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Biophysical Assessment of a Reciprocal Vertical Force System on Posterior Teeth Out of Occlusion in a Rhesus Monkey

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BIOPHYSICAL ASSESSMENT OF A RECIPROCAL VERTICAL FORCE SYSTEM ON POSTERIOR TEETH OUT OF OCCLUSION IN A RHESUS MONKEY

BY

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LIFE

Dale K. Kostiwa was born on July 4, 1931, and attended elementary and secondary schools in Berwyn and Cicero, Illinois.

He attended Morton Junior College, in Cicero, Illinois and Augusta Junior College in Augusta, Georgia. He received his B. S. degree from Northern Illinois University, DeKalb, Illinois.

In 1960 he received his D. D. S. from Loyola University College of Dentistry. Prior to entering Graduate School, he practiced general dentistry in Berwyn, Illinois and was on the faculty of Loyola University College of Dentistry.

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CHAPTER I

INTRODUCTION AND STATEMENT OF THE PROBLEM

A. Introductory Remarks:

Our immediate thoughts of orthodontics are that of moving teeth. Yet nothing could be further from the truth. Orthodontics is the changing of the biologic environment of a tooth through the medium of forces applied to the teeth. The process of moving teeth by means of force is therefore biophysical.

As scientific inquiry reduces the many physical and biologic unknowns currently plaguing the clinicians, the profession will begin to rise from an art to a science. Ideas will become hypotheses to be tested analytically and tested hypotheses will become laws to be adhered to in a meaningful approach.

A force is defined as the action of one body upon another. In orthodontics, forces do not function separately, but act as a complex of forces on a tooth or teeth. This complex of forces represents a force system. The components of a force system have a specific peak magnitude, point of application, line of action, and direction. The biologic environment in which an orthodontic force system is applied produces a specific tissue response to the stimulus.

B. Statement of the Problem:

The purpose of this study is to assess the biophysical effect of a reciprocal vertical force system on posterior teeth out of occlusion of a rhesus monkey. The physical changes of the teeth in relation to space will be measured by suitable instruments. The biologic changes in the periodontal environment will be studied histologically.

CHAPTER II

REVIEW OF THE LITERATURE

The knowledge of static forces used by early man is seen in the phenomenal construction of the ancient pyramids of Egypt.

Newton (1687) postulated three laws of motion. These indroduced concepts of dynamic forces and methods of assessment. His postulations were those of the influences of action and reaction of forces.

The first significant histologic study dealing with orthodontic tooth movement was performed by Sandstedt (1904) on one year old dogs. He observed osteoclastic activity and capillary thrombosis on the pressure sides of the roots. His findings substantiated the theory of bone resorption and apposition as a result of orthodontic tooth movement.

Oppenheim (1911) performed similar experiments, however, on the deciduous teeth of monkeys. He observed the formation of osteoid tissue laid down perpendicularly to labially tipped teeth. From his findings he stated that the entire bone architecture was transformed as a result of orthodontic tooth movement. Both he and Sandstedt failed to calculate the direction and magnitude of the force systems.

Irish (1927) constructed the "Irishometer", an instrument to measure forces generated from labial and lingual arches and auxillary springs. Although there was no description of the instrument or evaluation as to its accuracy, a photograph of the instrument illustrates that it is based on the principle of a calibrated spring balance.

Schwarz (1932) studied the effect of known forces applied to move three premolar teeth of a dog in a buccal direction. He concluded that gentle pressures of not more than 20-26 gm. /sq. cm. could bring about tooth movement without damage. Although his evidence does not completely justify the findings, his conclusion of an optimum force for tooth movement is significant.

Richmond (1933) realizing the need for measuring orthodontic forces clinically, devised a calibrated spring balance that could be used in the mouth. The design was a force and tension gauge.

Peyton and Moore (1933) devised a simple apparatus for the measurement of orthodontic auxillary springs. It consisted of a cathetometer, a short range telescope with cross hairs that could be focused on the upper portion of the spring. The spring was held in place by a pin vise. The free end of the spring was loaded with various weights. An upright rod was graduated in millimeters and equipped with a vernier that enabled readings to 0.10 millimeter.

Orban, (1936) from previous studies on animals and in more recent studies on human jaws found that in cases of excessive or irregular stress in the periodontal environment created by orthodontic appliances changes appear in the jaws. He states that root cementum is less sensitive to pressure than bone. Root resorption, in contrast occurs in tooth movement from the application of too intense a pressure. He concurs with Schwarz that the force by which a tooth is to be moved orthodontically must not be so intense as to interfere with the vitality of the periodontal connective tissue. "Tooth-jiggling", the injurious phenomenon in which pressure is applied and released in rapid order results in resorption.

Stuteville (1937) demonstrated changes that took place in the teeth and supporting tissues when orthodontic forces are applied. Dogs and human beings were used for the studies. Measured forces active over a known distance were used. He observed that if the force is active through a distance greater than the width of the periodontal space and the tooth occludes with teeth in the opposing arch, root resorption will be found. If the force applied was just above capillary blood pressure in the area of the periodontal ligament, it would probably be possible to move teeth without resorption, even though the force was active for a distance greater than the width of the periodontal space.

Oppenheim (1942) studying human tissue response to orthodontic intervention of short and long duration agrees with Stuteville, Skillen, and others that strong forces crush the periodontal tissue and locally, necrotic bone is removed after weeks of osteoclastic activity by undermining resorption. He reports that light forces must be used and the right diagnosis should be made before treatment. There will be no need to change the direction of movement of the teeth, thereby reducing the danger of tooth damage.

Reitan (1951), (1953), (1957), (1958) using dogs monkeys, and human beings in a series of comprehensive studies produced significant histological orthodontic findings. He described the zone of hyalinization of the periodontal fiber bundles on the pressure side. This cell-free zone is not removed by osteoclastic activity but must be undermined by resorption beginning at a distance from the site. In young animals, the initial tissue changes comprising the formation of osteoid tissue and proliferation of young connective tissue cells were frequently observed after only thirty-six hours. Osteoid tissue, formed on the pressure side, will cause a delay in the onset of resorptive changes. In the studies on epithelial rests found in human beings, dogs, and monkeys, he finds that epithelial rests are more numerous in eleven to twelve year old children than in thirty-five year old adults. During direct bone resorption, epithelial rests on the pressure side move slightly toward the root surface. Hyalinization of periodontal fibers causes atrophy of the cellular structures with connective tissue cells disappearing rapidly and epithelial cells a few days later. As soon as resorption of the area is complete, the regeneration of capillaries and proliferation of fibroblasts occur. The epithelial cells once destroyed in the zone of hyalinization do not reappear. In the monkey, epithelial rest concentration appears apically. In a recent study Reitan (1960) finds that mechanics producing a bodily movement tend to favor direct bone resorption on the pressure side. The description of the force systems used was not completely analyzed.

Storey and Smith (1952) using five, twelve to fifteen year old patients applied cuspid retraction springs to both sides of the dental arches. One side carried a heavy spring activated to apply a known load of 400-600 grams. The other side carried a light spring activated to a known load of 175-300 grams. Measurements of the amount of movement were made weekly by using three points of reference. The measurements were made with needle point calipers and were calculated to be accurate to within 1/100th of an inch. They concluded that the surrounding tissues can tolerate forces up to a point without the resorption of bone. Beyond this point, resorption continues until an optimum point is reached. Beyond the optimum point, increasing force will cause undermining resorption to take place. Variables which will affect this range of forces are age, sex, health, and differences in the surface of the root of a tooth. Heavy forces were found to cause the anchor units to move first until 200-300 grams of force were reached; then the canine began to move. From the assessment of various designs, they find that the most efficient cuspid retraction springs are those that apply forces that are light and continuous. The determination of the deflection load curves of each spring was similar to Peyton and Moore's method of spring evaluation. The various springs were deflected by weights attached to the free end of the spring. Using a traveling microscope deflections of 0.1 mm. could be detected. There was no histologic evidence to substantiate the tissue response in either of their experiments, however, they realized the importance of including this evidence in future studies. They did include radiographic evidence of changes in the cribiform plate.

Johns (1953) conducted a study to determine the exact forces which the different types of orthodontic appliances exert on the teeth. The measurement of force in the mouth was accomplished with the use of a Statham Strain Gauge, an electronic gauge utilizing a transducer. The electrical energy produced was transferred to a Brush Stain Analyzer where it was amplified. Finally, the impulse was recorded in written form by a direct inking oscillograph. Deviations of 1/10th of one gram were measured. Sufficient histologic evidence was not presented in this study. Johns concluded that forces generated by less resilient wires were greater than formerly realized. The majority of these forces were active at much higher levels than the minimal occlusal blood pressure and were pathological in nature.

Huttner and Whitman (1958) using rehsus monkeys conducted experiments involving the elongation or extrusion and depression of teeth. In the periodontal space of the extruded teeth, the periodontal fibers followed the line of tooth movement and new alveolar bone spicules were seen to be forming at the apical end. No pulpal pathology or resorption of the root was observed. In the depression of the mandibular incisor teeth, they reported a loss of lamellated alveolar bone and osteoclastic activity at the apexes of the roots. A depression of 4 mm. was noted. Little cementum resorption was seen, however, compression of the periodontal ligament was observed at the apexes. Since no provision was made for cross-section of the involved areas, the possibility of tipping cannot be ruled out.

Jarabak (1960) in the development of the concept of treatment objectives confirms the investigations of Schwarz, Storey, Smith, Reitan, and others; and establishes tangible values for light and excessive forces used in orthodontic tooth movement. A light force is evaluated as being in a range of one to four ounces. A force in the intermediate range is from five to six ounces. Forces greater than six ounces are considered to be excessive for a normal tissue response in the alveolar process. Jarabak, also concludes that light forces from small diameter highly resilient straight arches or helical loop differential force arches come nearer the requirements for physiologic tooth movement than less resilient heavy gauge wire.

White (1963) and Vestevich (1963) studying the active components which produce orthodontic forces used an especially designed apparatus to measure both the magnitude of activation and range of movement of an arch wire segment. The machine consisted of two mounted stages, one of which was movable. On this movable stage were pin vises and brackets to which the springs or segments to be evaluated could be affixed. A dial indicator calibrated in 0.01 mm. divisions was included to measure the linear displacement. The magnitude of the applied force was measured by a force gauge mounted on the non-movable stage, and had a range of 0 to 1,000 grams in ten gram divisions.

Jarabak and Fizzell (1963) have combined the disciplines of analytical mechanics, applied physics, and biology into a new science, "the biophysics of orthodontic forces". Basic definitions of forces, force systems, and engineering principles are related to radiographic and histologic evidence of the biologic tissue response to orthodontic tooth movement. The biologic appraisal of the qualities of forces are defined as being either threshold, optimal, maximal, or excessive. With an understanding of the biologic response in the dentoalveoloperiodontal environment, numerical force values are assigned for optimal tooth movements. They established a sound foundation in the biophysics of orthodontic force systems. Then these principles were widely applied to orthodontic appliance design and treatment.

CHAPTER III

MATERIALS AND METHODS

A. Materials:

1. Animal Selection:

This investigation has as its object the physical and histologic assessment of a specific orthodontic force system on two female Macaca Mulatta (Rhesus) monkeys. The approximate age of the monkeys as indicated by the source of procurement was between three to four years of age. It was required that each animal be caries free and have a fully erupted complement of permanent teeth excepting third molars. The first animal weighed 9.25 pounds and was assigned an identification tag M II. The second animal weighed 8.1 pounds; it was labeled as M III.

2. Care and Feeding:

The animals were housed in individual cages in the monkey colony of the Franklin Boulevard Hospital Animal Research Center. Regular care was given by the animal handlers of this research facility so that feeding and sanitation procedures were standardized. The daily diet of the animals consisted of Purina Monkey Chow in biscuit form and an orange which had been injected with a vitamin supplement. The biscuits were softened with water into a soft mash in order to prevent the dislodgement of the bands or deformation of the appliance during mastication. A period of two weeks was allowed to acquaint the animals with their surroundings before the experiment was begun. Caps, gowns, face masks, and rubber gloves were worn to protect both animals and the operator from infection during the execution of this experiment. A restraint cage was used to facilitate handling the animals. This cage consisted of one collapsible wall used to compress the animal and one sliding wall to allow the retraction of either the arm, leg, or head of the animal from the cage.

All intra-oral procedures were accomplished with the aid of a general anesthetic. Once the animal was restrained and the site of the injection prepared, fifty milligrams of Nembutal Sodium per five pounds of body weight were injected intravenously. The animals was then removed from the restraint cage and a suture was placed through the tongue. An open airway was maintained by the retraction of the tongue with the aid of this suture. An opthalmic ointment, butyn sulfate and metaphen, was applied to the animal's eyes to prevent post operative infection. This discipline was followed in each operative procedure.

3. Selection of Teeth and Type of Movement:

In order to select the appropriate teeth to be studied, a visual examination and records were made on each animal. The animals were given a general anesthetic to facilitate handling and full mouth periapical roentgenograms, impressions, and Kodachrome photographs were taken. It was determined from the examination of the records of both animals that there was a full complement of permanent teeth with well formed apexes except for the unerupted third molars (Figure 1). Monkey II had a gingival inflammation and there were calculus deposits about the teeth which were removed at the time of the examination. Monkey III had little gingival inflammation and no calculus deposits.

The teeth selected for the application of the vertical reciprocal force system were the maxillary right first and second premolars and the maxillary right molar. The first premolar and molar teeth were used in anchorage for the depression of the second premolar. The buccal surfaces of these teeth were closely aligned in the mesio-

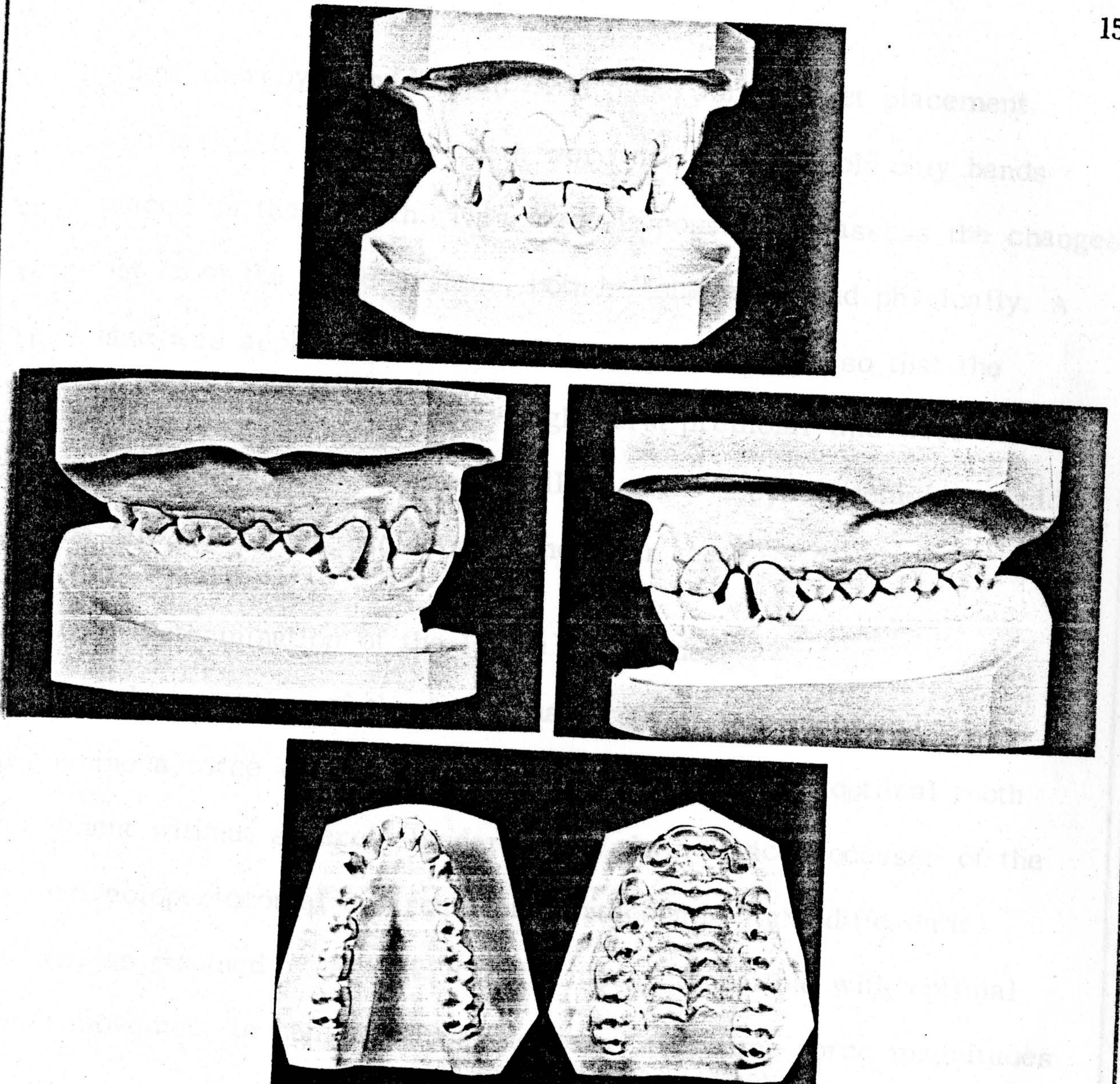


FIGURE 1

MONKEY STUDY MODELS

distal plane thereby providing an even plane for bracket placement. The maxillary left posterior teeth were used as controls only bands were placed on these teeth. This made it possible to assess the changes resulting from the force systems both histologically and physically. A bite plane was applied to the maxillary anterior teeth so that the extrusive effect on the maxillary right first premolar and first molar and the intrusive effect on the maxillary right second premolar would not be affected by the occluding mandibular teeth.

