ROTATIONAL AXES IN HUMAN INCISOR TEETH

by

Stephen I. Miller, D.D.S.

A Thesis

Presented to the Department of Orthodontics
and the Graduate Education Committee of the
University of Oregon Dental School
in partial fulfillment
of the requirements for the degree of
Master of Science
August, 1966

APPROVED

[redacted], M.S.
Chairman, Thesis Committee

[redacted]
Chairman, Graduate Education Committee

ACKNOWLEDGEMENTS

The author wishes to thank Dr. Ernest H. Hixon and Dr. David B. Mahler for their continuous constructive advice and valuable criticisms from the inception of this work through its completion, and Dr. Kuo H. Lu, Dr. Fred M. Sorenson, and Dr. Walter B. Hall for numerous stimulating and informative discussions.

The author also wishes to thank Jan Van Eysden, Lewis VanWinkle, and Kay Gleim for their very capable technical assistance which greatly aided in the completion of this work.

TABLE OF CONTENTS

Page

INTRODUCTION 6

Statement of the Problem 6

REVIEW OF THE LITERATURE 8

Axis of Rotation 8

Long-term tooth movement 8
Instantaneous movement 12

Rate of Tooth Movement 16

METHODS AND MATERIALS 20

Sample 20

Instantaneous Tooth Movement 20

Instrumentation 20
Experimental procedures 22
Calibration and error estimation 24
Axis location 26
Determination of incisor tooth lengths 26

Long-Term Tooth Movements 27

Appliance design 29
Force determination 29
Axis location 29
Incisal edge displacement 32

RESULTS 33

Instantaneous Tooth Movement 33

Influence of tipping force magnitude on rotational axis . . 33
Effect of site of force application on rotational axis . . . 36
Influence of force magnitude and time on rotational axis . . 37

Long-Term Tooth Movement 37

Influence of force magnitude and time on rotational axis . . 37
Effect of force magnitude on rate of incisal edge displacement 40

Comparison of Axes Produced During Instantaneous and Long-Term Tooth Movement 42

Page

DISCUSSION 43

Axis of Rotation 43

Rate of Tooth Movement 50

SUMMARY AND CONCLUSIONS 52

BIBLIOGRAPHY 54

APPENDICIES 57

A. Derivation of Equation Used in the Determination of the Rotational Axis 58

B. Maxillary Central Incisor Dimensions 61

C. Rotational Axes and Force Magnitude 62

D. Rotational Axes and Time 67

E. Weekly Locations of the Rotational Axes 69

F. Weekly Tooth Displacement 70

LIST OF FIGURES

Figure | Page

1. Schematic Representation of the Displacement Measuring Apparatus 19
2. Occlusal Splint with Displacement Transducers and Force-Guiding Rod 21
3. Dynamometer 21
4. Geometric Determination of the Rotational Axis Position . . 25
5. Graphic Recordings of the Incisal and Gingival Displacement, Force and Time 25
6. Orthodontic Appliance Employed to Deliver Tipping Forces . . 28
7. Tooth Markers 28
8. Determination of the Rotational Axis Position 31
9. The Effect of Tipping Force Magnitude on the Location of the Rotational Axis 35
10. The Effect of Force and Time on Tooth Displacement 39
11. The Mean and Range of the Rotational Axis Positions Produced During Instantaneous Tooth Movement 41
12. The Mean and Range of the Rotational Axis Positions Produced During Long-Term Tooth Movement 41
13. Mean Positions of the Rotational Axis Arising During Instantaneous Tooth Movement 45
14. Mean Positions of the Rotational Axis Arising During Long-Term Tooth Movement 49

LIST OF TABLES

Table | Page

1. Mean Axis Position of Each Tooth at Different Magnitudes of Force, Applied to the Crown Midway Inciso-Gingivally 33
2. Regression Analysis Relating Axis Position and Magnitude of Force 34
3. Analysis of Variance Used to Test the Effects of Time and Magnitude of Force Application on the Position of the Rotational Axis 37
4. Mean Tipping Force Applied to Each Tooth Over a Twenty-Eight Day Period 38
5. Analysis of Variance Used to Test the Effects of Time and Magnitude of Force Application on the Position of the Rotational Axis 38
6. Mean Rotational Axis Position Observed During Twenty-Eight Day Experimental Period 40
7. Mean Rotational Axis Position Observed During Instantaneous and Long-Term Tooth Movements 42

INTRODUCTION

The fact that a tooth moves when force is delivered to its crown has been known for centuries (1). The initial motion reflects changes of a complex physical nature taking place within the periodontal membrane. Hydraulic, compressive and tensile elements are present simultaneously. When this force is maintained for an extended period of time these physical alterations result in a biologic response. The mechanism of this transformation is unknown. The result is bone resorption and apposition; thus, the tooth is able to move through bone over great distances.

