteal bone on the posterior ramal border. Woodside et al. (1983), using a Herbst type appliance in young monkeys, found a small amount of condylar remodeling in a superior direction only. Vital stain showed extensive remodeling at the anterior border of the ramus. He concluded that "continuous or chronic alteration in mandibular position within the neuromuscular environment produces extensive condylar remodeling and a change in mandibular size."

The results of these studies and others (Baume and Derichsweiler, 1961; Harvold, 1975, 1983; McNamara et al., 1975; McNamara and Carlson, 1980), indicate that mandibular growth can

be increased in young growing animals. This mandibular growth is increased in both rate and amount along with an alteration of growth direction patterns.

There has been much less emphasis and interest in the area of mandibular growth restriction, especially in North America where the prevalence of mandibular prognathism has been relatively small. As far back as the early 1800's appliances similar to the chin cup were being used to try and restrain the growth of the mandible. In the late 1940's, the idea of using orthopedic forces along with the chin cup, during the period of growth, was developed. This mode of treatment has remained relatively unchanged up to the present day. Class III intermaxillary elastics have also been used in trying to reduce mandibular prognathism.

Animal studies have been used to determine the effects of retrusive forces applied to the mandible. Breitner (1940) and Adams et al. (1972), found regressive remodeling changes on the posterior surface of rhesus monkey condyles resulting from the use of light Class III intermaxillary elastics.

Janzen and Bluher (1965), using rhesus monkeys, placed a retrusive force on the mandibles by using head caps attached to wires placed through the body of the mandible. A force of 150 grams on each side was applied for a period of 140 days. They found no change in mandibular body length, a decreased ramus height, increased apposition of bone on the posterior ramal bor-

der, a closed gonial angle, antegonial notching, and short, thick condylar necks. They felt that retrusive forces do not affect ramal remodeling, but that they produce a "bending" effect of the neck of the condyle.

Belhobek (1974), placed progressive transcondylar traction in young growing guinea pigs. A spring-loaded appliance was placed between the zygomatic arch and body of the mandible. Initially, the appliance was passive, but as growth occurred, the restrictive force increased. He found that loaded mandibular condyles grew significantly less than unloaded condyles.

Petrovic et al. (1975), used a modified chin cup on rats for 8-12 hours per day over a four week period. They found that the distance from condyle to mental foramen was decreased, the mandibular angle was decreased, and that cell divisions in the prechondroblastic zones of the condylar cartilage were decreased.

Tsolakis (1981), studied both heavy and light retrusive forces placed on the mandibles of rabbits. He discovered that there was a significant decrease in mandibular growth in animals treated with both heavy and light forces. The heavy force induced reversed remodeling patterns of the condyle and superior part of the ramus. Condylar and ramal remodeling resulting from light forces was similar to controls. He found a definite change in the structural and cellular morphology of the disc and condylar cartilage resulting from heavy retrusive forces.

STATEMENT OF THESIS

The purpose of this study is to investigate the effects of continuous posterior traction and functional hyperpropulsion of the mandible on growth and remodeling of the ramus. The experimental design involves two different experimental devices to be used on young growing pigs. The functional hyperpropulsor consists of an interior inclined plane placed on the mandibular dentition, which upon jaw closure, elicits a 4 mm functional protrusion. A continuous posterior traction of 16 ounces per side is accomplished by placing an anterior splint on the mandibular dentition, with a wire hook exiting each side of the mouth connected by springs to a chest harness.

Most previous experimental studies concerning changes in mandibular growth have been centered around the condyle. This study will attempt to determine the response of the entire ramus to radically different mandibular postural alterations. The adaptive adjustments of the ramus to the different postural alterations will be described by the use of lateral head radiographs and vital dyes.

MATERIALS AND METHODS

Three domestic pigs (Sus scrofa domesticus) were utilized in this study. The animals were obtained from the Animal Resource Center of Case Western Reserve University and upon receipt they were approximately five weeks old and newly weaned. The pre-experimental weights ranged from 13 to 17 kilograms.

The pig was selected as the experimental animal in this investigation for the following reasons:

1. The mandible of the pig (especially the ramus) is very similar to that of the human.
2. It is a large enough animal to facilitate appliance fabrication.
3. The pig has a very rapid growth rate between five and ten weeks old.
4. The size of the mandible is large enough that any alterations in growth would be more readily apparent.

Pig 1 was fitted with a mandibular retrusive appliance. Pig 2 was fitted with a mandibular postural hyperpropulsor. Pig 3 acted as a control.

Experimental Procedure

On the first experimental day, each animal was weighed (Table I) and impressions of the maxillary and mandibular dental

TABLE I

ANIMAL WEIGHTS DURING THE EXPERIMENTAL PERIOD

	Day 1 Weight kg.	Day 12 Weight kg.	Day 22 Weight kg.	Day 30 Weight kg.
Pig 1 (Retrusive Appliance)	17	21	23.9	34.3
Pig 2 (Protrusive Appliance)	16.8	20.1	22	29.9
Pig 3 (Control)	13	19	21.3	31.3

arches were taken. At the same time metallic implants were inserted and initial lateral cephalometric radiographs were take. Table II outlines the experimental time schedule.

Two days after insertion of the implants, the two different intraoral appliances were placed in the experimental animals and the first vital dye was administered to all three animals. A second vital dye was administered on the 12th experimental day. This was followed by a third vital dye injection on the 22nd experimental day. A fourth vital dye was administered 24-48 hours before sacrifice, and the final set of lateral cephalometric radiographs was taken immediately after sacrifice. The entire experiment lasted for a period of 30 days.

Design and Construction of the Appliances

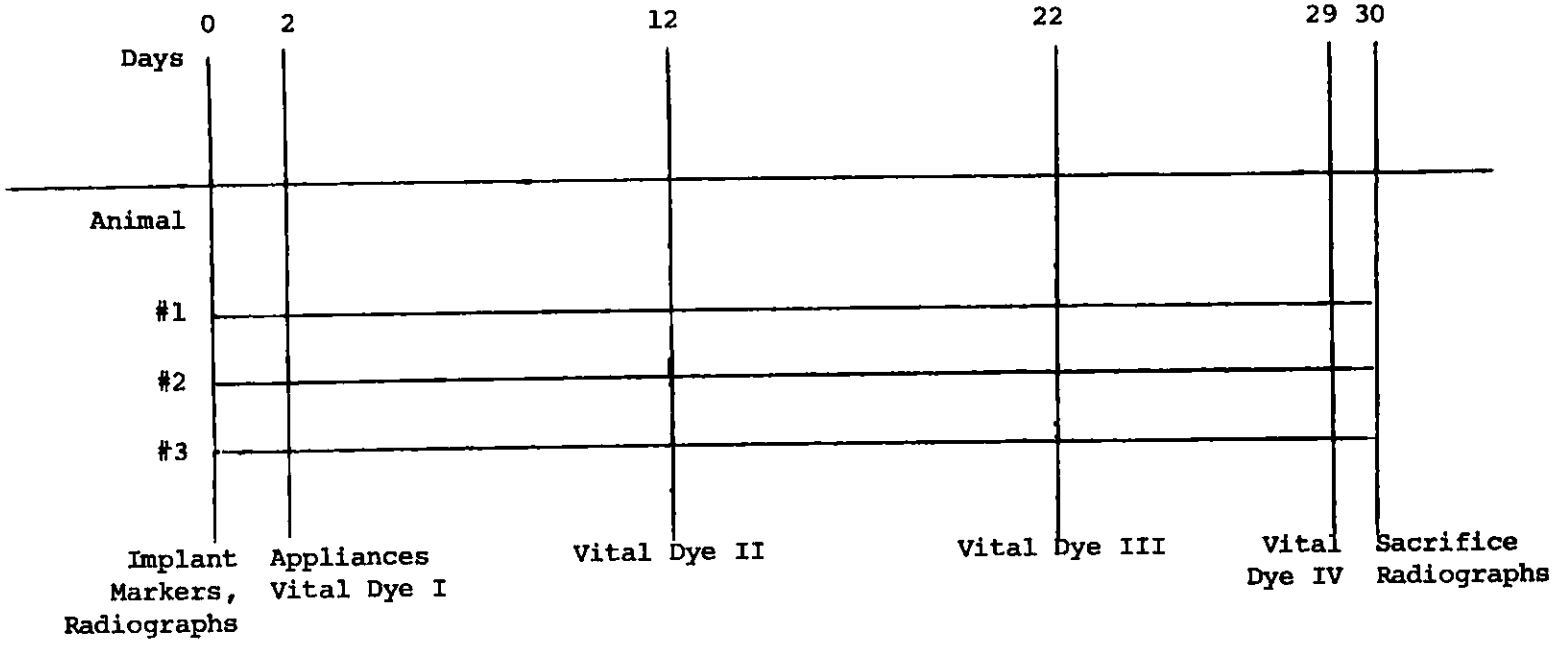
The appliance that was used to exert retrusive forces on the mandible consisted of three main components:

1. an intraoral anterior mandibular splint,
2. an anchoring harness, and
3. a calibrated spring to connect the splint and harness.