4. Determination of the Force Magnitudes:

In the selection of the force magnitude it was of essence to determine a force value which would be compatible to optimal tooth movement without severely hindering the physiologic processes of the dentoalveoloperiodontal environment. Orthodontic light differential forces, as outlined by Jarabak, can be made compatible with optimal tooth movement in human beings, however, the same force magnitudes might be considered excessive in the Rhesus monkey because the root surface area is proportionately smaller. This fact made it necessary to calculate a force magnitude specifically for the tooth movement of the teeth of the Rhesus monkey using empirical data from studies of human teeth. The force system, being reciprocal, generated forces that would have a tendency to either intrude or extrude certain teeth. Since the maxillary right second premolar had been selected to be the tooth to receive the intrusive force, which incidentally was the force of greatest mangitude, it was necessary to calculate the maximum force magnitude for this tooth. With the aid of x-ray findings of teeth moved orthodontically without apparent root damage and the average tooth size values from Black's Tooth Size Table, a maximum intrusive force magnitude was arrived at empirically for human maxillary premolars. Since the dimensions of the monkey teeth could be determined from the periapical roentgenograms, there was established a ratio between human and monkey second premolar teeth. This was then used to calculate the maximum intrusive force magnitude which could be used on a monkey second premolar tooth.

a) Average length of human maxillary premolar - 14.5 mm.

b) Maximum intrusive force magnitude on human premolar - 180 grams

c) Length of monkey maxillary second premolar - 9.8 mm.

d) Maximum intrusive force magnitude of monkey second premolar - x grams

The maximum intrusive force to be applied to the monkey premolar was found to be 121 grams.

$$\frac{b}{a} = \frac{d}{c} \text{ or}$$

$$d = \frac{c}{a}\, b$$

$$x = \frac{9.8}{14.5} \times 180 = 121 \text{ grams}$$

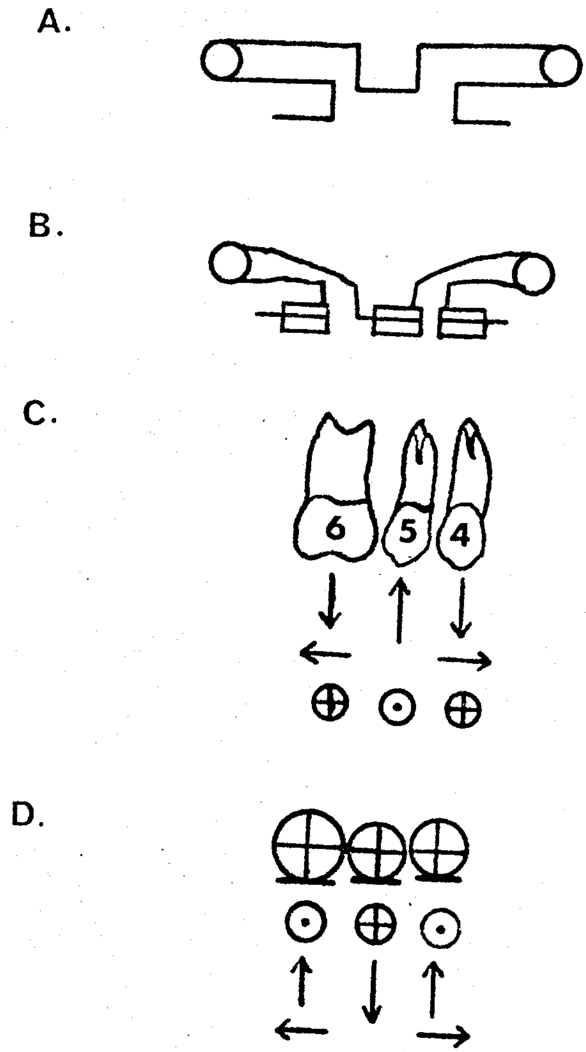
5. Forming a Reference Base for the Physical Assessment of Tooth Movements:

In order to establish a reference base which would be stable, the maxillary second molars and canines were selected to be the reference teeth. By creating cross line registration marks on the buccal surfaces of these teeth, a definite base line was established from which all tooth movements could be measured. By using a knife edge diamond disk, uniform cross reference marks were cut into the buccal surfaces of the maxillary canines and the buccal surfaces of the maxillary second molars in line with the mesio-buccal cusps.

6. Determination of the Force System and Appliance Design:

The specific peak magnitude for the application of an intrusive force on the maxillary second premolar has already been calculated as stated above. The line of action and point of application must be parallel and as close to the long axis of the tooth to provide vertical movement and to minimize tipping moments. The direction of the force in the vertical plane was chosen to put an extrusive force on the monkey maxillary right first premolar and molar and an intrusive force on the maxillary second premolar. With these basic principles in mind, the force system was developed.

The appliance designed to deliver the force system to the selected teeth consisted of two horizontal helical loop springs with one and one half turns in each helix (Figure 2A). These loops when activated would be stressed in contraction. The loops were located in the maxillary buccal vestibule, one loop directed anteriorly and the other loop posteriorly. The horizontal legs of the helical loop springs starting from the helixes converge toward the second premolar. At a point above their respective brackets, a step was made to engage the vertical slots of the Jarabak mandibular incisor brackets. The



A. APPLIANCE UNSTRESSED
B. APPLIANCE STRESSED
C. BUCCAL ASPECT
D. OCCLUSAL ASPECT

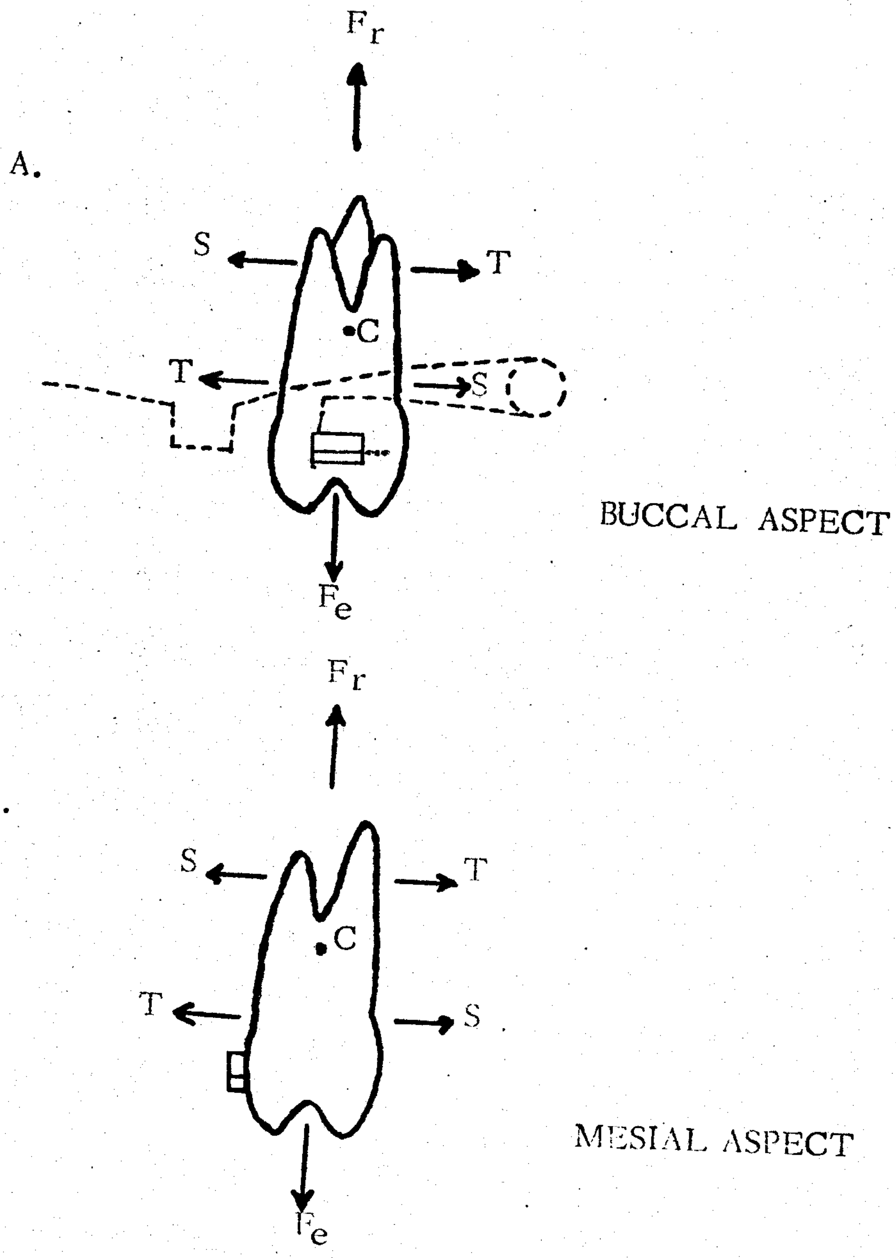
SYMBOLS
↑ VECTOR OF FORCE
⊙ EMERGENT VECTOR
⊕ IMMERGENT VECTOR

FIGURE 2

FORCE SYSTEM DIAGRAMS

vertical extensions compressing the riser of the step engaged the mesial vertical slots of the brackets on the second premolar and first molar. The distal vertical slot of the first premolar was also engaged (Figure 2B). The horizontal segment of the step engaging the second premolar bracket not only served as a stabilizing segment but also provided the connecting link between the two helical loop springs. The other horizontal segments were the terminal limits of the entire appliance. By securely ligating the vertical extensions into the vertical slots, the appliance was stabilized in the buccal-lingual plane.

To illustrate the effect of the force system on the maxillary first molar, a free body diagram has been made showing both the mesial and buccal aspects (Figure 3). The extrusive force generated in the line of the long axis of the tooth (Fe) has an approximate value of 61 grams. An equal and opposite force (Fr) is created by the periodontal ligament in an attempt to maintain equilibrium, thereby retaining the tooth in the alveolus. This situation exists only at the time of appliance activation and is altered by the changes created in the periodontal environment as a result of the tissue response to the force. Since the initial activating force is not in line with the long axis of the tooth but



F_e - EXTRUSIVE FORCE
F_r - RESISTING FORCE
T - COUPLE RESISTING TIPPING
S - TIPPING COUPLE
C - CENTROID

FIGURE 3

FREE BODY DIAGRAMS

instead is transmitted to the tooth through the bracket on the buccal surface of the tooth, a moment of force is created. The initial activating force is a line six millimeters mesial to the long axis of the tooth. Since the initial activating force is sixty-one grams, a tipping moment of 366 gram millimeters is produced. A moment of force when applied to a bracket may be considered as a force (Fe) and a couple (S). The force tends to extrude the tooth, while the couple applied to the bracket has the tendency to tip the tooth in a counter clockwise direction. Since this couple is applied to a tooth in its dentoalveoloperiodontal environment, it will in reality tip the tooth around centroid (C). A resisting couple (T) will be created by the periodontal ligament at the time of appliance activation to equalize the tipping couple (S). The stabilization of the tooth resulting from the resisting couple (T) exists only at the time of appliance activation and until biologic bone changes resulting from the force begin to occur. A free body diagram of the maxillary first premolar may be described similarly. The couple in this case would produce a clockwise type of tipping. Since the force that is being applied to the maxillary second premolar is balanced by the closely symmetrical horizontal loops, little mesial tipping was expected. In the mesial aspect of the free body diagram a moment of force is developed by the application of the sixty-one gram forces applied four millimeters buccal to the long axis of the tooth. This force (Fe) and couple (S) will create a lingual tipping of the crown of the tooth. Since the vertical extension of the helical loop arch is secured in the vertical slot of the bracket, a resisting counter couple is developed by the bracket. The second premolar, conversely, with an intrusive force applied to the bracket will tend to be tipped in a buccal direction. The vertical extension of the helical loop arch being secured in the vertical slot of the second premolar bracket will produce a counter couple to offset the buccal tipping. The counter couple produced by the securing of the vertical extension into the vertical slot of the brackets is aided by a resisting couple formed by the periodontal ligament (T).

7. Appliance Fabrication and Assessment:

Working dies were made of the teeth to be banded. The base of the model was scored and a plaster index was poured as a reference base (Figure 4). The teeth were then separated with a .0075" thick

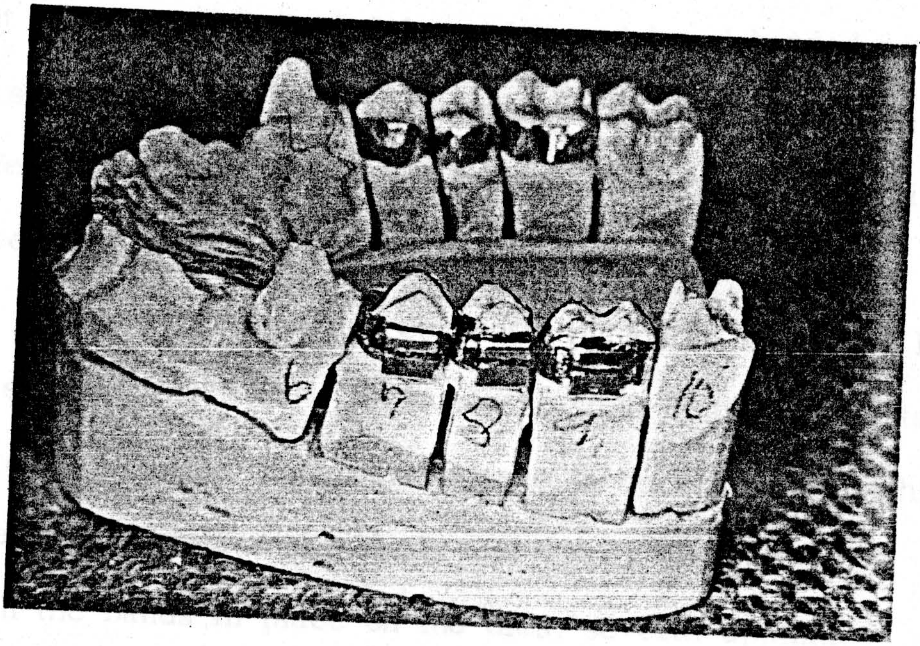


FIGURE 4

WORKING DIES WITH BANDS

diamond lightning strip. This reduction of mesial-distal sides of the teeth was necessary to pass the thickness of banding material through the interproximal spaces. The maxillary first and second premolars and first molars were divided from the model and banded with .125" x .004" stainless steel banding material. Since the dies were scored on their inferior surface, they could be repositioned accurately in the index. The three right teeth had Jarabak mandibular incisor brackets attached to them. These brackets were correctly placed in the bands by placing a small segment of .016" x .016" square wire in the horizontal slots of the brackets. Once the brackets were in correct relationship to the bands they were luted to the bands and finally spot welded.

With the bands in place on the dies, several appliances made with selected diameters of round wire were fabricated and tested to determine the peak activation magnitude for the desired deflection. It was found that .014 inch ductile yellow Elgiloy round wire produced the most satisfactory results. All of the appliances were heat treated in a Huppert electric oven at 900° F. for ten minutes.