Displacement of teeth can be classified as being either bodily or tipping in nature. With the former, the tooth maintains its original angular relation to the adjacent teeth throughout its movement. Tipping, on the other hand, involves rotation about a horizontal axis located, most probably, within the root.

Tipping movement constitutes a major portion of orthodontic therapy; therefore, a knowledge of the rotational axis and the factors which affect its location is required if controlled tooth movement is to be achieved. Intensity and site of force application have been mentioned as possible influencing factors; however, a review of the literature has revealed that the information available to date in this area has been highly controversial.

The purpose of this investigation was to study the location of rotational axes of human incisors during instantaneous and long-term tooth movements. The variables tested were force magnitude, site of force application and duration of force application. Incisor teeth were selected since they present the least complicated model in which the rotational axis can be examined.

REVIEW OF THE LITERATURE

Axis of Rotation

Long-term tooth movement.

The earliest and most frequent methods employed in the study of tooth movement have been histological in nature. It is from these studies that the concept of a rotational axis arose.

The first histological investigation dealing with an orthodontic problem was based on a series of experiments carried out by Sandstedt (3) in 1901. He placed bands on the maxillary canines of a dog. A labial arch was passed through horizontal tubes, and by tightening screws each day the first maxillary incisors were moved lingually about three millimeters in three weeks. The dog was then sacrificed and histologic sections of the teeth and supporting structures were made. These revealed osteoclasts, bleeding and even thrombosis of the capillaries at the pressure side of the root, with fibroblasts and certain blue stripes which he believed were compressed capillaries and nerve tissue. Several compressed areas were observed, around which undermining resorption took place. Movement of the teeth was interpreted as being rotational in nature with the axis slightly apical to the midroot.

In spite of the fact that Oppenheim had studied Sandstedt's report, the observations from his own tooth movement studies led him to somewhat different conclusions (4). Employing an Angle arch and ligatures, he tipped two deciduous incisors in a baboon. He concluded that teeth act as one-arm levers when tipped, with the root apex acting as the fulcrum point.

Johnson, Appleton and Rittershofer (5) experimented on a young monkey whose teeth were not fully developed. As a result of the tooth movement, which lasted 40 days, they observed deformation of the apical end of roots. This led them to the conclusion that teeth act as two-arm levers, with a rotational axis at the midroot when tipped.

Bodecker, (6) commenting on the contradiction between Oppenheim and Johnson et. al., suggested that the locus of the rotational axis is based on the degree of pressure existing along the root.

From his experimental work with dogs, Schwarz (7) made a quantitative evaluation of orthodontic forces which he divided into four groups. He was of the opinion that light continuous tipping forces produced less tissue damage than any other type of force application. Schwarz located the rotational axis in the apical third of the root. However, he felt that strong forces would cause the axis to move coronally (8).

This concept of an axis position dependent on force was supported by Orban (9). From his experimental work with dogs, he concluded that the hyalinized areas near the alveolar margins produced by strong force applications acted as leverage points, shifting the rotational axis from the apical area toward the midroot.

The first histologic study of human tooth movement was performed by Herzberg in 1932 (10). A premolar was tipped for seventy days with an orthodontic appliance. The tooth and its surrounding tissues were removed and prepared histologically. The findings were very similar to those of the earlier animal studies. The lack of osteoclastic activity in the apical areas led to the statement that "teeth tip about their apicies".

In 1934 Oppenheim (11) restated his earlier findings. "The tooth represents a single arm lever with the fulcrum at the apex. If gentle forces are applied there will be only a side of pressure but not an area of pressure. If the force is so strong that on the side of pressure there is contact between root and bone, then this point of contact will of necessity act as the fulcrum and the apex must deviate in the opposite direction of the crown. The reason others have found a deviation of the apex is that they worked with very strong forces."

His human histologic material revealed that even where gentle intermittent forces were employed, the apex would move in a direction opposite to the line of force whenever the force was applied for longer than eight weeks (12). He suggested that a rest period from active treatment be allowed every two months in order to avoid this "adverse" root movement.