Xantropren/Optosil (Unitek Co., Monrovia, California) impressions of the maxillary and mandibular arches of Pig 1 were taken with custom-made acrylic trays, previously constructed on the mandible of a dried pig skull. The final impression was

TABLE II

EXPERIMENTAL TIME SCHEDULE



poured in orthodontic stone. The wire extensions were constructed from a single piece of .072 stainless steel wire which was bent to conform to the labial surface of the mandibular anterior teeth at the labio-gingival junction. The wire exited both sides of the mouth, taking the lip location into account, and was bent into a hook at each end. The wire was held in place on the model by sticky wax and the splint was constructed over it using cold cure acrylic (European Orthodontic Products, St. Paul, Minnesota).

The anchoring harness was constructed by placing facebow neck pads (Orthoband Company, Antonia, Missouri) over a dog harness (Pet Rx, Cleveland, Ohio), which had been modified by cutting off the anterior section leaving only a belt. Additional holes were punched in the belt to allow adjustment of the circumference as the animal grew. To each side of the harness, a calibrated spring sheathed in plastic (Orthoband Company, Antonia, Missouri) was sewn using nylon thread. The wire used to connect the spring to the wire extensions was fabricated by braiding six strands of .012 stainless steel wire together (Plates I and II).

Maxillary and mandibular impressions of Pig 2 were taken as stated for Pig 1. A mandibular anterior inclined plane was constructed on the model from cold cure acrylic. The appliance was fashioned so as to effect a 4 mm postural protrusion of the

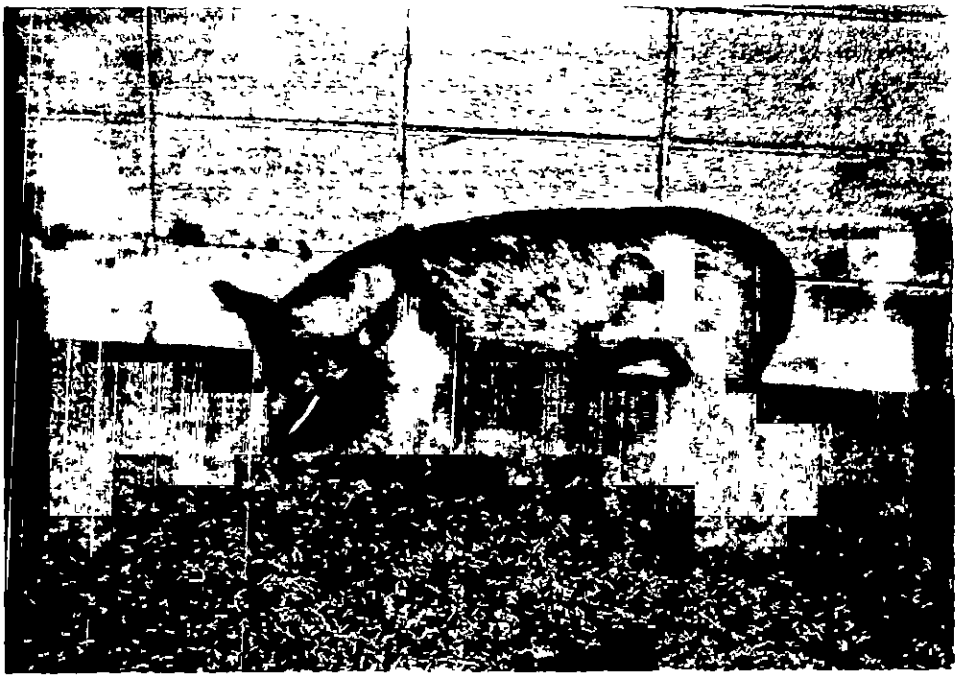
PLATE I

Intraoral retrusive appliance



PLATE II

Anchoring harness and headgear



mandible by using the maxillary model for orientation.

Anesthesia

All impressions, appliance fitting, metallic implants and radiographs were made with the animals under general anesthesia. An adequate level of anesthesia was obtained by using Halothane and Nitrous Oxide inhaled by the animals through a nose cone. A sedative, Nembutal (sodium pentobarbital) was administered intramuscularly at a dosage of 2 mg/kg body weight prior to application of the general anesthesia in order to relax the animals. The sedative was followed by an intramuscular injection of Atropine Sulfate (Butler Company, Columbus, Ohio) at a dosage of 0.1 cc/kg body weight. Atropine sulfate was administered because it decreases salivary secretion and stabilizes cardiac action. Nembutal was also used as a sedative prior to injection of the vital dyes.

Insertion of the Appliances

Under general anesthesia, the lower intraoral splint and anterior inclined plane were bonded onto the lower anterior teeth of the appropriate animals using orthodontic bonding material (Excel, Reliance Orthodontic Products, Itasca, Illinois). The harness was placed around the chest of Pig 1 just behind the front

legs and tightened snugly. The springs were connected to the splint with the ligature wire and tightened to a retrusive force of 16 ounces. The ligature wire was encased in surgical tape to prevent skin irritation.

Implants

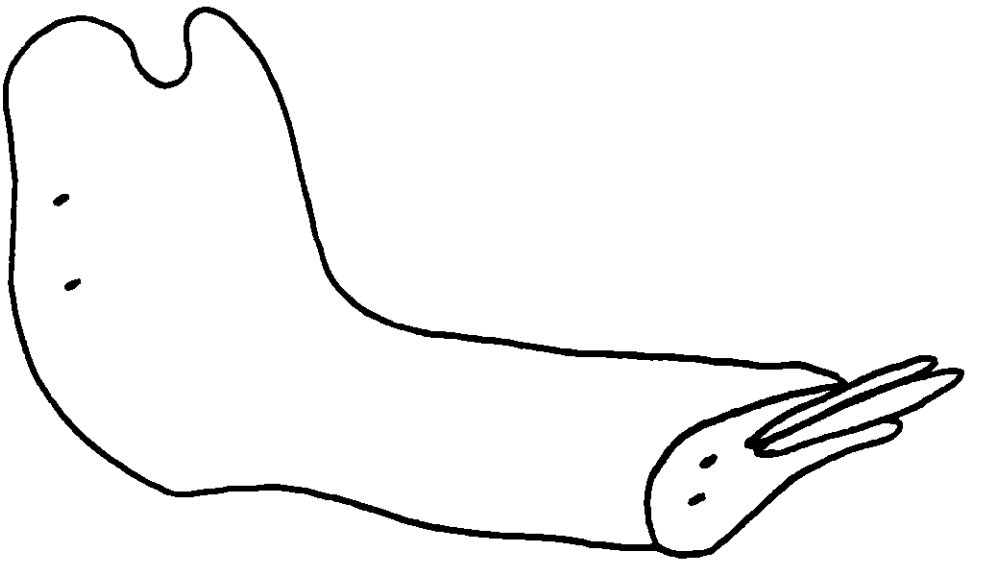
Stainless steel implants were made by cutting approximately 1.5 mm lengths of 0.020 orthodontic wire (Unitek, Monrovia, California). The implants were placed in cortical bone at specific locations of the mandible. The Holst implant gun was utilized (Aronson et. al., 1974). Each pig received a minimum of two implants in the posterior ramal border and two implants in the mandibular symphysis (Figure 1).

Radiographic Method and Procedure

Lateral head radiographs were taken as follows:

1. A midsaggital plane was drawn on each animal with ink.
2. A cross-hatch on the x-ray cassette was aligned with a cross-hatch on the x-ray table.
3. The pig's head was placed on the cassette in such a way that the horizontal cross-hatch bisected the nose and passed through the inferior orbital rim. The vertical cross-hatch passed just anterior to the eye. The mid-saggital plane was kept parallel to the cassette.
4. The central ray of the beam was directed through the junction of the ascending ramus to the body of the mandible.

Figure 1. Implant location



Lateral head radiographs were taken at the beginning and end of the experimental period with a fixed target-film distance of 40 inches. The radiographs were taken on Kodak X-Omat TL Ready Pack film at 0.1 seconds, 200 milliamperes, and 56-66 kilovolts. For initial radiographs, 56 kilovolts was used, and 66 kilovolts was used for final radiographs. The radiographs were manually processed with a developing time of 3 minutes and a fixing time of 6 minutes at 68°F. The films were washed for one hour and allowed to air dry.

Radiographic Procedure

Tracings of initial and final radiographs were superimposed on the mandibular implant markers to identify directional remodeling patterns.

In Vivo Bone Markers

Three different vital dyes were administered to each pig at three different times during the experiment with one of the three being administered again 24-48 hours prior to sacrifice. At the beginning of the experiment 50 mg/kg body weight of Oxytetracycline was administered intramuscularly (Teramycin, Pfizer Laboratories Division, Pfizer, Inc., New York, New York) to all three animals. On the twelfth experimental day, 30 mg/kg body weight of Alizarin Complexon (Eastman Kodak Company, Rochester, New York)

mixed in 2% $NaHCO_3$ solution (1 cc per kg body weight) was administered intraperitoneally. Twenty mg/kg body weight of DCAF (2, 4-Bis (n,N'-di (Carbomethyl) aminomethyl fluorescein (ICN Pharmaceuticals, Cleveland, Ohio) mixed in 2% $NaHCO_3$ solution (1 cc per kg body weight) was administered intraperitoneally to each pig on the twenty-second experimental day. Oxytetracycline was then administered intramuscularly at 50 mg/kg body weight 24-48 hours prior to sacrifice.