Each appliance was measured on a load-deflection testing instrument with three sample readings (Figure 5). The instrument has two

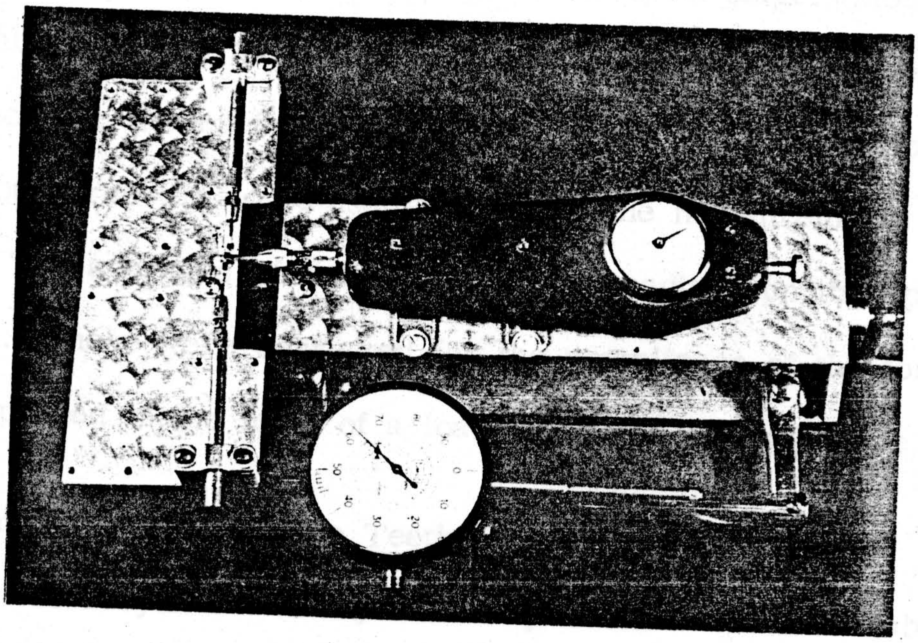


FIGURE 5

LOAD-DEFLECTION INSTRUMENT

stages one moveable with respect to the other. A Hunter force gauge to measure the magnitude of force and a dial indicator to measure the amount of deflection were associated with the fixed stage. Mountings for the stabilization of the appliance to be tested were on the other stage. Since the Hunter force gauge had "follow along" or compliance, a correction curve had to be used to correct the measurements of deflection. The averages of the three sample readings on the appliance were taken. These were corrected for the compliance of the force gauge and plotted in the form of a load-deflection graph (Figure 6).

8. Transfer Units for the Teeth:

Individual acrylic maxillary buccal quadrate trays were fabricated so that rubber base impressions could be taken periodically of both left and right maxillary buccal quadrants (Figure 8). These impressions were taken at the time of appliance activation and at the end of ten, twenty, and thirty days. Dies or transfer units were made by pouring up these impressions according to the manufacturer's specifications with Kerr Vel-Mix Stone.

A test of the reliability of the impression material, (Coe heavy rubber base) was conducted to determine the margin of error which

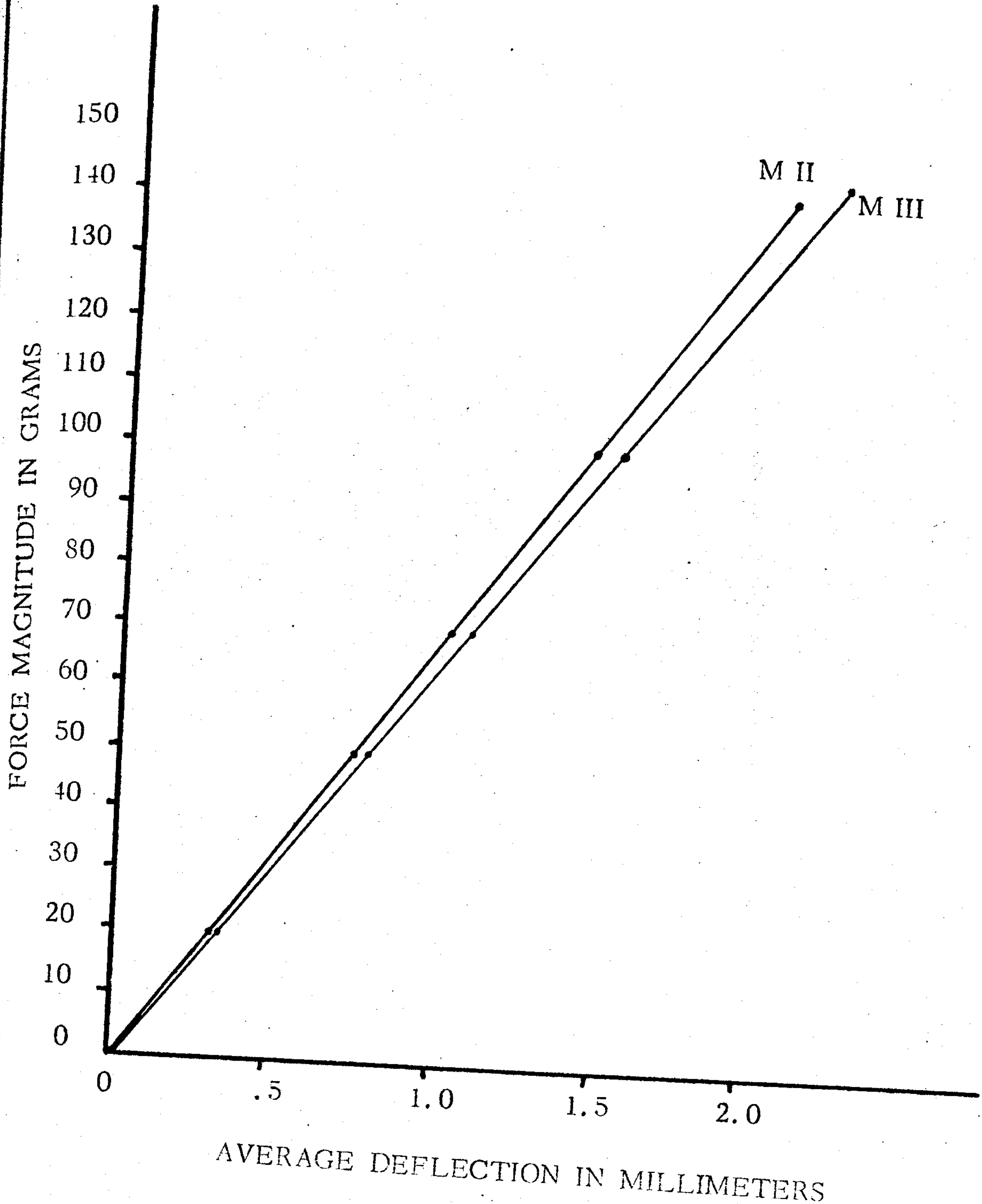
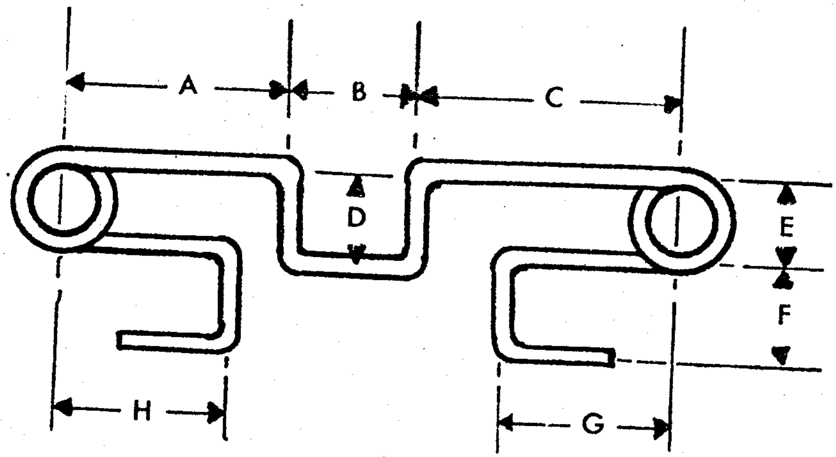


FIGURE 6

LOAD-DEFLECTION CURVES OF APPLIANCES



KEY	M II APPLIANCE	M III APPLIANCE
A.	10.4	10.1
B.	4.1	3.9
C.	10.7	12.6
D.	3.7	4.4
E.	2.9	2.8
F.	3.7	4.0
G.	7.4	7.9
H.	7.3	7.1

FIGURE 7

DIMENSIONS OF APPLIANCES IN MILLIMETERS

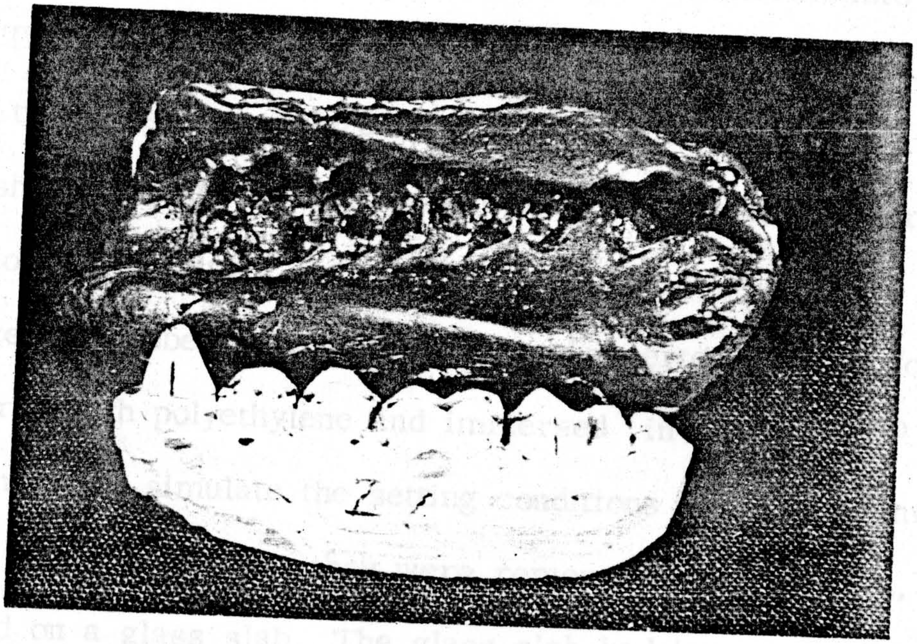


FIGURE 8

RUBBER BASE IMPRESSION AND STONE TRANSFER UNIT might be attributed to dimensional changes of this material. Three samples were prepared by mixing the rubber base material according to manufacturer's specifications and casting the material into rectangular blocks. The form for casting these blocks consisted of a base plate, in which two cross line reference marks had been inscribed, and two "L" shaped pieces of metal which could be placed together on the base to form a rectangle.

Once the rubber base was mixed and inserted into the form it was covered with polyethylene and immersed in water at 37° C. for seven minutes to simulate the setting conditions in the oral environment. After the samples had set, they were removed from the form, inverted, and placed on a glass slab. The glass slab had been coated with talc to reduce friction and to allow the sample to exhibit any dimensional change. A traveling microscope was used to measure the original distance between the cross marks on the base plates and the corresponding reference marks left in the impression material. The measurements of the samples were done fifteen minutes, one hour, three hours, and twenty-four hours after the setting of the material had taken place. It was found that the coefficient of variation was 1/4 of 1%.

9. Transfer Unit Mounting Device:

It was necessary to mount the transfer units in a standardized manner so that measurements made upon them would be comparable. The two reference teeth described previously contained cross line reference marks that were reproduced on the transfer units. These marks were used to orient the transfer units when they were being set into their carriers. A special device was constructed to provide the necessary contact points to orient the transfer units.

The most precise and accurate means of practically orienting an object in a frame of reference is by use of a point, a line, and a plane. In this present mounting device the "point" was the tip of a cone on the end of a brass rod; the "line" was the edge of a chisel tip milled on the end of a different brass rod; the "plane" was a plastic surface on an adjustable angle bracket. These components were mounted on a block of aluminum which was set on an aluminum base plate. The reference surfaces of the block end plate were mutually perpendicular. Figure 9 shows the mounting device equipped to accept either right or left transfer units.

FIGURE 9

TRANSFER UNIT REGISTRATION INSTRUMENT

Five "U" shaped carrier devices were milled from solid steel with all external surfaces mutually perpendicular. These were used as holding devices for the transfer units as shown in Figure 10. Pink wax held each transfer unit into its carrier.

When being mounted, a transfer unit was placed on the transfer unit mounting device with the "point" at the center of the cross lines on the canine tooth and the "line" in the horizontal groove on the second molar tooth. The acrylic plane was then set so that the mesio-buccal and mesio-lingual cusps of the second molar contacted it. While the transfer unit was held in this position, the carrier unit was slid under it against the vertical reference surface. Then the pink wax was applied and allowed to cool.

10. Instrument for Measuring Tooth Movement:

The instrument that was designed to measure the tooth movement consisted of a horizontal aluminum stage, a vertical back plate, an Ames Dial Gauge, and measuring stylii (Figure 11). The horizontal stage was mounted perpendicular to the vertical plate and had an opening through it to allow the measuring stylii to pass through. The Ames Dial Gauge was graduated in .001 mm. per division. This

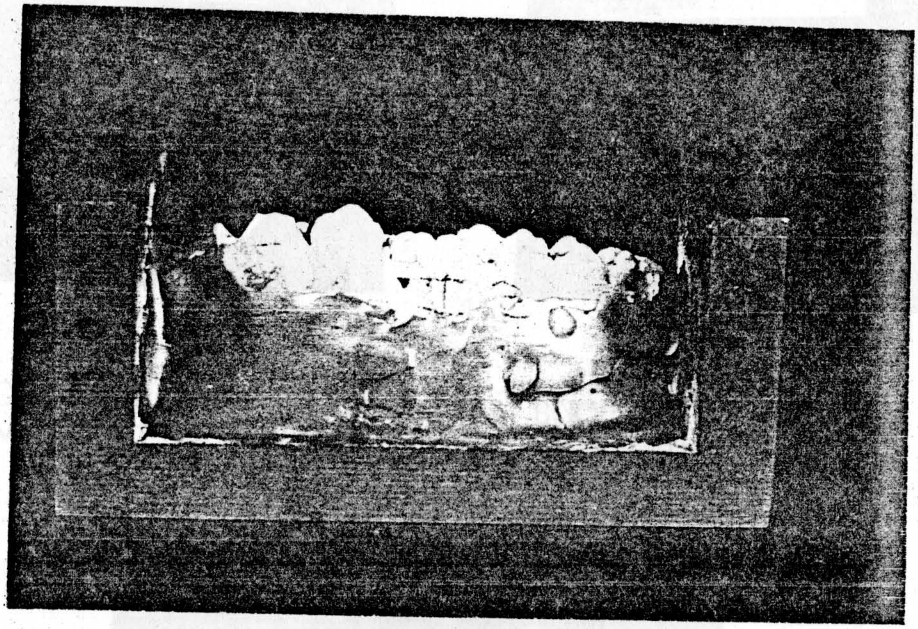
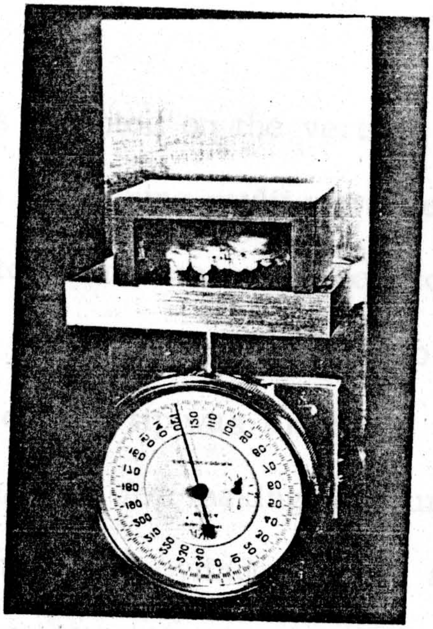
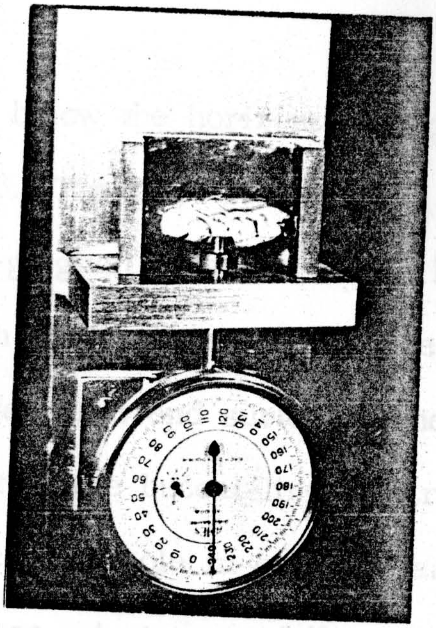


FIGURE 10

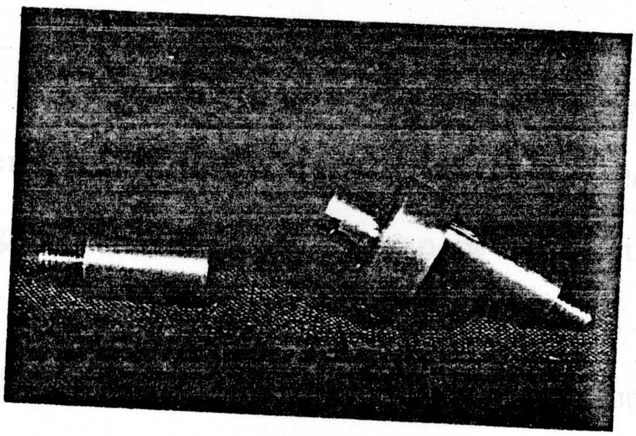
CARRIER DEVICE WITH MOUNTED TRANSFER UNIT



A. OCCLUSAL-GINGIVAL MEASUREMENT



B. BUCCAL-LINGUAL MEASUREMENT



OCCLUSAL-GINGIVAL STYLUS

BUCCAL-LINGUAL STYLUS

FIGURE 11

TOOTH MEASUREMENT INSTRUMENT WITH CARRIER DEVICE AND MEASURING STYLII gauge was mounted on the vertical plate below the horizontal stage.