Stuteville (13) performed a detailed study <u>in situ</u> of the tipping effect on the roots of monkeys' teeth. He dissected the alveolar process all along the roots and took motion pictures as the teeth were moved. The single-rooted teeth rotated about an axis located at the junction of the apical and middle root thirds. These findings were later corroborated in his histological studies with humans (14).

Frey (15), in a discussion of tissue changes caused by orthodontic treatment, suggested that the axis of tipping movements would be found somewhere near the junction of the middle and apical thirds of the tooth.

In an investigation of the periodontal responses to various tooth movements, Moyers and Bauer (16) found that during tipping movements the blood supply to the periodontal membrane was obstructed in two areas. One appeared as a region of compression just above the root end; the other was found diagonally across the tooth in the region where the root was pushed against the alveolar crest.

Storey (17) reported a radiographic study of cuspid retraction in humans in which he discussed bone changes associated with tooth movement. He observed that the axis of rotation resulting from tipping forces was near the root's apical third.

Reitan (18) compared adult teeth with those of young persons and noted that the adult teeth tipped less during movement. He attributed this difference to the presence of strong apical fiber bundles in adults. In a later article Reitan states that a tooth acts as a two-arm lever in tipping movements (19).

Massler (20), in a roentgenographic study of the changes in the lamina dura during tooth movement, found that these changes mirrored the type of movement, i.e. whether the tooth had been tipped or moved bodily. In those that tipped, the line of rotation appeared slightly apical to the midroot.

Huettner and Whitman (21) employed both tipping and bodily forces to retract cuspid teeth in monkeys for a twelve week period. The teeth which were moved bodily did not demonstrate any axis. Those that were tipped did so about the apex of their root. From these histologic sections they concluded that the position of the axis was determined by the type, amount and direction of force applied to the tooth. However they did not state how these factors altered the axis' location.

Kulis (22) studied the relation between force magnitude and centers of rotation in human maxillary incisors. Two groups of seven children each were selected, having spaced anteriors. Elastics were employed to tip the incisors together. The average force was 51 grams for the first group and 121 grams for the second. Location of the rotational axis was determined by superimposing periapical films taken before and after space closure. No significant difference in axis position was noted between groups.

The axis was just over one millimeter apical to the geometric center of the root.

In a histologic study performed on monkeys, Atta (23) attempted to relate force magnitude and centers of rotation. Using fixed appliances, he retracted incisor teeth over a two-month period. Different forces were applied to the two incisors of each animal. These ranged from 10 to 250 grams. Histologic pictures of the periodontal membrane revealed similar mid-root axis positions of each tooth. He concluded that the locus of the rotational axis was independent of force magnitude.

Instantaneous movement.

Another approach to the study of tooth movement has been the development of mathematical and physical models. These attempt to duplicate the tooth and its attachment apparatus in a simplified manner. This approach is, however, limited only to instantaneous motion within the alveolus.

In 1917, Fish (24) presented his views on the relation between tooth movement and the science of mechanics. He described a point located somewhere between the apex and gingival margin such that, if a force were applied through this point, there would be no tipping and no rotation of the tooth about its long axis. He stated that the locus of this point, defined as the center of resistance, was dependent on the intensity and the direction of the force applied.

Case (25), in his book, classified the action of tooth movement as levers or lever arms. He proposed that during tipping motions the apex would be displaced in a direction opposite to that of the force applied and that the rotational axis would be located at the junction of the middle and apical thirds of the tooth.

After reviewing the histologic findings of Sandstedt and Oppenheim, Schwarz (26) concluded that the tooth was suspended in its socket by a ligament having elastic properties. He felt that the mechanics of his elastic cord theory could easily be reproduced on a two dimensional model. Constructing a simple wood model shaped like an incisor tooth and anchored to a fixed piece of wood by elastic strands, he found in a series of experimental tipping force applications that the axis of rotation was always below the mid-root. On moving the site of the applied force in a gingival direction the developed axis shifted toward the apex.

Three years later, Synge (27) published his theory on the tightness of teeth, founded on a complex mathematical analysis. Among the properties he assigned the periodontal membrane was that of incompressibility. Formulae were derived to describe the amount of movement and pressures in various parts of the membrane when forces of different intensity and angle were applied. The locus of the rotational axis was independent of the force's intensity but dependent on its point of application. For a conical model of an upper incisor the axis was located at a distance from the apex approximately equal to three-quarters of the root length.

Gabel (28) expounded on Synge's theory and concurred with the findings relating axis position and force.