Histologic Procedures

The animals were sacrificed by administration of sodium pentobarbital intraperitoneally to achieve sedation and then intravenous injection of sodium pentobarbital until death ensued. The animals were weighed and radiographed. The mandibles of each animal were dissected out, cleaned, and placed in 10% buffered formalin for one week. The right ramus was cut off each mandible and embedded in Bio-Plastic (Ward's, Rochester, New York). The Bio-Plastic embedding process consisted of the following steps:

1. Rinsing fixed and cleaned specimens in running tap water for 2 hours.
2. Dehydration I in 70% alcohol for 24 hours.
3. Dehydration II in 90% alcohol for 24 hours.
4. Dehydration III in 95% alcohol for 24 hours.
5. Dehydration IV in 100% alcohol for 24 hours.

6. Dehydration V in 100% alcohol for 24 hours.

7. Placement of specimens in a solution consisting of equal parts 100% alcohol and Xylene for 24 hours.

8. Placement of specimens in pure Xylene for 24 hours.

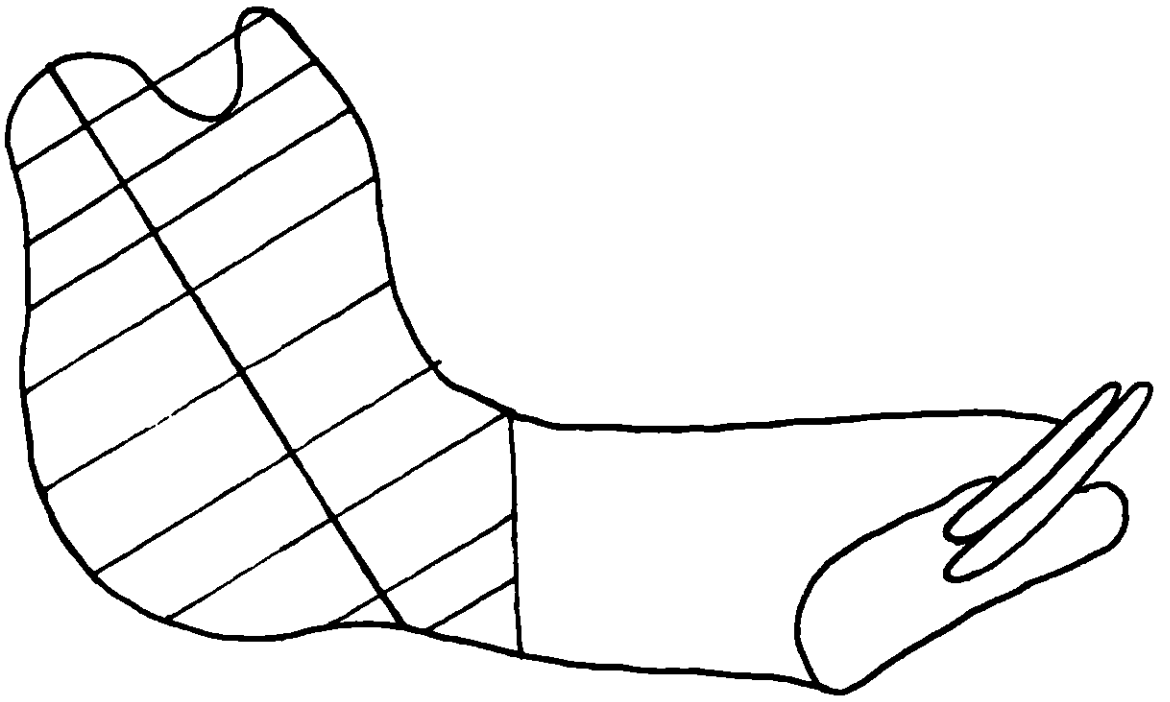
9. Placement of specimens in uncatalyzed Bio-Plastic I (resin without hardner) for 48 hours.

10. Draining and then placement of specimens in catalyzed Bio-Plastic (mixture of resin and hardner).

11. The Bio-Plastic was allowed to cure at 60°C for 48 hours.

Ground sections were taken on a bone cutting machine at 5000 RPM and a speed of 20 mm/minute. The ground sections were 75-100 microns thick. Each ground section taken from the specimens was cut perpendicular to the neutral ramal axis and at the approximately same location for each ramus (Figure 2). After cutting, each section was dehydrated again in 50%, 85%, 95%, and 100% alcohol for 2 minutes each followed by 2 minutes each in a 1:1 Xylene/ alcohol solution and pure Xylene. Each section was allowed to air dry and then mounted on a microscope slide using a mounting medium (Permount, Fisher Scientific Company, (Cleveland, Ohio). Each mounted ground section was examined using fluorescent microscopy for vital dye visability.

Figure 2. Neutral ramal axis and location of ground sections



RESULTS

Clinical Observations

The two animals with appliances experienced little difficulty in adapting to them. Eating and drinking remained at a comparable level with the control pig. The weight gain for each animal was roughly parallel to that of the others (see Table I).

At the conclusion of the 30 day experimental period, skeletal and dental adaptations to the altered oral environment and function induced by the appliances were observed. The most obvious changes were those at the anterior of the mouth. The protrusive pig displayed an anterior crossbite with extreme labial flaring of the lower incisors. The pig with the retrusive appliance had an anterior overjet of approximately 5 mm, with the lower anterior teeth being quite upright. The control pig exhibited a horizontal overjet of 1 mm with the lower anterior teeth flared labially less than the pig with the protrusive appliance.

After dissecting out the mandible of each pig, measurements were taken and recorded (Table III). Ramus height was measured perpendicularly from the top of the condyle to the inferior border of the mandible. Mandibular length was measured from the most superior-posterior point of the condyle (condylion) to the mental foramen. Ramus width was measured from the poster-

TABLE III

MANDIBULAR MEASUREMENTS POST SACRIFICE

	Ramus Height (mm)	Ramus Width (mm)	Mandibular Length (mm)
Pig 1 (Retrusive Appliance)	74	52.5	140
Pig 2 (Protrusive Appliance)	76	51.5	143
Pig 3 (Control)	73	54	141.5

ior ramal border at the height to where the ascending ramus joins the body of the mandible.

The morphology of the bone surrounding the lower anterior teeth of Pig 1 (retrusive appliance) was noticeably altered (Plate III). Instead of presenting a rounded arc as in Pig 2 (protrusive appliance) and Pig 3 (control pig) (Plate IV), the anterior of the mandible was broader and more squared. The bone staining by the vital dyes was quite apparent in the mandible of the pig with the protrusive appliance, even on visual examination (Plate V).

Radiographic Analysis

Regional remodeling adjustments in the mandible were examined by superimposing initial and final tracings on the metallic implants. During the 30 day experimental period differences were noted in the mandibular growth pattern of the three pigs. The untreated animal exhibited a mandibular growth pattern typical for the pig (Robinson and Sarnat, 1955). Condylar growth proceeded in an upward and backward direction as the ramus relocated posteriorly. There was tremendous apposition of bone on the posterior ramal border and correspondingly less resorption from the anterior border (Figure 3). This resulted in a much wider ramus.

The pig with the protrusive appliance demonstrated a difference in the amount of bone deposition and resorption. There