Two measuring stylii were required. The first stylus, used to measure tooth movement in the occlusal-gingival direction was a brass cylinder. One end was threaded to attach to the Ames Dial Gauge while the other end or tip was turned to provide a flat end surface. The second tip, used for making measurement in the buccal-lingual direction, was a short brass cylinder having an eccentric hole in one face and a central protruding boss on the opposite face. A step cut following a secant line had been milled across one side of the boss. This measuring tip was attached to a cylindrical stylus using the eccentric hole and a radial setscrew.

To measure in the occlusal-gingival direction, the carrier device in which a transfer unit had been mounted was inverted and placed on the horizontal stage so that the buccal cusp of one of the teeth contacted the flat surface of the measuring tip. The distance to each tooth was measured independently by two operators, providing duplicate measurements. To measure in the buccal-lingual direction the carrier device with the mounted transfer unit was placed on the horizontal stage of the measuring instrument so that the buccal surfaces of the teeth faced the stepped measuring tip. The tooth to be measured engaged the measuring tip in such a way that the tip of the buccal cusp rested in the step cut in the boss. Duplicate measurements were made on each of the transfer units.

11. Testing Precision of the Measuring Instrument:

Since this was a new method of assessing tooth movements, a test for ascertaining the precision of the measuring instrument needed to be devised. This was done as follows: Five sample transfer units were placed in carrier devices, and four different operators measured the samples in duplicate. The maxillary first and second premolars and maxillary first molar were measured in both the occlusal-gingival direction and buccal-lingual direction. The units were selected at random with the aid of a table of random numbers. A series of 240 measurements were made. To these the "Analysis of Variance" was applied to ascertain the precision of this measuring instrument (see Table I).

The standard error of duplicate measurements was calculated by taking the square root of the mean square (.00011515) for duplicates.

ANALYSIS OF VARIANCE FOR THE PRECISION MEASUREMENT TESTS

	D.F.	S.S.	M.S.	V. RATIO	F.
UNITS	4	2.741398	.685349	541.4	3.56 (.01)
STUDENTS	3	.005323	.001774	1.5	2.72 (.05)
TEETH	2	5.823006	2.911503	224.8	4.87 (.01)
DIRECTION	1	54.545926	54.545926	14.37	7.71 (.05)
U. x T.	8	.103953	.012994	10.3	2.75 (.01)
U. x D.	4	15.181872	3.795468	2998.	3.57 (.01)
T. x D.	2	18.824383	9.412191	251.	4.87 (.01)
T. x D. x U.	8	.300263	.03753	29.64	3.55 (.01)
RESIDUE	87	.110142	.001266		
DUPLICATES	120	.013815	.00011515		
TOTAL	239	97.650081			

TABLE I

Since this was acquired from 120 degrees of freedom, the 99% confidence limits are plus and minus .028 mm. The dial indicator was graduated in .001 mm. per division; so fifty-six times the least count of the measuring instrument would encompass the 99% confidence limits. This is a reasonable amount of error because the measurements were made on casts and some slight error may result from the placement and holding of the casts on the measuring instrument, a deformation of the cusp, creep of the pink wax, or zero reference setting.

In order to determine the amount of error contributed by the other factors of the measuring process, attention was directed to the residue mean square which was derived from eighty-seven degrees of freedom. The standard error of the overall measurement includes the entire process of applying these casts in six different situations and measuring them. The 99% confidence limits derived from eighty-seven degrees of freedom and the mean square of the residual error are plus and minus .0936 millimeters or approximately one tenth of a millimeter.

The normal distributions for the experimental errors of the overall process and of the process of taking duplicate measurements are illustrated in Figure 12.

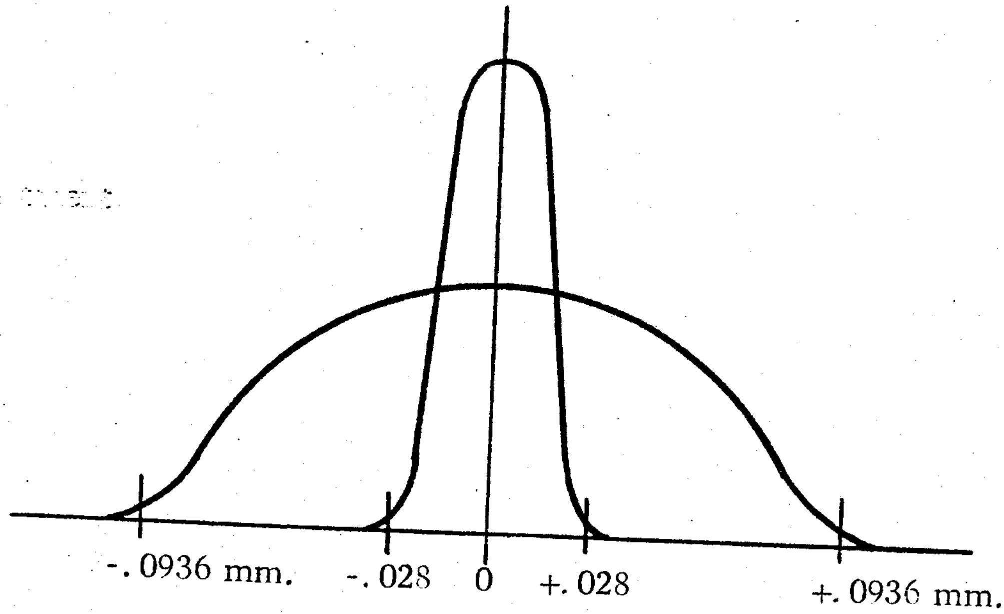
The "Analysis of Variance Table" lists the individual sources of variation, the differences between the performance of the operators, the differences between the teeth that were measured, the direction in which measurements were made, and the difference between sample units.

To determine the significance of each factor, comparisons were made between the mean squares of each factor and the mean square of the residue. Comparisons were also made using certain two-factor and three-factor mean squares as the reference. The proper comparisons were determined by the components of variance contained in the respective mean squares.

From the "Analysis of Variance Table", it can be seen that the three factor interaction was significantly large even when judged at .01 level of probability. The mean square due to direction of measurement was significant at the .05 level of probability. The mean square due to students, when judged even at the .05 level of probability, did not prove to be significantly large.

B. Methods:

1. Cementation of Bands, Activation of the Appliance, Restraint



A mean square of .001266 yields .0355809 as the standard error of measurement. 99% limits are + - (2.63 x .0356) equals .0936 mm. which includes all sources of experimental error.

A mean square of .00011515 yields .01073 as the standard error of duplicate measurements. With 120 degrees of freedom, the 99% confidence limits are +/- (2.62 x .01073) equals .02811 mm.

FIGURE 12

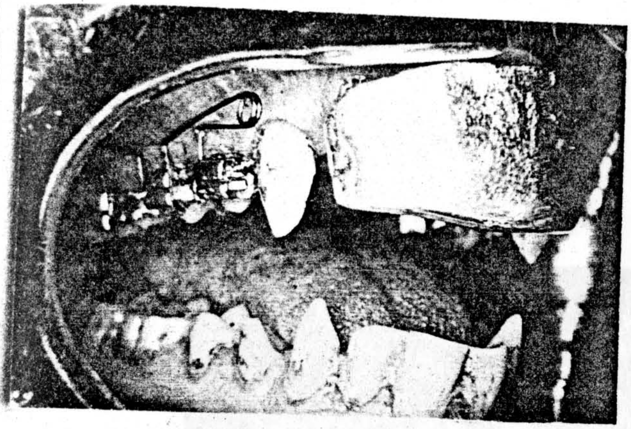
of the Animals, and Recording Tooth Movements:

The animals were anesthetized as previously described and reference teeth marked with the diamond disk. The contacts between the teeth to be banded were reduced with the same sized diamond lightning strip that was used to reduce the stone dies. The preformed bands were then adapted to the teeth and cemented with Black's Copper cement. A cast silver bite block covering the four maxillary anterior teeth was also cemented with Black's Copper cement. The bite block was designed to engage the mandibular incisor teeth before the posterior teeth could occlude. The bite was opened in the region of the maxillary first molar approximately three to four millimeters (Figure 13).

After the cementing was completed, rubber base impressions were taken of both right and left maxillary quadrants. These impressions were poured within one hour with Kerr Vel-Mix stone.

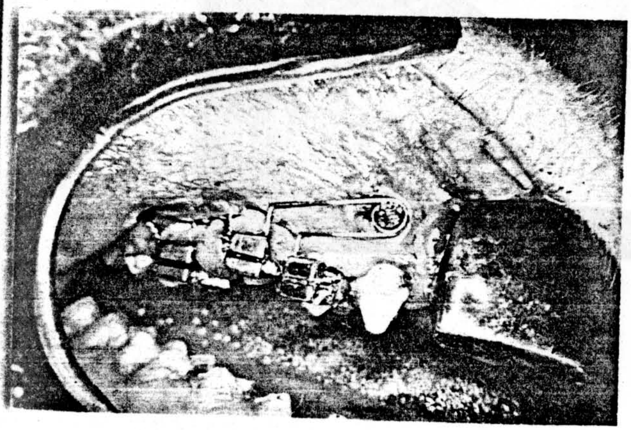
The fabricated wire appliances were then inserted into the brackets and ligated with .010" orthodontic ligature wire.

To prevent the animals from deforming or breaking the appliance, their paws and wrists were wrapped in gauze with an adhesive tape covering (Figure 14). These bandages were replaced when the animals

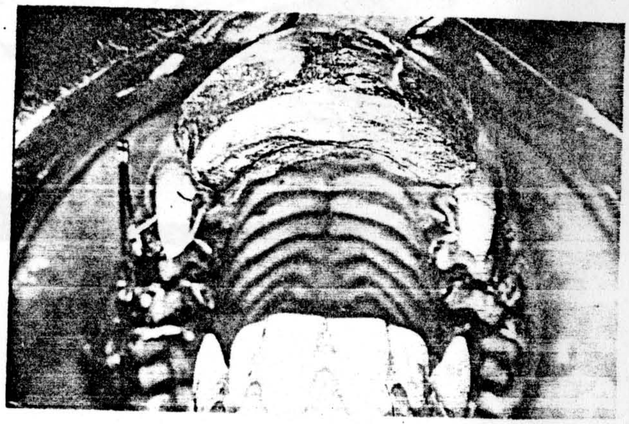


APPLIANCE STRESSED AND BITE BLOCK IN POSITION

LEFT SIDE FOR REFERENCE



APPLIANCE IN DEACTIVATED STAGE



OCCLUSAL VIEW

FIGURE 13

ANIMAL WITH EXPERIMENTAL APPLIANCE IN MOUTH

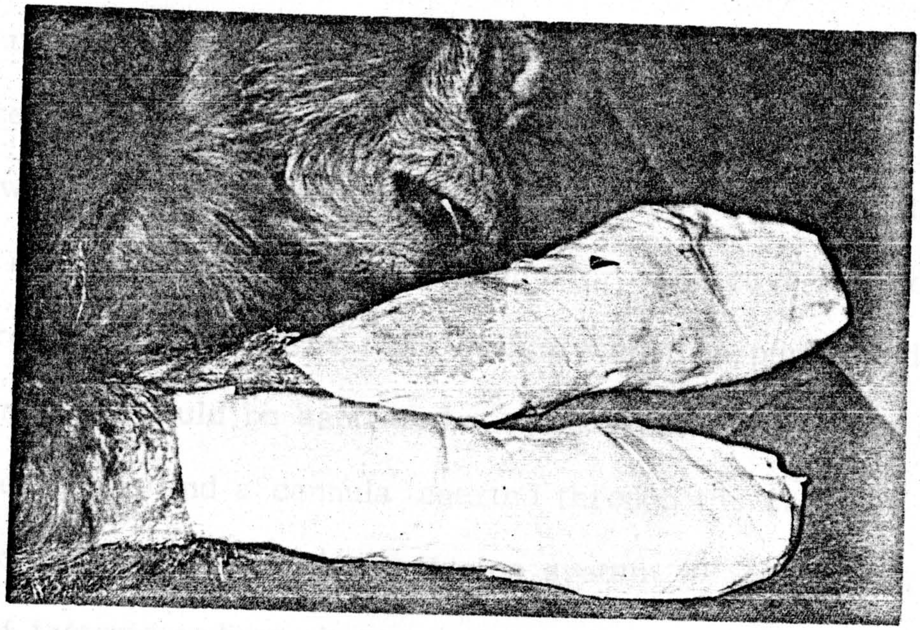


FIGURE 14

ANIMAL RESTRAINT DURING EXPERIMENT

were anesthetized to take the rubber base quadrant impressions.

2. Sacrifice and Perfusion of Animals:

The animals were sacrificed on the thirtieth day of the experiment and the head and neck perfused to provide adequate tissue fixation. They were anesthetized and a thoracic incision in the area of the sternum was made to expose the pericardium. The pericardium was reflected exposing the heart, and the inferior vena cava and descending aorta were clamped off. The right atrium was then perforated so that the venous blood could be aspirated. Another perforation was made in the left verntricle and a cannula inserted through the chamber and into the ascending aorta. Once the perfusion system was complete, a solution of isotonic sodium citrate was introduced through the cannula in the ascending aorta. The pressure of the system was regulated by either raising or lowering the level of the sodium citrate source. When all evidence of blood from the right atrium ceased, a solution of ten per cent buffered formalin was diverted through the perfusion cannula. When the tissues of the head and neck became rigid it was considered that the perfusion was complete.

3. Histologic Preparation of Sample Tissues:

Block sections of the experimental teeth and supporting structures were dissected from the animal and fixed for ten days in a solution of ten per cent buffered formalin. Before fixation the appliances were removed from the teeth.

Following fixation, the tissue blocks were washed in water for twelve hours before the decalcification stage. The tissue blocks were then allowed to decalcify in 50 per cent formic acid for a period of forty-eight days. During this time radiographs were taken to determine the degree of decalcification. The blocks were then washed prior to dehydration.

The blocks were dehydrated, double imbedded in celloidin and paraffin, sectioned, and stained by the Loyola University, School of Dentistry, Histology Laboratory.

The tissue blocks were serially sectioned at a thickness of ten microns and every fourth section was stained with hematoxylin and eosin stain.

To ascertain intrusion, extrusion or mesial-distal tipping, the sections of M II were cut mesio-distally in the long axis of the tooth.

Cross sections were made of the M III teeth in order to determine buccal-lingual and mesial-distal tipping.

CHAPTER IV

FINDINGS

A. Physical Findings:

1. Tooth Movement Records:

The data collected for each animal were recorded in especially prepared charts, samples of which are in Tables II and III. Each measurement was identified by six factors, number of monkey, side (right or left), number of transfer unit, operator making measurements, and direction of the measurement.

2. Analysis of Variance for Experimental Tooth Movement:

All of the data obtained for the measurements on the experimental teeth in the buccal-lingual direction were analyzed in one group by Fisher's Analysis of Variance. The data obtained for measurements in the occlusal-gingival direction were similarly analyzed in a separate group. These analyses were done to check the validity of the method and the accuracy of the data. In the design of the analyses several factors were considered. They are as follows: (1) the number of animals, (2) the teeth that were measured, (3) the examinations on transfer units, (4) the interaction between individual main effects, and (5) duplicate measurements.

MEASUREMENTS OF BUCCAL-LINGUAL TOOTH POSITIONS OF THE MAXILLARY RIGHT BUCCAL UNIT

Transfer Unit No.	Operator	Tooth		
		4	5	6
1	A	.939	1.393	2.182
1	B	.934	1.406	2.179
2	A	.768	1.638	1.761
2	B	.770	1.635	1.758
3	A	.595	1.952	1.730
3	B	.598	1.956	1.724
4	A	.406	1.983	1.719
4	B	.398	1.982	1.705

Monkey III

TABLE II

MEASUREMENTS OF OCCLUSAL-GINGIVAL TOOTH POSITIONS OF THE MAXILLARY RIGHT BUCCAL UNITS

Transfer Unit No.	Operator	Tooth 4	Tooth 5	Tooth 6
1	A	1.836	1.215	1.081
1	B	1.844	1.214	1.086
2	A	1.872	.740	1.113
2	B	1.870	.734	1.114
3	A	1.687	.227	1.070
3	B	1.684	.229	1.068
4	A	1.704	.057	1.209
4	B	1.701	.055	1.205

Monkey III

TABLE III

Table IV shows the results of analyzing the buccal-lingual measurements. It was estimated from the duplicate mean square in the analysis of the right buccal-lingual measurements that the standard error of the process of making duplicate measurements was .004707 mm. The 99% confidence limits are plus or minus .0132 mm. One division on the dial indicator was .001 mm.; so this range of plus or minus thirteen divisions on the dial indicator is a reasonably sized error.