PLATE III

Pig 1 (retrusive appliance): Mandibular morphology

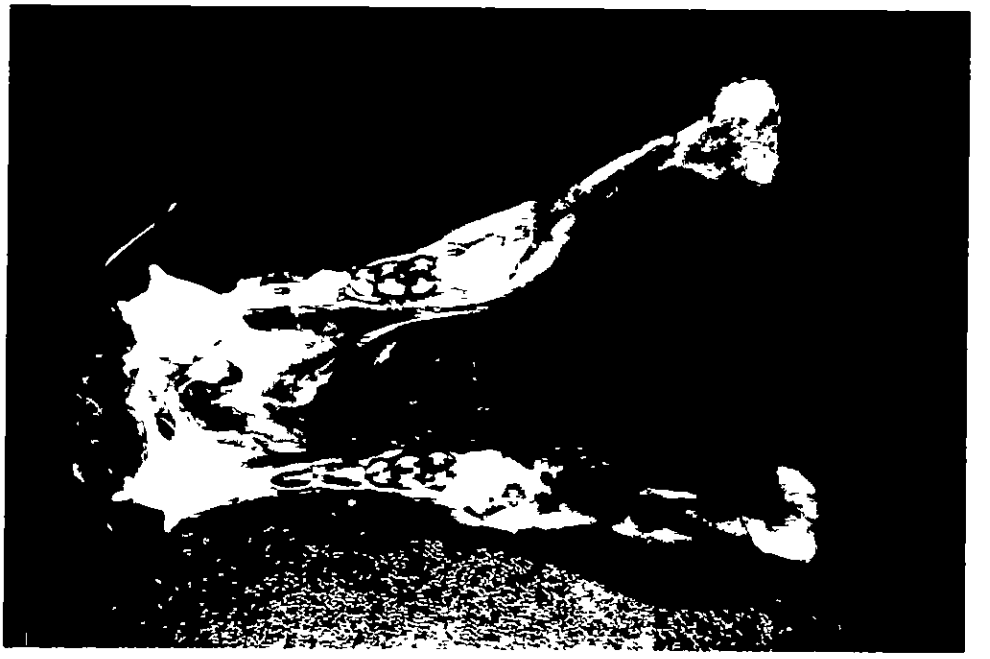


PLATE IV

Pig 3 (control): Mandibular morphology

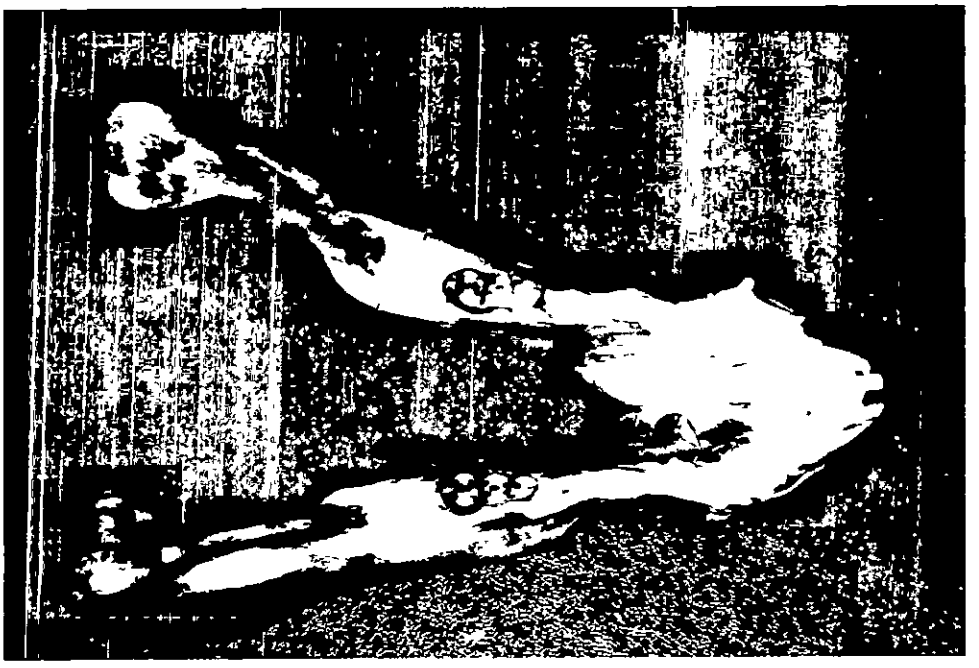


PLATE V

Pig 2 (protrusive appliance: Mandibular morphology and presence of vital dyes.

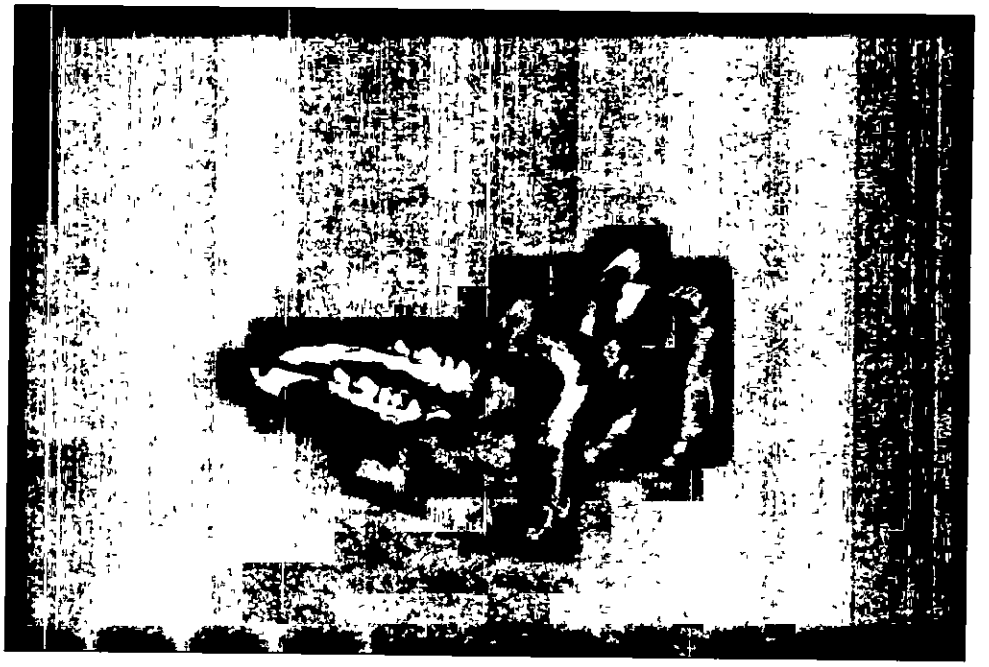
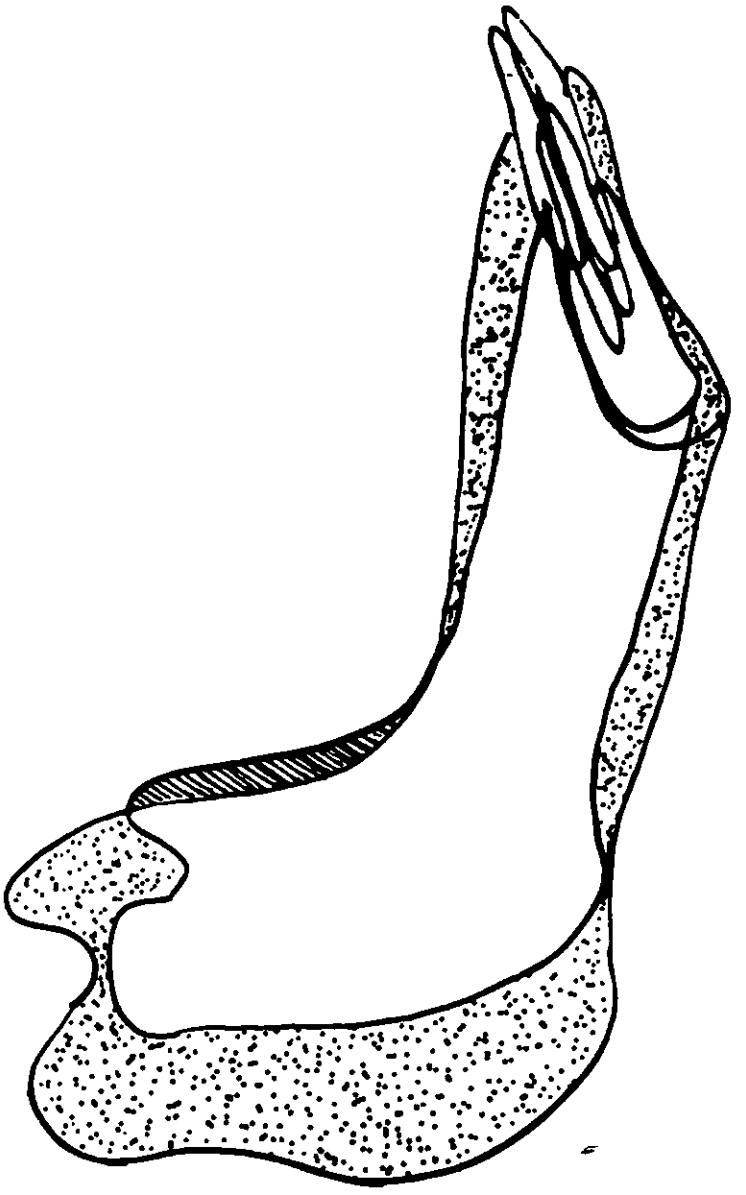


Figure 3. Mandibular superimposition of the initial and final radiographs from Pig 3 (control).



was less posterior ramal bone deposition and anterior ramal bone resorption, but an increase in deposition on the superior aspect of the condyle and coronoid process (Figure 4). There was also less apposition of bone on the inferior mandibular border except in the area of the antegonial notch which in the final tracing was entirely absent. The reversal line between deposition and resorption was located well below the tip of the coronoid process, in contrast to that of Pigs 1 and 3.

The growth pattern of the pig with the retrusive appliance was very similar to that of the control. The main differences were centered around the anterior of the mandible. There was an area of decreased bone apposition at the anterior of the inferior border and an increased deposition at the anterior symphyseal border (Figure 5).

Histologic Results

The serial ground sections taken from the rami of the three pigs also exhibited some differences. These consisted of differences in both the distribution and configuration of certain growth fields (their pattern), and the specific placement of the boundaries between the growth fields (their size). Each ramus displayed deposition of bone at the posterior border and resorption of bone at the anterior border. The medial surface of each ramus was largely resorptive except for a field of deposition

Figure 4. Mandibular superimposition of the initial and final radiographs from Pig 2 (protrusive appliance).

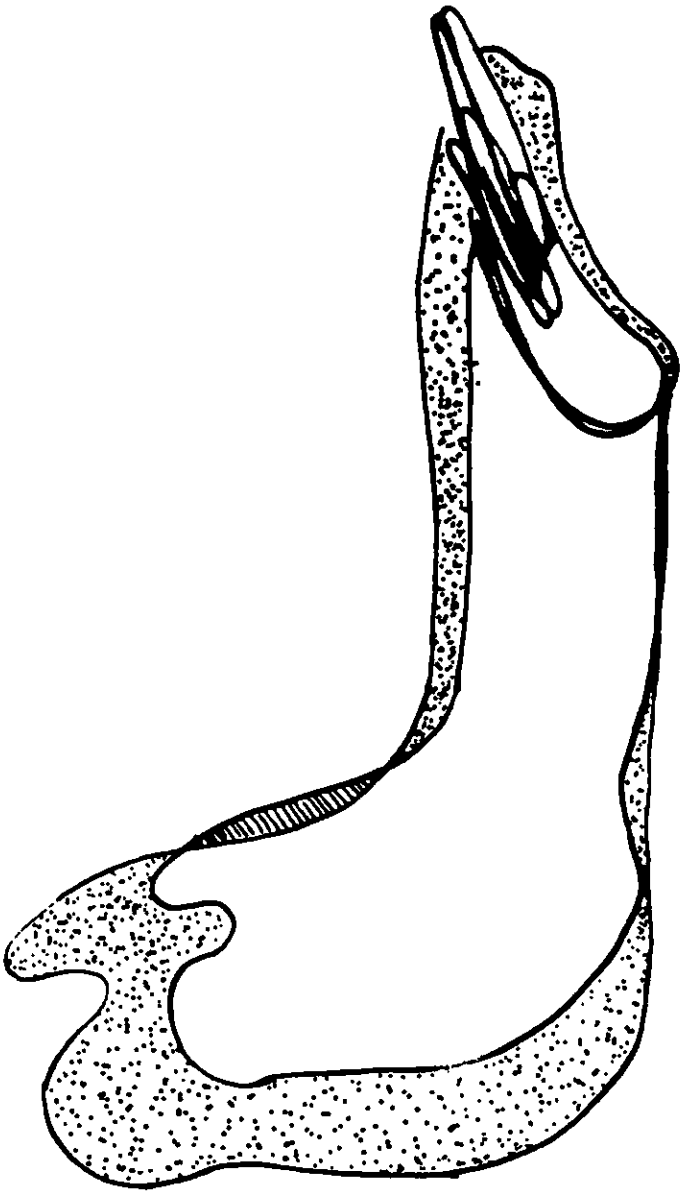
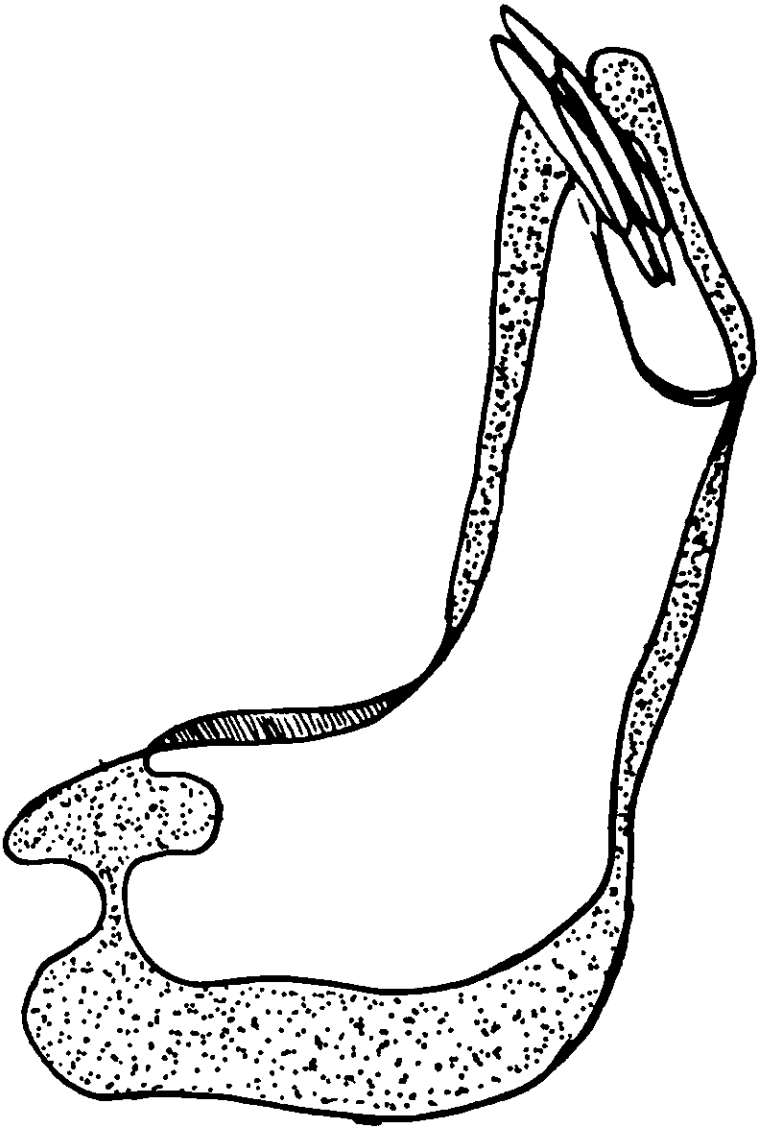


Figure 5. Mandibular superimposition of the initial and final radiographs from Pig 1 (retrusive appliance).

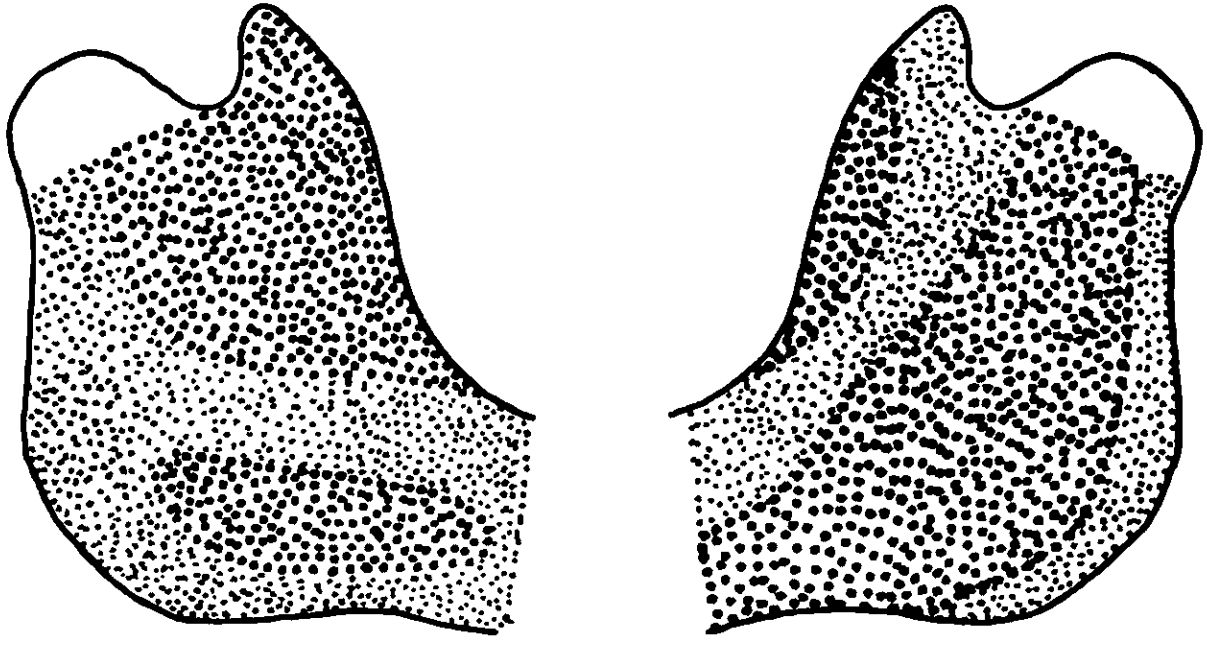


extending from the lingual tuberosity, to the tip of the coronoid process.

The composite of the pattern and boundaries of the growth fields for the ramus of Pig 3 (control) are shown in Figure 6a, b. The ramal growth field composite for Pig 2 (Figure 7a, b) reveal some important differences. The pattern of bone deposition extended on the medial surface of the ramus from the base of the coronoid process almost to the posterior border (Plate VI). A small amount of bone deposition was also found on the lateral side of the coronoid process (Plate VII), which was not present in the other two pigs. The resorptive field located at the inferior aspect of the lateral ramus was smaller than that of the control and the resorptive field covering much of the medial side of the ramus extended farther to the anterior. The resorptive field blanketing the ascending ramus of Pig 2 was also the smallest of the three pigs. This resulted in bone deposition on the anterior ramal border above the level of the mandibular notch (Plate VIII). The same area in the control pig was resorptive (Plate IX).

The ramal remodeling pattern composite for the pig with the retrusive appliance (Figure 8a, b) also exhibited some notable differences. On the lateral surface of the ramus a section of depository bone extended from the base of the mandibular notch to the start of the ascending ramus (Plate X). The resorptive field present on the lateral ramal surface just posterior to this depo-

Figure 6a and b. Pig 3 (control): Remodeling patterns of lateral and medial sides the ramus.