The mean square for the buccal-lingual dimension interaction, A x T x E, was larger than the mean squares for A x T and A x E. Assuming that these were the best estimate of experimental error, the weighted mean was taken and an estimate of experimental error of .1128 mm. derived. The 99% confidence limits are plus and minus .454 mm. or about .5 mm., which includes all sources of experimental error.

It was not possible to detect any difference between the two animals as far as these measurements were concerned. It was expected that the dimensions of the tooth positions would differ widely among themselves, and Table IV shows the variation to be highly significant statistically. There was not enough variation between examinations to show any statistical significance. Only one of the interactions was large enough to show

ANALYSIS OF VARIANCE TABLE

RIGHT SIDE - BUCCAL-LINGUAL DIMENSION

	D.F.	S.S.	M.S.	V Ratio	F
Animals	1	.0258540	.02585	2.03	N.S.
Teeth	2	12.1986986	6.099349	478.	13.27 (.01)
Exams	3	.0589002	.019633	1.54	N.S.
A x T	2	.0350372	.0175186	<1	N.S.
A x E	3	.0285334	.0095111	<1	N.S.
T x E	6	1.225508	.204251	6.02	4.28 (.05)
A x T x E	6	.203629	.033938	<1	N.S.
Duplicates	24	.000532	.000022		
Total	47	13.7766916			

TABLE IV

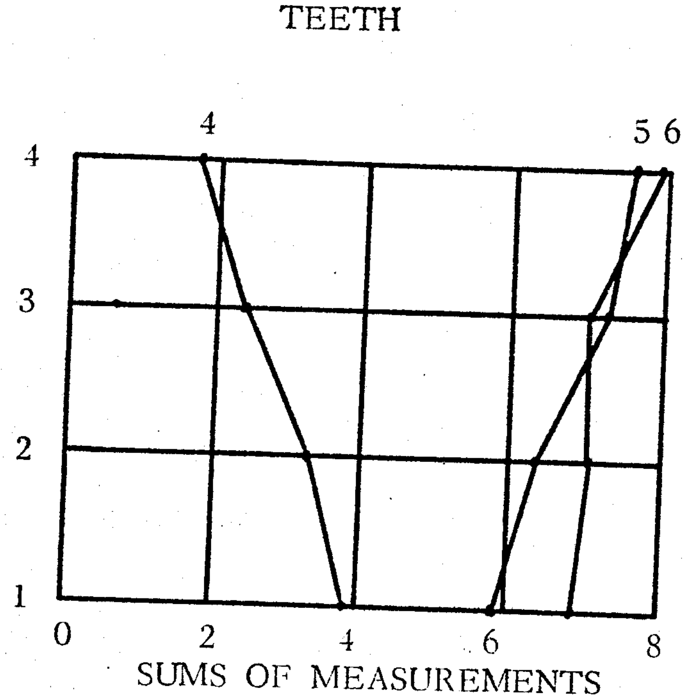
any statistical significance. This was the T x E interaction, and it means that the three teeth changed differently between examinations.

The T x E interaction is plotted in a graph, Figure 15A, to represent the variation that resulted between the three teeth. The lack of parallelism of the three lines indicates a statistically significant interaction. If the three lines representing the experimental teeth were parallel to each other, this interaction would simply be a measure of experimental error, Figure 15B.

From the duplicate mean square in the analysis of the right occlusal-gingival measurements (Table V) it was calculated that the standard error of making duplicate measurements was .0039 mm. The 99% confidence limits are plus or minus .0109 mm. Since the smallest division on the dial indicator was .001 mm., plus or minus ten divisions of variation was still a reasonable figure.

The mean square due to the three factor interaction in the analysis of the occlusal-gingival measurement appears to be unusually large suggesting that there may actually be a three factor interaction of significance. This possibility cannot be tested precisely because there was not an independent estimate of experiment error. One way of overcoming this

A. RIGHT SIDE - BUCCAL-LINGUAL DIMENSION
INTERACTION BETWEEN TEETH AND EXAMINATIONS



B. RIGHT SIDE - BUCCAL-LINGUAL DIMENSION
INTERACTION BETWEEN ANIMALS AND TEETH

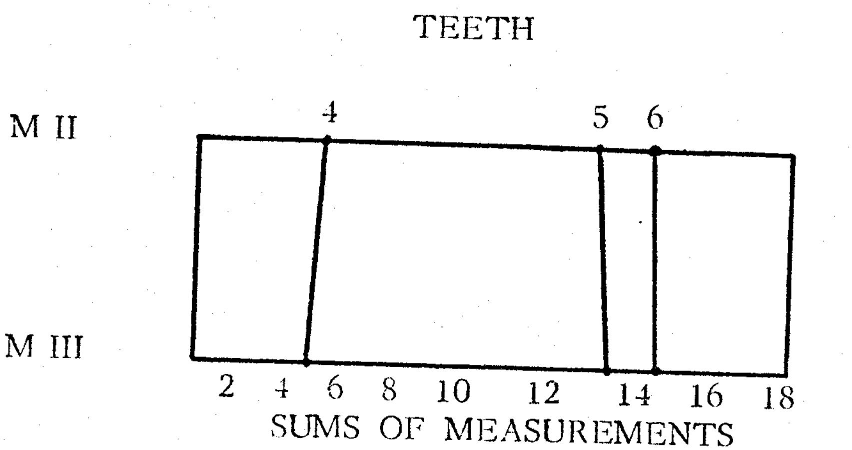


FIGURE 15

ANALYSIS OF VARIANCE TABLE

RIGHT SIDE - OCCLUSAL-GINGIVAL DIMENSION

	D.F.	S.S.	M.S.	V Ratio	F
Animals	1	.0275521	.02755	<1	N.S.
Teeth	2	11.8080436	5.90402	112.0	19.00 (.05)
Exams	3	.8506637	.28355	8.012	9.28 (.05)
A x T	2	.1054221	.052711	<1	N.S.
A x E	3	.1061718	.035906	<1	N.S.
T x E	6	2.5779313	.429655	3.755	4.28 (.05)
A x T x E	6	.686382	.114397	2.703	N.S.
Duplicates	24	.000359	.0000149		
Total	47	16.1625246			

TABLE V

deficiency is to lump the sums of squares and degrees of freedom for the two lowest interactions to provide an estimate of error. This mean square is .04231. When the three factor mean square is tested against this mean square, the variance ratio is 2.7, which is not significant at the .05 level because of the low number of degrees of freedom. An inspection of the entries in the three factor interaction table reveal that there is undoubtedly a genuine interaction of freedom. It was found that the tooth positions differed widely among themselves, and Table V shows the variation to be highly significant statistically.

3. Physical Assessment of Tooth Movement:

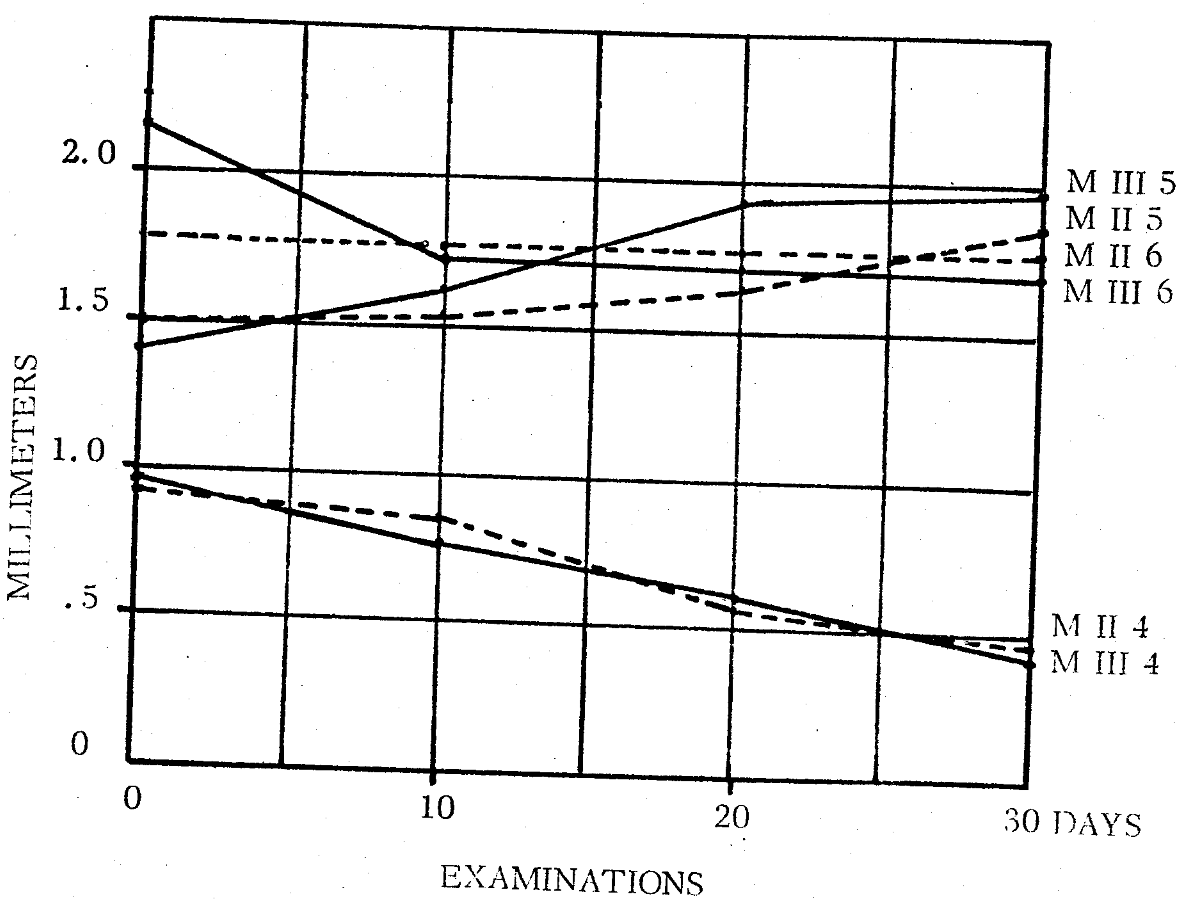
The results of the tooth movement on the experimental side were plotted on two graphs. These graphs were designed to indicate both the direction and magnitude of the tooth movement. The horizontal scale of the graph indicates the days on which each of the four transfer units was made, and the vertical scale indicated the measurements in mm. that were made on each of the teeth of these casts. The points that were plotted represent the measurements of a tooth for the stated examination days. Four points were plotted for each tooth and a line was drawn to connect these points. In the graph showing movements of the teeth in the buccal-lingual direction (Figure 16), a rising line indicates buccal tipping. Similarly, in the graph showing movements of the teeth in the occlusal-gingival direction (Figure 17), a rising line indicates extrusion.

The initial and first tooth positions were tested to see which teeth appeared to have shifted appreciably. Using the standard error derived in the analysis of variance, the appropriate Student's "T" tests were applied.

From the evaluation of the tooth movement in the buccal-lingual direction it was found that the maxillary first premolars of M II and M III and the maxillary first molar of M III tipped lingually. These teeth tipped .468 mm., .434 mm., and .468 mm. respectively. The maxillary second premolars of M II and M III tipped buccally. These teeth tipped .349 mm. and .583 mm. respectively. There was no apparent change, buccal-lingually, of the maxillary first molar of M II.

In the assessment of the tooth movement in the occlusal-gingival direction, it was found that the maxillary second premolars of M II and M III were intruded 1.101 mm. and 1.158 mm. respectively. The maxillary first premolar was extruded .647 mm. The maxillary first molars of M II and M III and the maxillary first premolar of M III did not show

MOVEMENTS OF THE TEETH IN A
BUCCAL-LINGUAL DIRECTION
ON THE EXPERIMENTAL SIDE



INCREASE IN DIMENSION (BUCCAL-LINGUAL) INDICATES
BUCCAL TIPPING

M - MONKEY

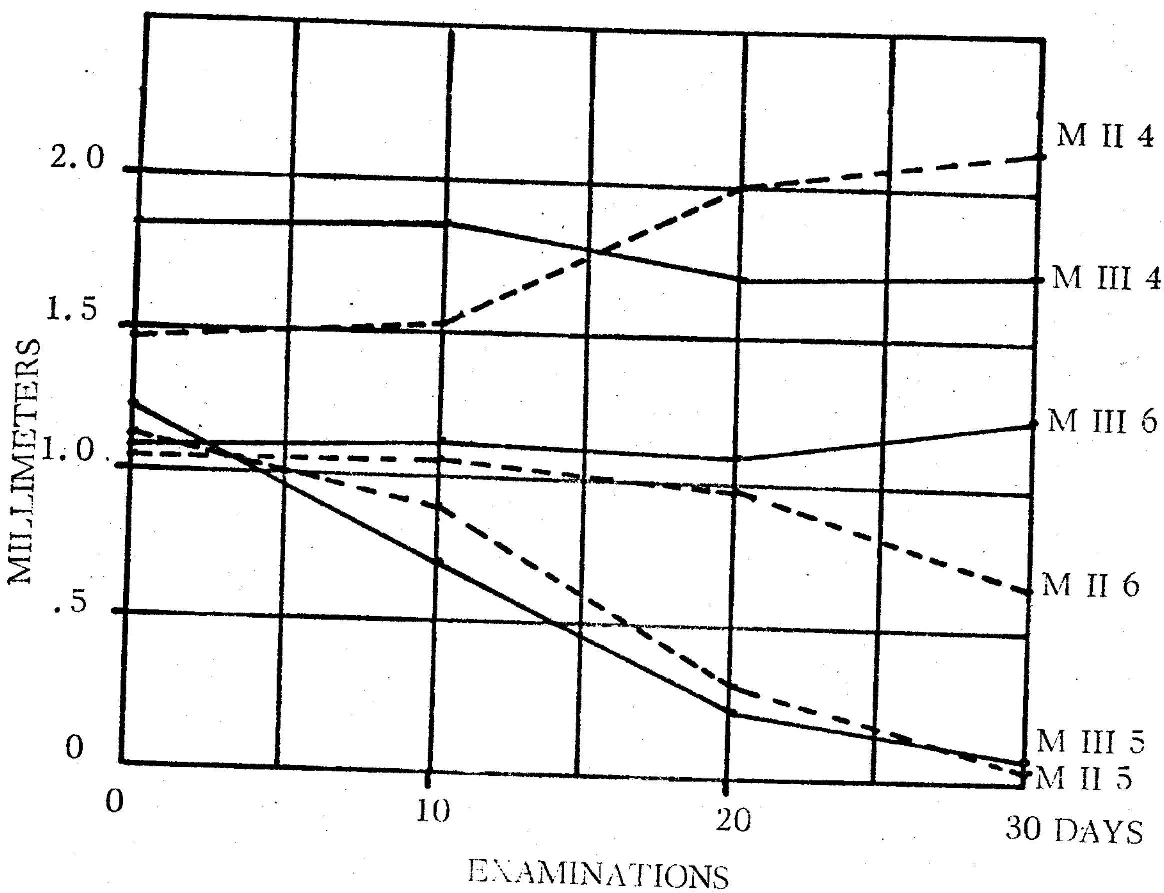
4 - MAXILLARY RIGHT FIRST PREMOLAR

5 - MAXILLARY RIGHT SECOND PREMOLAR

6 - MAXILLARY RIGHT FIRST MOLAR

FIGURE 16

MOVEMENTS OF THE TEETH IN AN OCCLUSAL-GINGIVAL DIRECTION ON THE EXPERIMENTAL SIDE



INCREASE IN DIMENSION (OCCLUSAL-GINGIVAL) INDICATES EXTRUSION

M - MONKEY

4 - MAXILLARY RIGHT FIRST PREMOLAR

5 - MAXILLARY RIGHT SECOND PREMOLAR

6 - MAXILLARY RIGHT FIRST MOLAR

FIGURE 17

appreciable changes according to the t-tests.

4. Assessment of Physical Changes of Teeth on the Reference Side:

In the assessment of the teeth in the left buccal quadrant, a standard deviation of .1147 mm. in the buccal-lingual measurements and .1452 mm. in the occlusal-gingival measurements was calculated.

To test for real tooth movement on the reference side Student's t-tests were applied to the initial and final measurements for each tooth. When tested at the .05 level of probability, it was found that no measurable change occurred to the teeth on this side. Whatever changes in measurement were noticed were well within the range of experimental error.

B. Histologic Findings:

1. Transverse Histologic Sections of M III:

Representative areas were chosen to illustrate the histologic changes in the alveolo-periodontal environment resulting from the application of the experimental force system, and included both the experimental and reference teeth. Transverse histologic sections were made on M III to assess buccal-lingual movement of these teeth.

A diagrammatic representation of tipping in the buccal-lingual direction is shown in Figure 18A. The relation of the root to the alveolus at levels either above or below the center of tipping are included to represent tipping, 18B.

The photomicrographs of teeth on the left buccal quadrant, Figures 19A, 19B, and 20A, and the view of the maxillary right second molar, Figure 20B, do not present any significant histologic changes. It was expected that there would not be any appreciable change of these teeth since they were not affected by the force system. These teeth in the left buccal quadrant had bands applied to them, but had no force system applied.