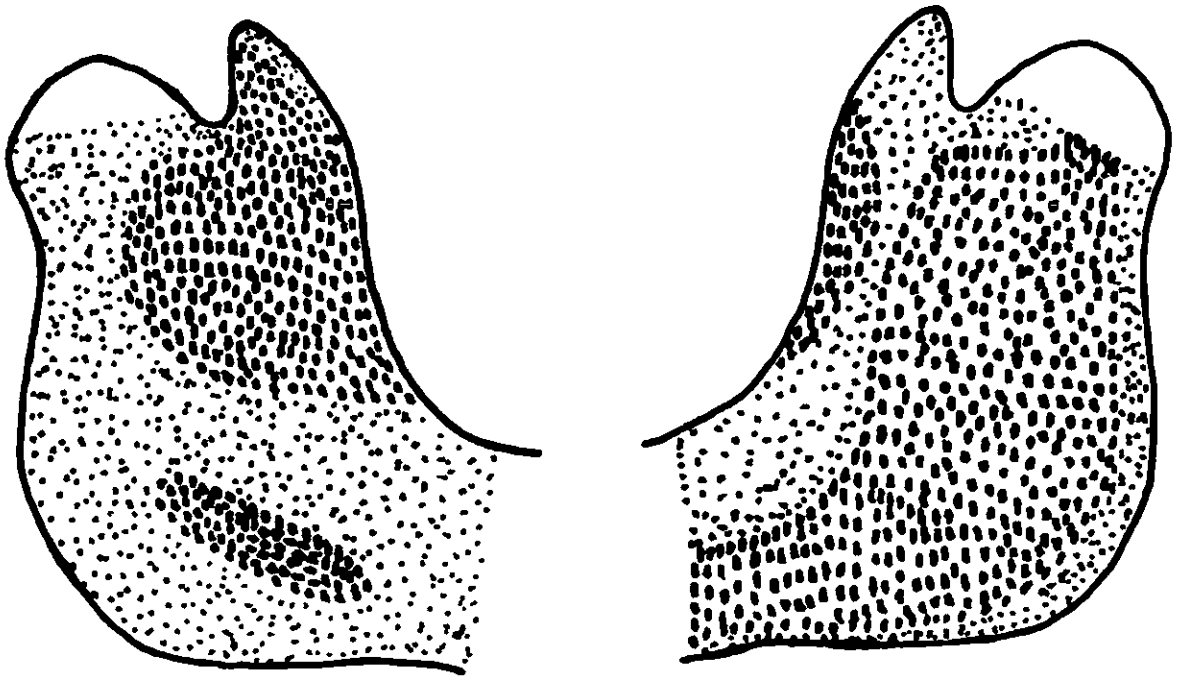
a. Lateral View

b. Medial View

- Resorptive Field

- Depository Field

Figure 7a and b. Pig 2 (protrusive appliance): Remodeling patterns of lateral and medial sides of the ramus.



a. Lateral View

b. Medial View

- Resorptive Field

- Depository Field

PLATE VI

Pig 2 (protrusive appliance): Fluorescent photomicrograph of ground section from the superior one-third of the medial aspect of the mandibular ramus. Bone deposition is present on the medial surface.

NOTE: Orientation of this and all following plates is as follows:

1. Right side of plate is anterior.
2. Left side of plate is posterior.
3. Top of plate is medial.
4. Bottom of plate is lateral.

Also for all plates:

1. Red = Alizarin complexon
2. Green = DCAF
3. Yellow = Oxytetracycline



PLATE VII

Pig 2 (protrusive appliance): Fluorescent photomicrograph of ground section from the coronoid process. Bone deposition is present on the lateral surface.

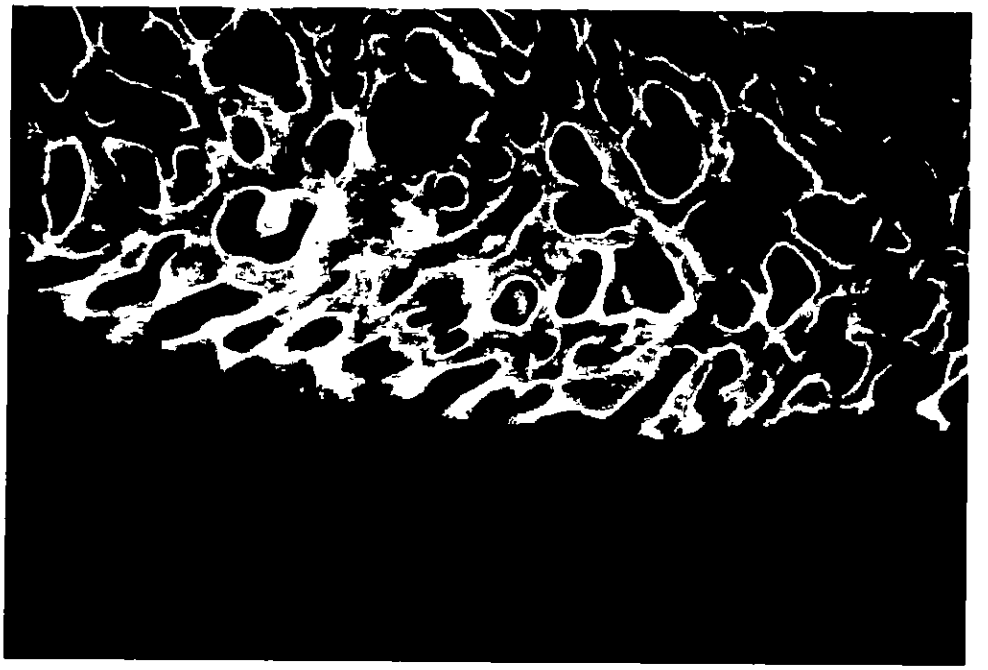


PLATE VIII

Pig 2 (protrusive appliance): Fluorescent photomicrograph of ground section from the superior one-third of the anterior border of the mandibular ramus. The anterior border is a depository surface.

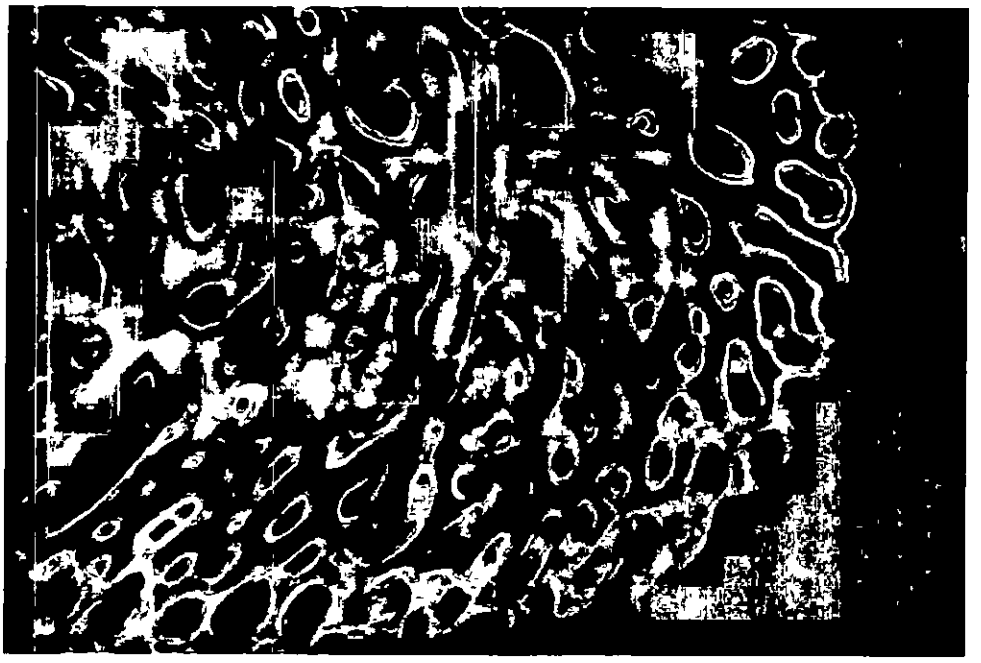
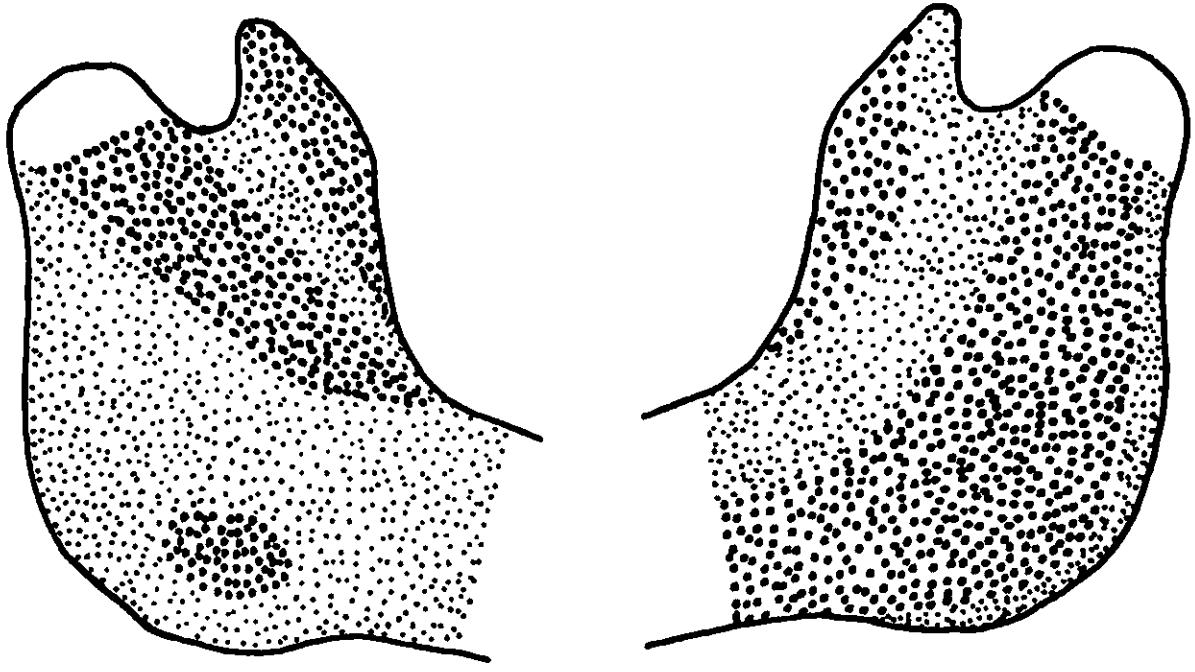


PLATE IX

Pig 3 (control): Fluorescent photomicrograph of ground section from the superior one-third of the anterior border of the mandibular ramus. The anterior border is a resorptive surface.