Physical measurements showed that the maxillary right first premolar of M III was tipped lingually. Histologically, there was an area of compression seen above centroid (Figure 21A). Seen in the same section was an area of tension found on the buccal side. A direct opposite was found to exist above centroid, that is in sections taken gingivally in relation to centroid, Figure 21B. In Figure 21A the periodontal ligament appears to be compressed on the distal-lingual surface. There was evidence of direct bone resorption, numerous osteoclasts, and unimpaired vascularity seen on the lingual surface. The area of tension seen in Figure 21B shows the wide periodontal space and unimpaired blood vessels. This is

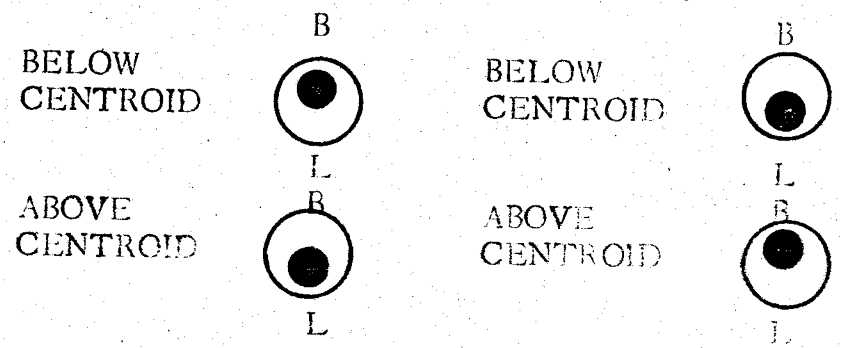
DIAGRAMMATIC REPRESENTATION OF TIPPING
IN A BUCCAL-LINGUAL DIMENSION

A. DISTAL ASPECT OF EXPERIMENTAL TEETH INDICATING DIRECTION OF TIPPING

4 AND 6 5

B. ROOT RELATION TO ALVEOLUS (TRANSVERSE SECTIONS)

4 & 6 5



C. SYMBOLS

B - BUCCAL

L - LINGUAL

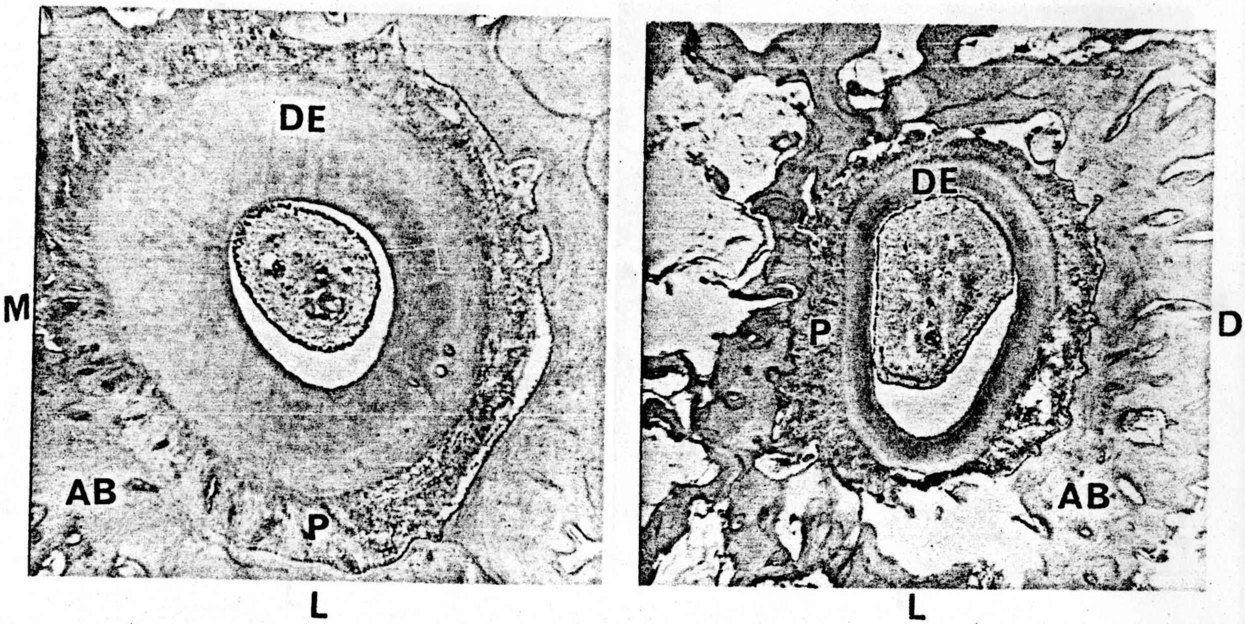
4 - MAXILLARY RIGHT FIRST PREMOLAR

5 - MAXILLARY RIGHT SECOND PREMOLAR

6 - MAXILLARY RIGHT FIRST MOLAR

FIGURE 18

A. B.



MAXILLARY LEFT
FIRST PREMOLAR
M III (8X)
MESIAL BUCCAL ROOT

MAXILLARY LEFT
SECOND PREMOLAR
M III (5X)
DISTAL BUCCAL ROOT

D DISTAL

M MESIAL

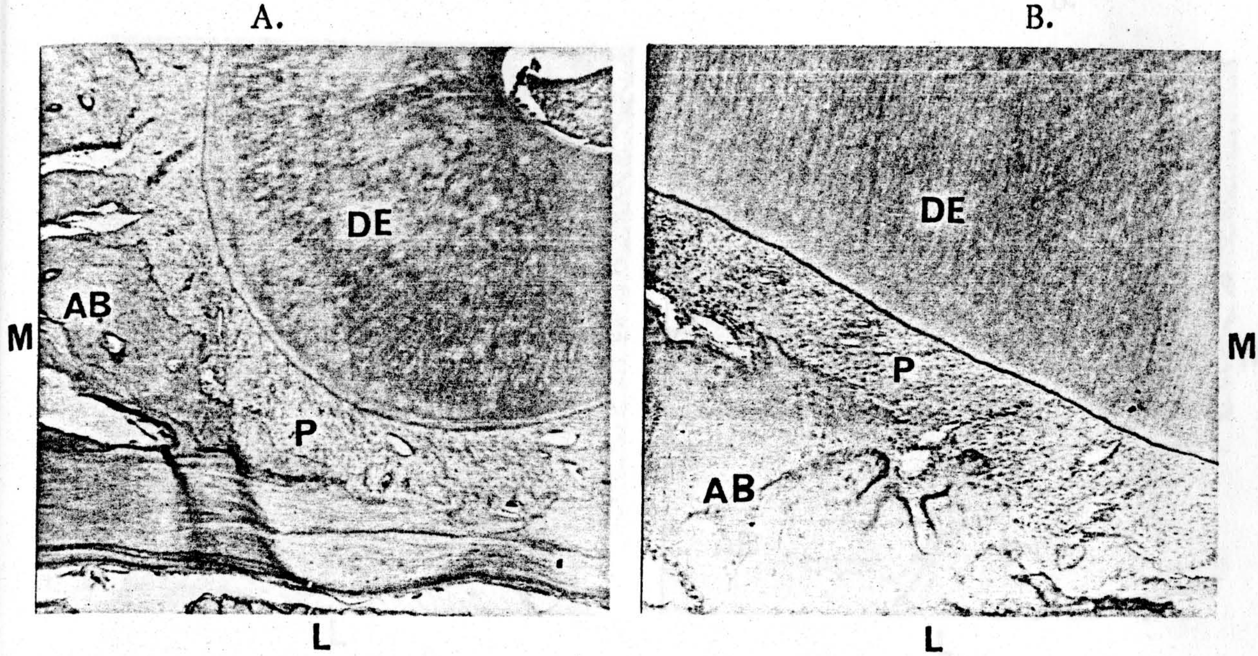
L LINGUAL

DE DENTIN

P PERIODONTAL LIGAMENT

AB ALVEOLAR BONE

FIGURE 19



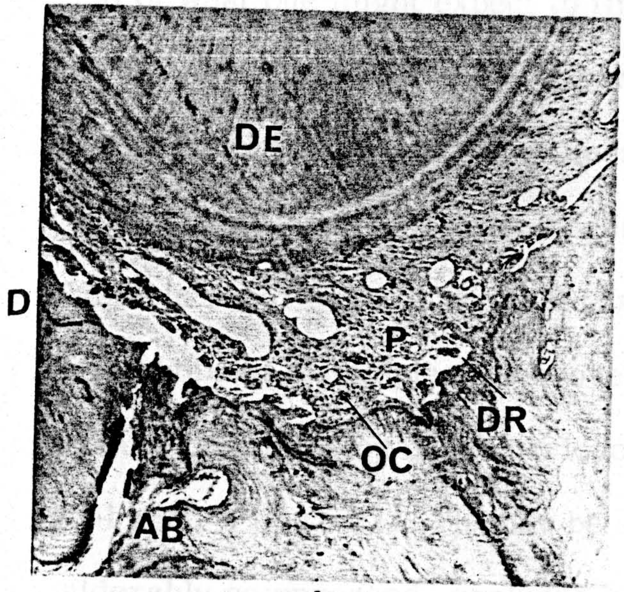
MAXILLARY LEFT
FIRST MOLAR
M III (8X)
LINGUAL ROOT

MAXILLARY RIGHT
SECOND MOLAR
M III (15X)
LINGUAL ROOT

L	LINGUAL
M	MESIAL
DE	DENTIN
P	PERIODONTAL LIGAMENT
AB	ALVEOLAR BONE

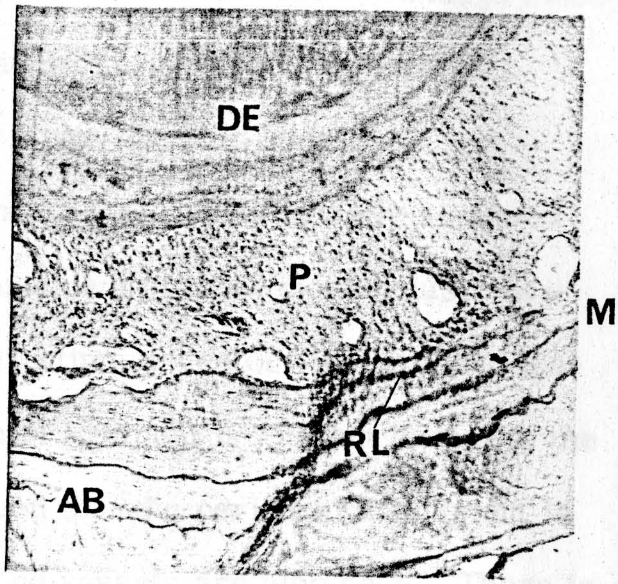
FIGURE 20

A.



MAXILLARY RIGHT
FIRST PREMOLAR
M III (15X)
MESIAL BUCCAL ROOT

B.



MAXILLARY RIGHT
FIRST PREMOLAR
M III (15X)
LINGUAL ROOT

D	DISTAL
L	LINGUAL
M	MESIAL
DE	DENTIN
P	PERIODONTAL LIGAMENT

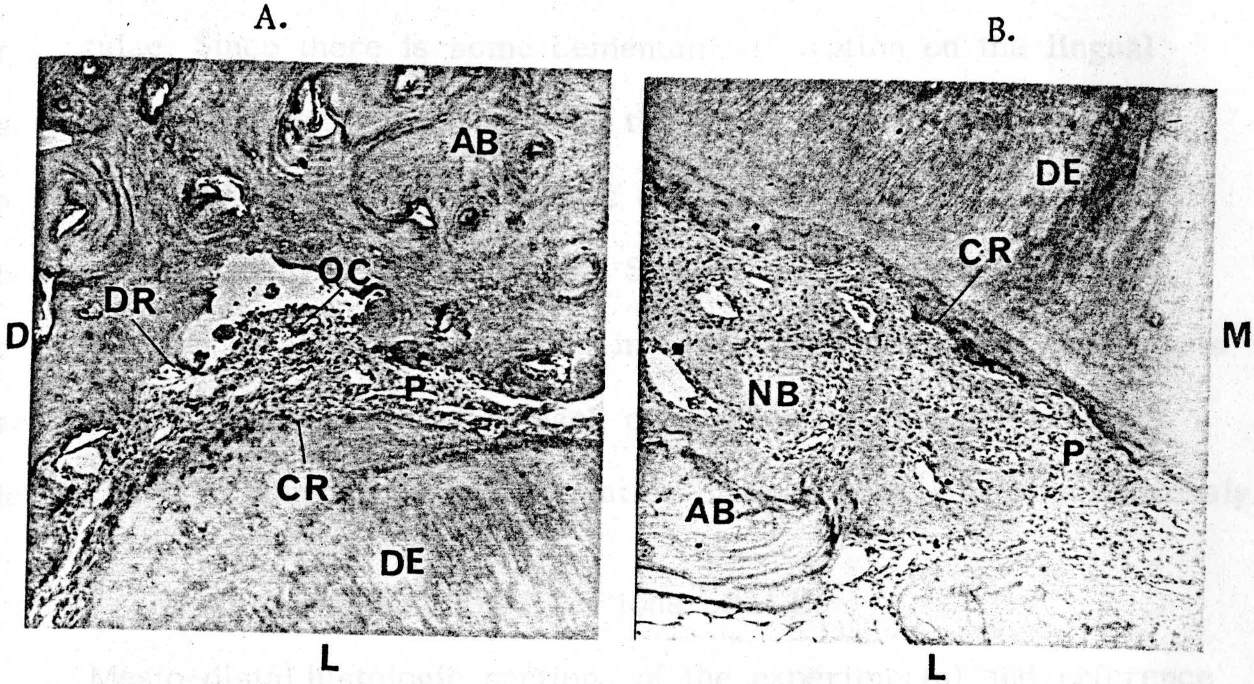
AB	ALVEOLAR BONE
RL	RESTING LINE
OC	OSTEOCLAST
OR	DIRECT BONE RESORPTION

FIGURE 21

typical of what one might expect to find on the tension side. Although osteoblasts may not be clearly seen, the evidence of new bone formation is shown by the presence of resting lines in the alveolar bone.

The maxillary right second premolar was tipped buccally as shown in the table recording the physical assessment of tooth movements. In a section obtained histologically, above the tipping center, it was found that an area of compression of the periodontal ligament is present buccal to the lingual root, Figure 22A. It may be seen that the periodontal ligament is considerably compressed, occluded blood vessels are also seen. There is considerable osteoclastic activity. This is illustrated by the scalloped margin in the alveolar bone where active resorption is taking place. Concurrent with these changes there is evidence of cementum resorption on the distal-buccal surface of this root.

It was found in the physical assessment that the maxillary right first molar tooth had been tipped lingually. In the histologic section showing the tension side of the lingual root, Figure 22B, there is an area of extensive formation of new bone. The vitality of the periodontal ligament in this area is characterized by the high degree of vascularity and numerous fibroblasts. Osteoblasts are also seen bordering the newly forming



MAXILLARY RIGHT
SECOND PREMOLAR
M III (15X)
LINGUAL ROOT

MAXILLARY RIGHT
FIRST MOLAR
M III (15X)
LINGUAL ROOT

D	DISTAL
L	LINGUAL
M	MESIAL
OC	OSTEOCLASTS
CR	CEMENTUM RESORPTION
DR	DIRECT BONE RESORPTION
AB	ALVEOLAR BONE
DE	DENTIN
P	PERIODONTAL LIGAMENT
NB	NEW BONE

FIGURE 22

trabeculae. Since there is some cementum resorption on the lingual surfaces of this tooth, it is believed the force magnitude was within a range which caused cementoclastic and osteoblastic activity to occur simultaneously. Weinman and Sicher, 1955, in Bone and Bones, call attention to a similar situation in which osteoclasts and osteoblasts are seen in close proximity to each other showing discrete areas of localization of destruction and formation of bone occurring simultaneously.

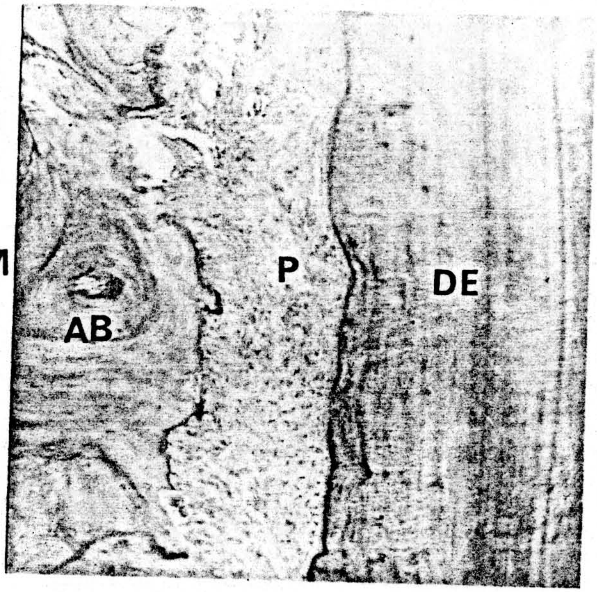
2. Mesio-distal Histologic Sections of M II:

Mesio-distal histologic sections of the experimental and reference teeth of M II were made through the long axis of the teeth. These sections were used to assess the histologic changes occurring in either extrusion or intrusion of the teeth. It was also possible to determine from these sections if any mesial or distal tipping had occurred.