Figure 8a and b. Pig 1 (retrusive appliance): Remodeling patterns of lateral and medial sides of the ramus.



a. Lateral View

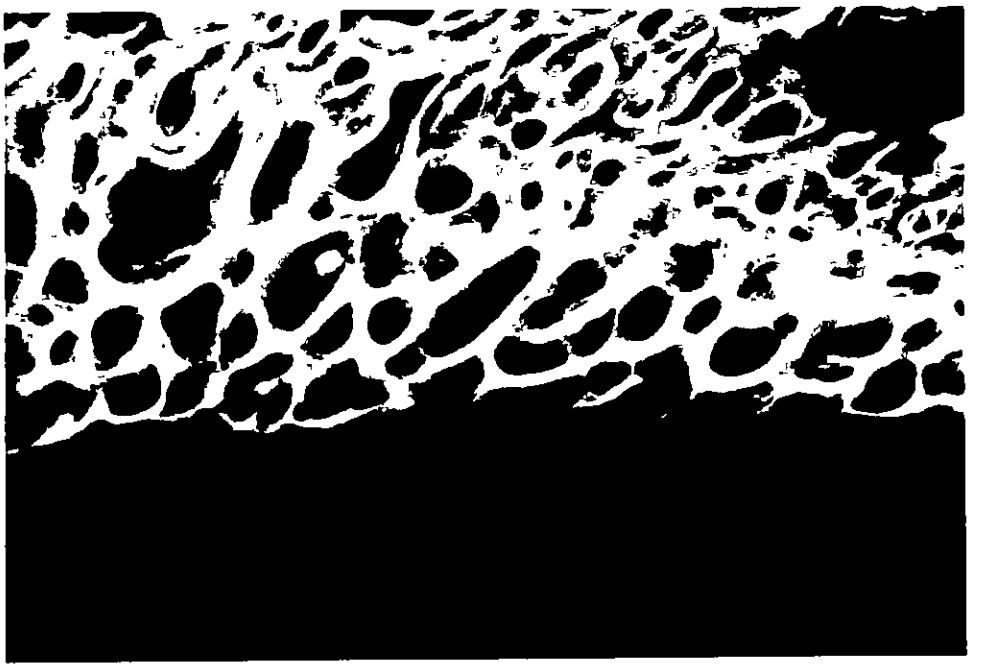
b. Medial View

- Resorptive Field

- Depository Field

PLATE X

Pig 1 (retrusive appliance): Fluorescent photomicrograph of ground section from the middle one-third of the lateral aspect of the mandibular ramus. The lateral surface is depository.



sitory field extended almost to the posterior border at the level of the mandibular notch. The resorptive area at the inferior portion of the lateral ramus was also smaller than that of the control. The resorptive field covering the ascending ramus on the medial side was the largest of the three animals.

DISCUSSION

The purpose of this study was to investigate the effects of continuous posterior traction and functional hyperpropulsion of the mandible on ramal remodeling in the pig. Previous studies investigating alterations in mandibular growth (Janzen and Bluher, 1965; McNamara, 1973; Petrovic et al., 1975; Woodside et al., 1983) have all used a different animal model than the pig and have concentrated primarily on the condyle. It has been theorized (Enlow, 1973) that the ramus plays a major role in mandibular growth compensations. Tsolakis (1981) demonstrated a reversal of ramal remodeling patterns in rabbits undergoing heavy retrusive forces to the mandible. Woodside et al. (1983), studying the effects of mandibular protrusion in monkeys, saw an increase of remodeling activity at the anterior ramal border. My study was based upon the hypothesis that by altering the forces applied to the mandible during growth, the ramus would compensate, resulting in an alteration of remodeling patterns.

As an animal model the pig demonstrates some important qualities, but numerous problems were encountered with this animal during the course of the study. The pig, due to its large fat stores, is not easily anesthetized, and once anesthesia is achieved, the margin of safety is very small. Extreme caution must be used in not allowing the animal to be too deeply anesthetized.

Frequently, the result is a level of anesthesia inadequate for optimum working conditions. The pig is also an extremely strong animal. Any appliance used must necessarily be extremely durable and located so that it is very difficult for the animal to destroy it. Numerous appliance failures were encountered before the final design was achieved.

The design and construction of the retrusive and protrusive appliances were a major concern because their use should not interfere with the animals' normal dietary intake and yet be strong enough to last for 30 days. A major difficulty encountered was due to the very young age of the pigs. Eruption of the posterior deciduous teeth had not proceeded to the point where an appliance could be cemented on with any assurance of retention. Combining the poor retention with the pig's extremely rapid growth rate, which requires that a cast appliance be fabricated and cemented in place within a short period of time, the decision was made to use acrylic appliances bonded to the teeth. The importance of keeping the appliance in place continuously was such, that after a review of a previous study using pigs (Ward, 1983), a decision was made to limit the appliance to the mandibular anterior teeth. Immediate success was achieved in keeping the appliance in the mouth, but a certain sacrifice in efficiency of action was inevitable. Thus, while it was realized that a large amount of the forces were being exerted on the anterior segment of the

mandible, it was reasoned that enough postural alteration would be elicited to affect the entire mandible.

The results showed that a good many of the growth alterations observed were centered around the anterior of the mandible. The lower incisors uprighted with the retrusive appliance and flared labially with the protrusive one. The arch form was altered by the retrusive appliance. But, although the extremely small sample size negated any attempt at statistical comparisons, certain other differences between the mandibles were noted (see Table III). The mandibular length of Pig 2 (with the protrusive appliance) was the largest of the animals. Petrovic et al. (1975), found in his work with postural hyperpropulsors in rats, that their mandibular length was also increased (from the mental foramen to condylion). In the pig, this increased length appeared to be the result of an increased ramus height. The ramus height of Pig 2 (protrusive appliance) was the largest of the animals. Woodside et al. (1983), while working with protrusive appliances in monkeys, also found an increased remodeling in a superior direction. Interestingly, the width of the ramus of Pig 2 was the smallest of all three animals. This has not been noted in other similar studies and may be a result peculiar to the pig or within the realm of normal growth variability.

Pig 1 (retrusive appliance) had the shortest mandible. This is in agreement with Petrovic et al. (1975), in their study

with rats, but in disagreement with Janzen and Bluher (1965), in their study with monkeys. The ramus width of the Pig 1 was found to be less than that of the control, but the ramus height was found to be the slightly larger. It is interesting to note that the largest pig by weight was Pig 1, and he had the smallest mandible. The smallest pig by weight was Pig 2 and he had the largest mandible.

Radiographically, the mandibular growth pattern observed for Pig 3 (control) was similar to the findings of Robinson and Sarnat (1955). Each of the animals displayed a predominant posterior and superior direction of growth with deposition of bone on the posterior and inferior borders. There was also bone deposition at the mandibular symphysis and an increase of alveolar bone. The anterior border of the ramus showed bone resorption.

The superimpositions, although two dimensional, do serve to point out differences in amount of bone deposition and resorption which can be verified by histological examination. The most obvious differences in the amount of bone deposition and resorption centered around Pig 2 (protrusive appliance). As compared to the control, the ramus displayed an increased amount of bone deposition in a vertical direction and less deposition horizontally. This would account for the increase in mandibular length as measured from condylion to the mental foramen because the decrease in horizontal deposition on the posterior border was to a lesser degree than the increase in vertical deposition.

This increase in the vertical direction of growth is in agreement with the work of Woodside (1983), but differs from that of Elgoyhen et al. (1972) and McNamara (1973a). The latter investigators found that the direction of growth became more horizontal when using protrusive appliances in monkeys. The difference could be the result of either the type of protrusive appliance or animal used in the study. The protrusive appliance used in my study not only protruded the mandible 4 mm on closure, but also opened the bite. This bite opening resulted in the supereruption into occlusion of the posterior teeth. This can clearly be seen by comparing the amount of posterior alveolar growth in Pig 2 and Pig 3 (control) (Figures 3 and 4). Supereruption of the posterior teeth was not possible in the Elgoyhen and McNamara studies. The degree of bite opening in their studies was also much less. Although not measured in the present study, it could have been as much as 4 mm. The resultant direction of muscle pull would certainly have been altered, and thus, according to Wolff's law, so would the corresponding pattern of remodeling.