The photomicorgraphs of reference teeth on the left side, Figures23A and 23B and of the teeth on the right side not engaged in the force system (Figure 24A) show no appreciable histologic changes. This is to be expected because in effect no force system was applied

A.

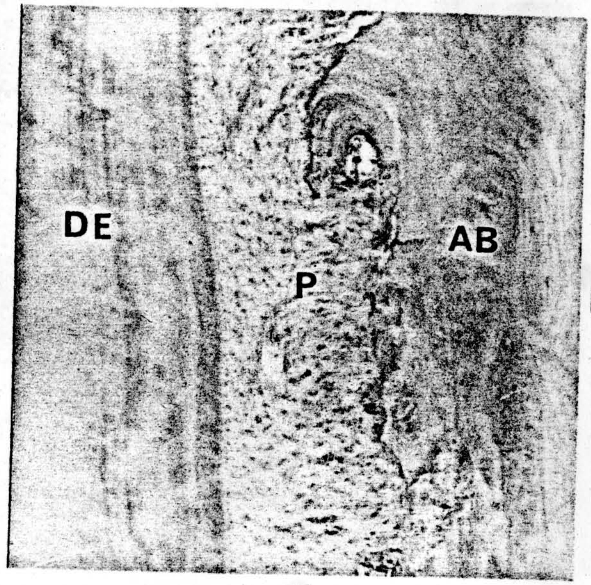
M



O

MAXILLARY LEFT
FIRST MOLAR
M II (21X)
MESIAL BUCCAL ROOT

B.



D

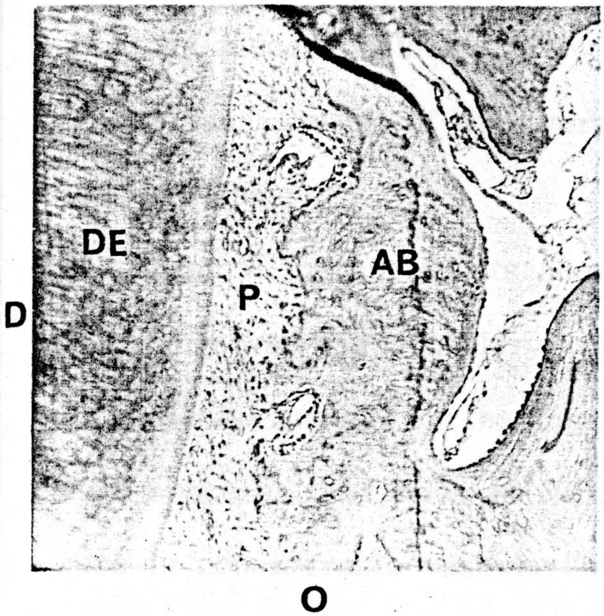
O

MAXILLARY LEFT
SECOND PREMOLAR
M II (21X)
MESIAL BUCCAL ROOT

O	OCCLUSAL
M	MESIAL
D	DISTAL
DE	DENTIN
P	PERIODONTAL LIGAMENT
AB	ALVEOLAR BONE

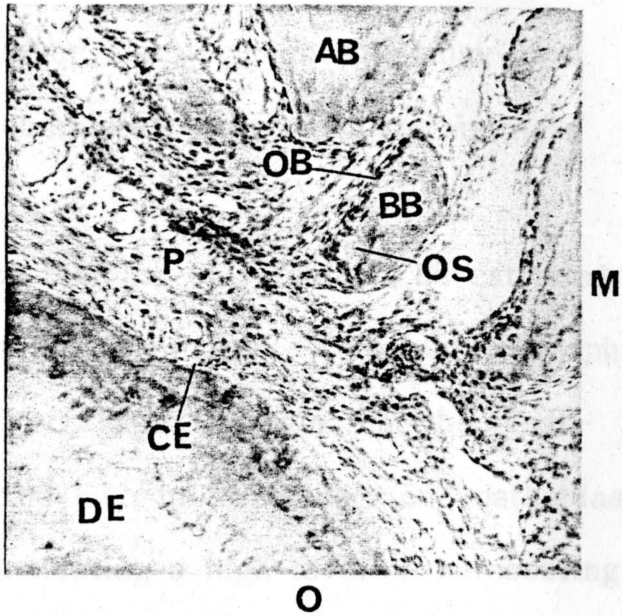
FIGURE 23

A.



MAXILLARY RIGHT
CANINE
M II (15X)

B.



MAXILLARY RIGHT
FIRST PREMOLAR
M II (21X)
LINGUAL ROOT

O	OCCLUSAL	AB	ALVEOLAR BONE
M	MESIAL	BB	BUNDLE BONE
D	DISTAL	OS	OSTEOID TISSUE
DE	DENTIN	OB	OSTEOBLASTS
P	PERIODONTAL LIGAMENT	CE	CEMENTOID TISSUE

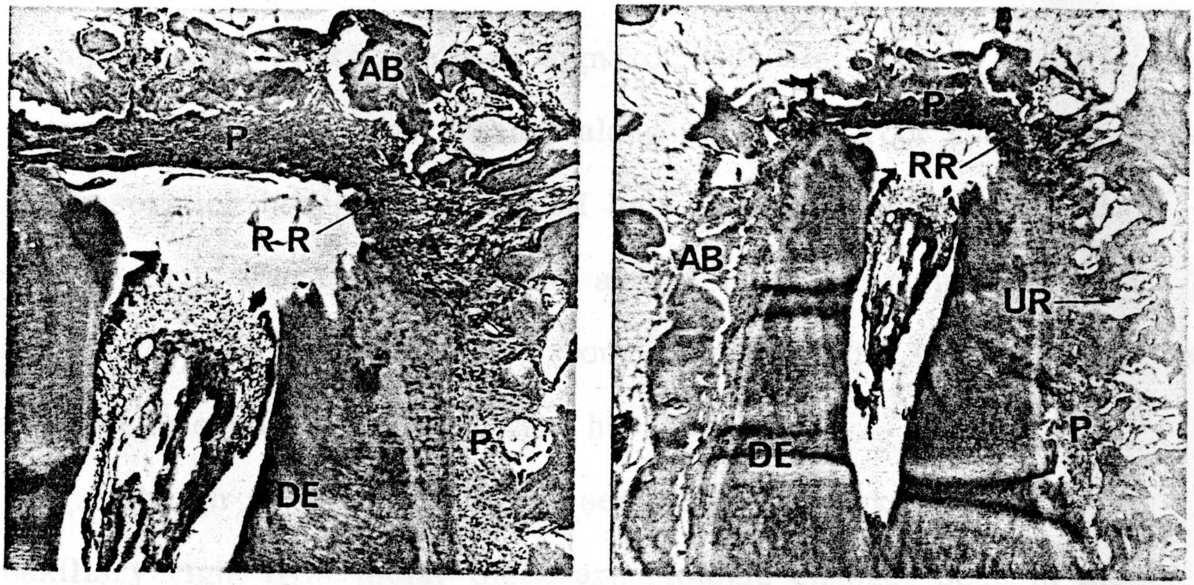
FIGURE 24

to any of these teeth. It must be recalled that the reference teeth had bands placed on them, but whatever histologic changes may have occurred as a result of this were completely gone when the animals were sacrificed.

Physical measurements showed that the only tooth to be extruded appreciably was the maxillary right first premolar. A photomicrograph of the mesial surface of the lingual root apex reveals that the periodontal space at the fundus is wide and rich in fibroblasts and osteoblasts There is considerable vascularity indicating a high level of remodeling. This is substantiated by numerous osteoblasts lining the trabeculae and being in intimate contact with the newly formed osteoid tissue. A thin layer of cementoid tissue is seen on the apex of the tooth. There appears to be no mesial-distal tipping.

Physical measurements indicate that the maxillary right second premolar was intruded. The photomicrographs, Figure 25A and 25B illustrate the extent of the intrusion by changes seen in the root surface and supporting alveolar structures. First, there is considerable compression of the entire periodontal ligament and an occlusion of the vascular structures in this area. Second, the periodontal ligament is

A. B.



D M

O O

MAXILLARY RIGHT
SECOND PREMOLAR
M II (15X)
LINGUAL ROOT

MAXILLARY RIGHT
SECOND PREMOLAR
M II (5X)
LINGUAL ROOT

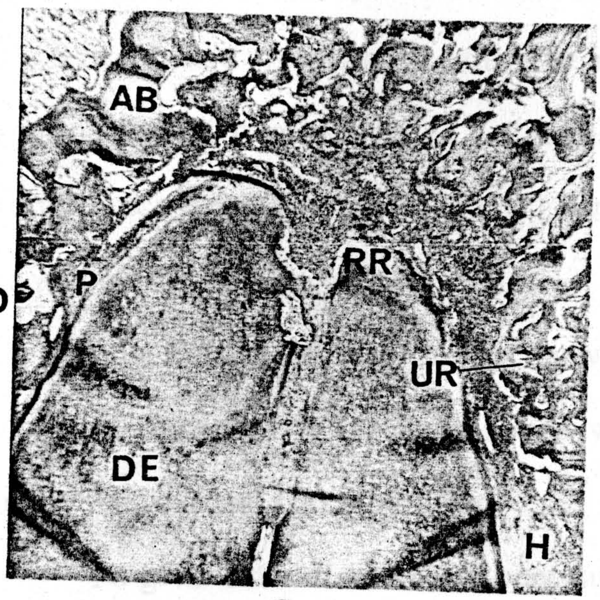
O	OCCLUSAL	DE	DENTIN
D	DISTAL	RR	ROOT RESORPTION
M	MESIAL	UR	UNDERMINING RESORPTION
P	PERIODONTAL LIGAMENT	AB	ALVEOLAR BONE

FIGURE 25

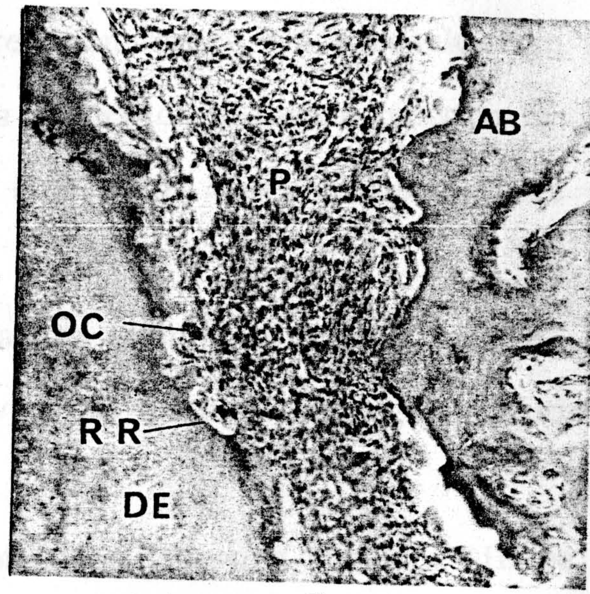
compressed at the apex so that normal structures are no longer distinguishable. There are also signs of necrosis. Third, there is extensive root resorption present along the entire root surface area. The resorption has penetrated well into the dentin at the apex of the root. Fourth, there are numerous areas of undermining resorption seen in the surrounding alveolar bone. Mesial-distal tipping cannot be seen because so much destruction has occurred.

Although no physical change seems to have taken place in the maxillary right first molar there are biologic changes seen in the histologic sections, Figures 26A and 26B which need to be discussed. It was found that the periodontal ligament on the mesial and distal sides of the lingual root was compressed and an area of hyalinization had developed on the mesial of the apical one-third of this root. Undermining resorption had taken place along the entire root surface area. On the mesial apical surface of the tooth, root resorption has taken place and has penetrated into the dentin in some areas. It may be seen in Figure 26B in a higher magnification (36X) that the cementoclasts are in close approximation to the dentin. Histologically, it appears that this tooth has experienced a "jiggling" type of movement.

A.



B.



MAXILLARY RIGHT
FIRST MOLAR
M II (5X)
LINGUAL ROOT

MAXILLARY RIGHT
FIRST MOLAR
M II (36X)
LINGUAL ROOT

O	OCCLUSAL
M	MESIAL
D	DISTAL
P	PERIODONTAL LIGAMENT
DE	DENTIN

AB	ALVEOLAR BONE
OC	OSTEOCLAST
RR	ROOT RESORPTION
UR	UNDERMINING RESORPTION
H	HYALINIZATION

FIGURE 26

to contemplate a simple force when we consider applying it to teeth. We are always confronted with the reaction forces which result from the application of a given force. Forces and reacting forces function in accordance with Newton's Third Law (1687), for every action there is an opposite and equal reaction.

One aspect of this research was an attempt at correlating the physical changes of teeth in space with the histologic changes resulting from the unique force system.

To give this discussion continuity, the following subjects will be discussed in the order mentioned: (1) force systems, (2) selecting force magnitudes, (3) the physical measurements of tooth movements, and (4) histologic findings. Before the physical or histologic findings are meaningful it is necessary to define certain terms. As previously stated in the "Introduction", a force is defined as the action of one body upon another. In orthodontics, forces do not function independently, but act as a complex system of forces on a tooth or teeth. Characteristics of a force are peak magnitude, point of application, line of action, direction, and duration. Since the point of application of a force is restricted to the bracket on the tooth, tipping movements are anticipated. A moment of force is the product of that force and the perpendicular distance from a fixed point, the moment center, to the action line of the force. A couple, which may aid or counteract a moment of force, is a system of two forces acting upon a given body. These forces are equal, opposite, parallel, and coplanar, but not collinear. They do not have the same action line or the same point of application.

In this study, the force system was applied to the brackets parallel with the long axis of the teeth. Since an intrusive force was applied to the maxillary second premolar, reciprocal extrusive forces were applied to the adjacent maxillary first premolar and first molar teeth. Since the point of application of the working force was on the bracket of the maxillary second premolar a tipping moment was applied to this tooth. This moment of force had a tendency to tip the tooth in a buccal direction about a point in the middle one-third of the root. The reciprocal moment of force directed to the maxillary right first premolar and first molar tended to tip these teeth in the lingual direction. Countercouples were created to minimize the effect of these tipping moments by securing the vertical legs of the appliance into the vertical slots of the brackets. The Jarabak mandibular incisor bracket is uniquely designed to function most efficiently in such a force system.

Tipping and translation of teeth may be accomplished within the limits of optimal tooth movement if the forces from orthodontic appliances can be of a magnitude and direction which will slightly tense the periodontal ligament. This must be done within the physical limitations of the collagenous fibers on the tension side. Compression on the pressure side must not interfere with nutritive functions of the periodontal ligament. Jarabak and Fizzell, 1963, have shown, using radiographic material, that appliances which possess properties of high deflection and low force magnitude approach these objectives.

A balanced horizontal loop appliance was selected to meet both the mechanical and the physiologic objectives. Since the peak intrusive force that may be applied to the second premolar of a monkey was calculated to be 120 grams, it was necessary to design the appliance that would develop this force and have a working range of about 2 mm. It was found that .014 inch round yellow Elgiloy wire when used in the appliance produced a spring rate of 70 gm. /mm. This implies a peak force of 140 grams at 2 mm. deflection. While this slightly exceeds the calculated value, it is the best compromise. The reciprocal forces applied to the maxillary right molar and first premolar were only about half of values for the maxillary second premolar.

Storey and Smith, (1952) proposed a method of calculating the direction teeth moved and force magnitude. Their method though good is not actually precise. It was decided to employ an instrument which gave greater precision. This precision was necessary if correlations were to be made with findings seen histologically.

One of the objectives of this experiment was the determination of the precision of the tooth movement measuring instrument. In the experiment by Storey and Smith, 1952, experimental tooth movement was measured by means of a needle point caliper. They stated that measurements made in this manner were accurate to the nearest 1/100th of an inch, but did not discuss the quality of precision of their instrument and method. Precision implies the closeness of agreement of repeated measurements of a quantity. In contrast, accuracy denotes the degree of conformance to some recognized standard value of the quantity. The determination of the degree of precision of the measuring instrument in this experiment was derived from the mean square due to duplicate measurements made on five sample transfer units. From 120 degrees of freedom, the 99% confidence limits were calculated to be plus or minus .028 mm. This degree of precision of the measuring instrument is more than adequate for the limitations of measurement required by this experiment.

It is also interesting to note that in the same study by Storey and Smith, 1952, tooth movement measurements were made directly on the experimental subject. Since rugged precise measuring instruments cannot ordinarily be used in the oral cavity, it seemed advisable to use a tested dental technique of making casts rather to measure the teeth <u>in situ</u>. Although the use of casts of the experimental teeth should introduce additional eror to this method of measuring tooth movement, it was hoped that the amount of error due to the duplication process would not invalidate the findings. The design of the experiment provided an estimate of the experimental error.

The registration instrument used to orient the casts established a stable reference base from which successive measurements could be made, and the advantages derived from this method minimized the error involved in the overall process. It may be recalled that the engineering principles of orienting any three dimensional object in space required the application of three geometric criteria, a fixed point, a line, and a plane. The fixed point orients the object in one point of reference, however, rotation of the object in the vertical and horizontal directions is still possible. By adding the fixed line of reference to the instrument, motion of the object is limited to rotation about a line. The application of a fixed plane of reference completes the orientation of the object, thereby producing an instrument in which consecutive three-dimensional objects may be accurately and repeatedly orientated.

The physical assessment of the tooth movement resulting from a vertical reciprocal force system is concerned primarily with measuring tooth movement in the occlusal-gingival direction. Since a tipping moment was anticipated to produce buccal or lingual tipping, measurements in the buccal-lingual direction needed also to be made.

It must be realized that these movements do not act independently, but do produce a combined translatory and tipping movement. It is possible under these circumstances for the results of tooth movement in one direction to mask the results of movement in the other. If we visualize a tooth being tipped buccally about a tipping center (Figure 18A), it may be seen that the tip of the buccal cusp moves gingivally in relation to the occlusal plane. It appears that this tooth is experiencing intrusion when measurements are made in the occlusal-gingival direction.

The maxillary right second premolars of both experimental animals were found to have been intruded and tipped buccally. The intrusive forces caused axial changes of these teeth. It was found, in the histologic findings that intrusion of these teeth actually did occur, and was not appreciably caused by the axial changes.

In the assessment of the maxillary right first premolars, it was found that the first premolar of M II was extruded and tipped lingually. The first premolar of M III was also tipped lingually, but did not produce significant changes in the occlusal-gingival dimension. It is conceivable that the premolar of M III may have extruded, but this measurement is masked by the lingual tipping.

The maxillary right first premolar of M III tipped lingually. This tooth may have experienced some extrusion. Since the histologic sections for this animal were made in the transverse plane, substantiation of this fact is not possible.

On the twelfth day of the experiment the maxillary right first molar band on M II was broken. A new band was fabricated and cemented the same day. It may be seen from the physical assessment of this tooth that no appreciable tooth movement in either plane had taken place during the time the band was broken. It is believed that the placement of the new band did not coincide with the original band position, this casts doubt on the significance of the physical findings for this tooth.

Histologic sections were made to examine the biologic response to the force system. Transverse sections of M III, were made to assess, buccal-lingual or mesial-distal tipping of the teeth. Extrusion, intrusion, or mesial-distal tipping were able to be observed in the mesial-distal sections of M II.

The histologic findings for the maxillary right first premolar and first molar of M III indicated that these teeth had indeed tipped lingually, as suggested by the physical measurements. The periodontal ligament of each tooth was compressed on the buccal side of each apex and areas of tension were seen on the lingual sides of each apex. On the side of compression of the teeth that were tipped only direct bone resorption was observed.

Reitan, 1951, in experiments involving orthodontic tooth movement observed that both direct and undermining resorption had occurred as a result of a tipping force. He also stated that in the areas of compression, hyalinization of the periodontal ligament was found. Since the normal structures in the periodontal ligament were destroyed in his experiment, it must be assumed that the magnitude of force was excessive. Excessive forces destroy, at least temporarily the cellular structures of the periodontal ligament.

When light continuous tipping forces were applied to the teeth in this experiment, the cellular structures of the periodontal ligament were not destroyed. These observations support the concept that light continuous forces when applied to teeth can move these teeth without permanently destroying the function and cellular structures at the alveoloperiodontal environment.

The histologic findings for the maxillary second premolar of M III indicated that this tooth had tipped buccally. Although some cementum resorption was found, it was believed that the intrusive force was responsible for this. The observation that the depressive forces used in this experiment tended to destroy root structure is born out by these findings.

The new bone that had formed on the inner surface of the alveolus in response to the extrusive force applied to the maxillary right first premolar of M II was expected because all of the periodontal fibers were tensed. The periodontal organ was rich in fibroblasts and osteoblasts suggesting normal vitality. The histologic findings support the fact that the force applied to this tooth was optimal. An optimal force, as defined by Jarabak and Fizzell, 1963, is one that will catalyze cellular activity to cause an accelerated breakdown of bone on the pressure side with a simultaneous build up on the tension side. Since only tension of the periodontal ligament results from an extrusive force, a build up of bone was expected on the inner surface of the alveolus.

Although no appreciable physical movement was found for the maxillary right first molar of M II, dramatic biologic changes were observed. It must be recalled that on the twelfth day of the experiment, a new band had to be made for this tooth. Originally an extrusive force was placed upon this tooth. In contrast, the histologic evidence indicates the biologic results of "tooth jiggling". This evidence suggests band or bracket positioning did not duplicate the original band placement. The histologic evidence also indicates that an excessive magnitude of force was created by this situation. This fact may be substantiated by the extensive undermining resorption and zone of hyalinization.

Significant intrusion of the maxillary right second premolar of M II was found from the physical findings. From the histologic evidence it may be assumed that the intrusion of this tooth caused resorption seen on the root surface. It is apparent that the magnitude and direction in which the force was applied produced a movement that caused irreparable damage to the dentin. It would be interesting in future studies to ascertain whether such tooth movement could be achieved without the extensive root resorption.

CHAPTER VI

SUMMARY AND CONCLUSIONS

A. Summary:

The purpose of this study was to develop and test a new measuring technique by assessing the biophysical effects of a vertical force system designed to intrude the maxillary right second premolar of a Macaca rhesus monkey. Since this force system was reciprocal, an extrusive force was placed on the maxillary right first premolar and first molar.

The appliances designed to deliver this force system consisted of two horizontal helical loop springs of one and one half turns in each helix. It was fabricated from .014 inch yellow Elgiloy round wire and heat treated for ten minutes at 900° F. Load-deflection curves were made for each tested appliance. Jarabak mandibular incisor brackets were used to secure the appliance to the teeth. The vertical end slots of these brackets were engaged by the vertical legs of the appliance to minimize buccal-lingual tipping.

A metal bite block was secured to the maxillary anterior teeth to eliminate the influence of the opposing mandibular incline planes.

A new method of measuring tooth movement was devised to assess the physical changes resulting from the application of the force system. This method utilized casts of the experimental teeth. These casts were then oriented by a specially designed instrument and secured to carrier devices. The carrier device served to stabilize the cast during the measurement of the teeth. A new measurement instrument was designed and consisted of an Ames dial indicator and special measuring stylii. These stylii engaged the buccal cusp of the tooth to be measured and were designed to provide measurements in either the buccal-lingual or occlusal-gingival dimension. The precision of this measuring instrument was calculated from the mean square of duplicate measurements. From 120 degrees of freedom, the 99% confidence limits were determined to be plus or minus .028 mm. Both maxillary right and left experimental teeth were measured, and the data were recorded. The teeth on the left side served as a reference and were only banded.

It was found from the physical assessment that a combination tipping and translatory type of movement had occurred. The buccal-lingual movement was attributed to three factors. Since the teeth were out of occlusion, there was no influence from opposing incline planes. The second factor resulted from a tipping moment produced by the application of the force to the bracket. A close tolerance between the vertical end slot of the brackets and vertical leg of the appliance was not realized and resulted in a third factor. Significant extrusion and intrusion of teeth were found.

Histologically, it was found that those teeth that were tipped showed areas of compression and tension of the periodontal ligament. On the side of compression only direct bone resorption was seen. The periodontal ligament of the extruded maxillary first premolar of M II, was wide and rich in fibroblasts and osteoblasts. In contrast, the histologic evidence of the tooth that was intruded indicated that the force was destructive to the root of the tooth, the cellular structures, and collagenous elements of the periodontal environment. Although the force applied to this tooth was considered to be of a low magnitude, further studies of this type of movement should be conducted to determine if this movement can be accomplished without permanent damage to the root.

B. Conclusions:

1. The reliability and precision of the new method of measuring tooth movement have been validated and quantitated by a low

experimental error found in this experiment.

2. Intrusion and buccal tipping occurred when an intrusive force was applied to the bracket of the second premolar tooth. Since this force had reciprocal components histologic changes indicate the anchor teeth extruded and tipped lingually.

3. Low magnitude extrusive forces derived from a helical loop orthodontic appliance produced histologic changes which did not damage the root or surrounding structures in any appreciable amount.

4. Direct bone resorption was found on the compression side of those teeth that were tipped.

5. Localized cementum resorption was found on the compression sides of those teeth that were tipped, but did not penetrate to the dentin.

6. Bone apposition occurred on the tension side of those teeth that were tipped and on the inner surface of the alveolus of the tooth that was extruded.

7. Intrusive forces derived from the helical loop appliance produced histologically damaging changes on the alveolar bone, cementum, and dentin.

8. Root resorption on the intruded teeth penetrated into the

dentin with the most extensive damage occurring at the apexes of the teeth.

9. Extensive undermining resorption was found in the alveolar bone surrounding the intruded teeth.

BIBLIOGRAPHY

Aisenberg, M. The tissues and changes involved in orthodontic tooth movements. American Journal of Orthodontics, 34:854-856, 1948.

Alexander, R. H. Rationale and application of the Jarabak light wire technique in orthodontics. New York Journal of Dentistry, 33: 149, 1963.

Anderson, D.J. Tooth movement in experimental malocclusion. Archives of Oral Biology, 7:7-15, 1962.

Arkin, H. and Colton, R. Tables for Statisticians. Barnes and Noble, Inc., New York, 1950.

Bien, S. M. Analysis of the components of force used to move teeth. European Orthodontic Society, 33:70-78, 1957.

Breitner, C. Bone changes resulting from experimental orthodontic treatment. American Journal of Orthodontics and Oral Surgery, 26:521-547, 1940.

Burstone, C.J., Baldwin, J. J., and Lawless, D. T. Application of continuous forces to orthodontics. Angle Orthodontist, 31:1-14, 1961.

Butterfield, H. The Origins of Modern Science, MacMillan Company, New York, 1957.

Cohen, B. J. The early history of animal experimentation and animal care. Animal Care Panal, 9:39-45, 1959.

Cushing, C. R. Observations of pressure phenomena on bone in vivo. American Journal of Orthodontics, 47:150-151, 1961.

Diamond, H. D. Practical application of light wire technique. American Journal of Orthodontics, 48:650-669, 1962.

Fisher, R. A. The Design of Experiments. Oliver and Boyd, London, England, 1960.

Gillings, Barrie, et al. Apparatus for cutting thin undecalcified section of teeth. Journal of Dental Research, 38:702, 1959.

Haack, D. C. The science of mechanics and its importance to analysis and research in the field of orthodontics. American Journal of Orthodontics, 49:330-344, 1963.

Hartman, C. and Straus, W. The Anatomy of the Rhesus Monkey. The Williams and Wilkins Company, Baltimore, 1933.

Herzberg, B. L. Bone changes incident to orthodontic tooth movement. The Journal of the American Dental Association, 19:1777-1788, 1932.

Hemley, S. The clinical significance of tissue changes incidental to tooth movement. American Journal of Orthodontics, 41:1-26, 1955.

Hopewell-Smith, A. A process of osteolysis and odontolysis or so-called "Absorption" of calcified tissue. A new and original investigation. Dental Cosmos, 72: 323-345, 1930.

Huettner, R. J. Experimental histologic study of the effects of orthodontic movement on the gingiva and periodontal membrance in the Macaca rhesus monkey. American Journal of Orthodontics, 46:929, Abstract.

Huettner, R. J. and Whitman, C. L. Tissue changes occurring in the Macaque rhesus monkey during orthodontic movement. American Journal of Orthodontics, 44:328-345, 1958.

Irish, R. E. Conscious constructive applicationof pressure. International Journal of Orthodontics, Oral Surgery, and Radiology, 13:528-539, 1927.

James, W. W. The Jaws and Teeth of Primates. Pitman Medical Publishing Co., Ltd., London, 1960.

Jarabak, J. R. and Fizzell, J. Technique and Treatment with the Light Wire Appliances. The C. V. Mosby Co., St. Louis, 1963.

Johns, E. E. Study of the forces inherent in orthodontic appliances and the selection of forces for tooth movement. Journal of the Canadian Dental Association, 19:423-436, 1953.

Lindquist, J. T. Indirect band technic. Angle Orthodontist, 29:114-122, 1959.

Myers, H. I. and Wyatt, W. P. Some histopatholic changes in the hamster as the result of a continuously acting orthodontic appliance. Journal of Dental Research, 40:846-856, 1961.

O'Donoghue, D.J. Comparative Responses of Paradental Tissues to Continuous and Intermittent Application of Forces. Unpublished Masters Thesis. University of Illinois, 1963.

Oppenheim, A. Tissue changes, particularly to the bone, incident to tooth movement. American Orthodontist 3:57-67, 113-132, 1911.

_____ Biologic orthodontic therapy and reality. International Journal of Orthodontics and Dentistry for Children, 19:1201-1213, 20:18-24. 137-144, 250-258, 331-336, 461-466, 639-644, 759-769, 964-968, 1072-1076, 1178-1181, 1933 and 1934.

_____ Biologic orthodontic therapy and reality. Angle Orthodontist, 6:5-38, 69-116, 154, 183, 1936.

_____ Human tissues response to orthodontic intervention of short and long duration. American Journal of Orthodontics and Oral Surgery, 28:299, 1942.

Orban, B. Biologic problems in orthodontia. The Journal of the American Dental Association, 23:1849-1870, 1936.

Parfitt, G. J. Measurement of intrusion of the upper incisor teeth with forces below 1,000 grams. Journal of Dental Research, 38:661, 1959.

Peyton, F. A. and Moore, G. R. Measuring forces of displacement in orthodontic spring appliances. International Journal of Orthodontics and Dentistry for Children, 19:683-686, 1933.

Reitan, K. The initial tissue reaction incident to orthodontic tooth movement as related to the influence of function. Acta Odonto. Scandinav. (supp. 66), 1951.

_____ Tissue changes following experimental tooth movement as related to the time factor. Dental Record, 73:559, 1953.

_____ Tissue reaction as related to the age factor. Dental Record, 74: 271, 1954.

_____ Some factors determining the evaluation of forces in orthodontics. American Journal of Orthodontics, 43:32-45, 1957.

_____ Retraction of upper canines after removal of first premolars. Relation to tissue reaction. Europ. Ortho. Soc. Tr., 34:172-176, 197-210, 1958.

_____ Tissue behavior during orthodontic tooth movement. American Journal of Orthodontics, 46:881-889, 1960.

_____ Effects of force magnitude and direction of tooth movement on alveolar. Angle Orthodontist, 34:244-255, 1964.

Rich S. and Cohn, B. J. A restraint unit for large monkeys. Animal Care Panal, 12:113-116, 1962.

Richmond, J. E. An appliance analysis with measured pressure. International Journal of Orthodontics and Dentistry for Children, 29:898-903, 1933.

Sanderson, I. T. The Monkey Kingdom. Chilton Co., New York, 1963.

Sandstedt, C. Einige Beitrage zur Theorie der Zahn Regulierung, Nordisk. Tand. Tidsk. no. 4, 1904, no. 1, 1905.

Schwarz, A. M. Tissue changes incidental to orthodontic tooth movement. International Journal of Orthodontics and Oral Surgery, 18:331-351, 1932.

Sicher, H. and Weinmann, J. Bone growth and physiologic tooth movement. International Journal of Orthodontics, 28:331-351, 1944.

Storey, E. and Smith, R. The importance of force in orthodontics; the design of cuspid retraction springs. Australian Journal of Dentistry, 56:291-304, 1952.

_____ Force in orthodontics and its relation to tooth movement. Australian Journal of Dentistry, 56:11-18, 1952.

_____ Bone changes associated with tooth movement. Australian Journal of Dentistry, 57:57, 1953.

Stuteville, O. H. Injuries to the teeth and supporting structures caused by various orthodontic appliances. American Dental Association Journal, 24:1494-1507, 1937.

Weinmann, J. P. and Sicher, H. Bone and Bones, The C. V. Mosby Co., St. Louis, 1955.

Wescott, R. and Rabstein, M. Important factors contributing to reduction in mortality in a monkey colony. Laboratory Animal Care, 13:474-484, 1963.

APPROVAL SHEET

The thesis submitted by Dr. Dale K. Kostiwa has been read and approved by members of the Departments of Anatomy and Oral Biology.

The final copies have been examined by the director of the thesis and the signature which appears below verifies the fact that any necessary changes have been incorporated, and that the thesis is now given final approval with reference to content, form, and mechanical accuracy.

The thesis is therefore accepted in partial fulfillment of the requirements for the Degree of Master of Science.

May 18-65
DATE

Joseph R. Jaszlak
Signature of Advisor