Pig 1 (retrusive appliance) also encountered a similar situation. The lower incisors encased in the appliance were not only uprighted but also extruded. This tended to open the bite slightly. As seen by the measurements in Table III, the ramus height was slightly larger for Pig 1 than the control.

The radiographs revealed that the antegonial notch of Pig

2 (protrusive appliance) was eliminated. This was confirmed on visual inspection. Along with the increase in ramus height for Pig 2, this indicates compensatory activity relating to the altered position caused by the protrusive appliance. To increase mandibular length the ramus could either increase its size in a horizontal or a vertical direction (or some combination of the two). In this case the ramus increased vertically resulting in a rotation and closure of the gonial angle which was maintained by supereruption of the posterior teeth. This closure of the gonial angle is what contributed to the elimination of the antegonial notch (Enlow, 1982).

The radiographic superimposition for Pig 1 (retrusive appliance) revealed a slight increase in vertical growth as compared to the control. A decrease in the deposition of bone on the posterior border of the ramus was also noticed. These two findings are in contrast with those of Janzen and Bluher (1965) who found an increase in bone deposition on the posterior ramal border and a decrease in ramus height when applying a retrusive force to the mandibles of monkeys. An explanation for these discrepancies can be found in the action of the appliances. Janzen and Bluher placed a wire through the body of the mandible to which they applied a retrusive force. This held the mandible back and tended to keep the bite closed. The appliance in my study had a tendency to gradually open the bite as the mandibular incisors super-

erupted. Thus, the resultant force was to not only hold the mandible back, but to also rotate it as the bite opened and the posterior teeth supererupted. The pull of the muscles was, therefore, quite different in this study than in that of Janzen and Bluher.

A problem was encountered that made accurate superimposition difficult. In developing the final lateral head radiographs, the films were inadvertently left in the wash too long resulting in the emulsion being lifted from the film. At this point two of the mandibles had already been dissected out. Radiographs of all three mandibles were taken with the same x-ray machine as before in a position that was as close as possible to what had been radiographed initially. This resulted in a certain amount of error, but it was still possible to superimpose the initial and final radiographs on the implants on a best fit basis. In this regard the ground sections showing vital dye lines confirmed the accurate superimposition of the radiographs.

The histologic sections confirmed what was found using radiographs that the predominant pattern of growth was upward and backward, with deposition of bone on the posterior ramal aspect and resorption of bone from the anterior border of the ramus. It appeared from the spacing of the vital dye lines that growth, in all three animals, proceeded at a fairly rapid and constant rate throughout the experimental period of thirty days. It was not

possible to measure the differential amounts of deposition and resorption in each field due to the fact that, unfortunately, the uptake of alizarin complexon in the control and the pig with the retrusive appliance was somewhat variable.

In many ways the growth and remodeling of the pig ramus resembles that of the human. As in the human, the coronoid process of the pig is twisted so that its lingual side faces posteriorly, superiorly, and medially. This explains the characteristic pattern of deposition on the lingual side resulting in growth both posteriorly and superiorly, and resorption on the buccal side facing away from the direction of growth. The condylar neck of the pig is not nearly as pronounced as in the human, but the condyle itself is so wide that resorption must take place on both the lateral and medial surfaces as it remodels into the thinner neck area.

The differing patterns of resorption and deposition among the pigs, while probably in part a result of individual variation, also suggest that the ramus was compensating for the imbalances created by an alteration of mandibular posture. The presence of a large growth field opposite in character to that normally found in the same location [e.g., on the lateral surface of Pig 1 (retrusive appliance) or the medial surface of Pig 2 (protrusive)] provides some evidence that there is a causal relationship between altered position and growth compensation by the ramus.

The factor of morphologic compensation plays an extremely vital role in the growth and development of the face. Compensatory adjustments strive to provide a state of functional and structural "balance" among the various interrelated parts that make up the face (and the rest of the body). The growth of a part of a bone is not only related to that bone, but also to the muscles, connective tissues, blood vessels, nerves, etc. which are developing in conjunction with that bone. Thus, there is a chain of interrelated parts, all of which are affected by any change placed within the system. Where the chain begins and ends has yet to be determined, but the ability to introduce a change within the system which predictably alters various elements in the chain is extremely important for the orthodontist.

The thrust of much research at the present time is in trying to determine exactly what is compensating in response to a particular change. This study has shown that the mandibular ramus is highly responsive to certain functional or postural alterations. This responsiveness is only logical when it is realized how intrinsically involved the ramus is in the adaptive requirements of the mandible. The ramus bridges the pharyngeal compartment and places the mandibular dentition in a position to occlude with the maxillary dentition. The width of the ramus determines the anteroposterior position of the lower arch. The height of the ramus accomodates the vertical dimension and growth of the nasal

and masticatory components of the mid-face. The ramus serves as a site of attachment for the masticatory muscles and accomodates their growth and size. The mandibular ramus is a vital link in the chain of compensatory events leading to "functional balance". Its many regional growth sites give the ramus a large latitude of possible adjustments which have ramifications throughout the face. Thus, it is the ramus, and not just the condyle, which must be considered when trying to affect the course of mandibular growth.

My experience in using the pig shows that there are severe problems involved in anesthesia and adequate appliance construction. A better initial age for studying remodeling changes in the pig would be around eight weeks postnatal. This would afford more tooth structure available to provide anchorage for appliances and still allow for plenty of growth. While the protrusive appliance used in this study simulates (to a certain extent) certain appliances used clinically (activator, bionator), it would be interesting to see the effect a passive type hyperpropulsor would have on growth and remodeling of the ramus. This would best be accomplished by the use of cemented castings. The retrusive appliance used for this study has no real counterpart in clinical use. The bite opening produced was an undesirable side effect of using only the mandibular incisors for anchorage. An interesting study which would help shine light on the role of the ramus as a target for altering growth, would be to duplicate this study in animals having undergone either bilateral of unilateral condylectomies.

SUMMARY AND CONCLUSIONS

Three domestic pigs of approximately five weeks of age were used to study the effects of mandibular postural alterations on the growth and remodeling of the ramus. One pig received a retrusive force to the anterior of the mandible of approximately 16 ounces bilaterally. Another pig received an acrylic appliance bonded onto the mandibular anterior teeth which, upon jaw closure, would elicit a 4 mm functional protrusion. The third animal received no appliance and acted as a control. The experimental period lasted for 30 days.

The experimental procedure included:

1. placement of stainless steel implants in the mandible at the symphysis and the posterior ramal border;
2. lateral head radiographs of the animals on the 1st and 30th experimental days;
3. administration of vital dyes on the 2nd, 12th, 22nd, and 29th experimental days.

The mandibles of each animal were measured and compared for gross anatomic differences. The radiographs were superimposed and described. Histologic evaluation of serial ground sections was carried out.

The collected data led to the following conclusions:

1. The radiographic superimpositions showed specific differences in the patterns of mandibular growth and remodeling in the three pigs.

   a. Pig 1 (retrusive appliance) displayed a decrease in

bone deposition on the posterior border of the ramus and an increase of bone deposition at the mandibular symphysis.

b. Pig 2 (protrusive appliance) showed an increase in vertical growth of the ramus. There was a decrease in the amount of bone deposition on the posterior border of the ramus and a decrease in bone deposition on the inferior border of the mandible. Bone deposition was present at the area of the antegonial notch which, when coupled with the decrease in deposition in the rest of the inferior border, resulted in the elimination of the notch.

2. There were specific differences in the configuration, distribution, and size of the ramal growth fields in the three pigs.

   a. Pig 1 (retrusive appliance) had the largest resorptive field covering the ascending ramus. There was a depository field on the lateral surface of the ramus extending from the mandibular notch to the base of the ascending ramus that was not present in the other pigs. The resorptive field on the lateral ramal surface at the height of the mandibular notch extended the farthest posteriorly. The resorptive field on the inferior lateral surface of the ramus was smaller than that of the control.

   b. Pig 2 (protrusive appliance) showed a depository field of bone on the lateral surface of the coronoid process not present in the other pigs. The resorptive field covering the ascending ramus was the smallest of the three pigs. The depository field of bone on the medial surface of the ramus at the height of the mandibular notch extended the farthest posteriorly. The resorptive field at the inferior of the lateral surface of the ramus was smaller than that of the control.

3. Pig 1 (retrusive appliance) had the shortest mandible.

4. Pig 2 (protrusive appliance) had the longest mandible, the largest ramus height, and the smallest ramus width.

5. Pig 3 (control) had the widest ramus.

6. Both appliances, in addition to their intended action, also had a bite opening effect.

This study investigated the effects of continuous posterior traction and functional hyperpropulsion of the mandible on growth and remodeling of the ramus. Although the extremely small sample size negated any attempts at achieving statistical significance, specific differences were noted upon gross morphological examination, radiographic evaluation, and histological examination of the rami of the three pigs. This responsiveness of the ramus to altered mandibular posture indicates that it may be an important contributor to compensatory alteration of the mandible and could actually be the principal clinical target for many of the appliances used in orthodontics. Very few investigations of growth and remodeling have used the pig as an experimental model. This study provides evidence that the pig is a good biological model for investigating ramal remodeling. More research needs to be done in this area with the pig, using larger samples to check statistical significance of the results.

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