Hay (29) formulated his own mathematical expression which when applied to similar models, produced numerical results differing little from Synge's. Hay had assumed that the membrane was slightly compressible.

From a physical analysis of the periodontal membrane, Thurow (30) reported that "A tooth subjected to a tilting force is supported by two fulcra; one near the alveolar crest on the side where the force is applied and the other near the apex on the opposite side. The tooth rotates about an axis lying apical to the midroot. The exact location of this axis varies with the direction, point of application and intensity of the applied force." He claimed that moving the point of force application from the incisal edge toward the root would shift the axis apically.

Bien (31), in a study of force vectors resulting from orthodontic appliances stated that "the locus of the rotational axis varies with the load applied to the tooth." There was no elaboration of this statement.

Muhlemann and Zander (32) reported a method for the in vivo determination of an instantaneous axis of rotation. Using dial micrometers, they measured tooth mobility at two different places on the crown when a horizontal tipping force was applied to the tooth. By knowing the crown excursion of these two points and the distance between them, the approximate location of the axis was calculated. The authors found that, in their monkeys, the position of the rotational axis varied between different teeth and in the same teeth when different forces were used. Some of the values obtained showed that the axis was located coronal to the cervical region. This was attributed to methodological errors. From the data published, it appeared as if the axis moved apically as force intensity was increased from 100 to 500 grams. Other variables were shown to affect the axis position. These included the absence or presence of contact points and in vivo-versus-post mortem testing. Elastic distortion of the alveolar bone was demonstrated with similar strain gages, when forces greater than one hundred grams were applied.

Wheatly (33) reported that when a tooth is tipped mechanically, it pivots about a fulcrum which varies in position depending upon the force's point of application and magnitude. He claimed that the axis would move further from the apex if the force were increased or moved from the middle of the crown incisally.

Burstone (34) derived a mathematical expression to predict the location of the rotational axis when the applied force systems were known. He assumed that stress distribution was uniformly varied in pure rotation, uniformly distributed for pure translation and that a linear stress strain relationship existed. The axis of rotation was independent of force magnitude when a simple tipping force was applied. Its distance from the centroid of the root was dependent on the site of force application. Where a couple and a simple force were present simultaneously the axis was critically dependent on the moment-to-force ratio and not on the absolute value of each.

Jarabak and Fizzel (35), in their text, derived a similar mathematical expression. It described the same relationships for force and axis position when a single tipping force was applied. The authors stated that in the event that a couple was employed besides the tipping force, the locus of the axis would vary inversely with the magnitude of the tipping movement and directly with the magnitude of the translating force. The axis position referred to was in relation to the centroid of the root and apical to it.

Haack and Weinstein (36) fabricated a two-dimensional model of a tooth and subjected it to various force systems. It was demonstrated that a simple force directed at a given point, in a given direction, produced the same center of rotation regardless of the force intensity. This was located at approximately one-third of the root length from the root apex.

Christianson (37) refined Muhlemann's <u>in vivo</u> method of instantaneous axis location and applied it to human subjects. Both experimental and theoretical (Burstone Analysis) centers were calculated. Initial test results were erratic. The experimental axes for the last three teeth remained approximately at the mid-root position and close to the theoretical values for all forces ranging from 50 to 700 grams. It was concluded that the intensity of a tipping force is not related to axis position.

Rate of Tooth Movement

Although the primary interest of this investigation was the rotational axis, it was felt that a study relating force magnitude and rate of tooth movement should be included since the necessary data would be readily available.

Reitan (38) tipped both upper and lower central incisors in young dogs for period of 12-48 hours. In each arch one of the incisors was moved with a force of 45-60 grams while the other had 15-30 grams applied. Histologic sections (60 teeth) showed little within-pair difference in the amount of movement. It was concluded that the time factor was far more important than the amount of force applied during the initial stage (0-2 days) of tooth movement.

Storey and Smith (39) applied known forces to retract lower cuspid teeth distally in five orthodontic subjects. Helical springs delivered the forces and were anchored to the first molar and second bicuspids. Weekly measurements of displacement were made in relation to a fixed point in the maxillary arch. Radiographs revealed that the teeth were being tipped. Light forces of 175-300 grams caused the cuspid to move rapidly until the force decreased to 135-180 grams where the tooth continued at a slow rate or ceased. With the heavy springs, there was little or no initial cuspid movement. Instead the "anchor" or posterior teeth moved mesially in a very marked fashion until the applied force diminished to the range of 200-300 grams. Then the anchor unit stopped and the cuspids began to move.

The authors concluded that an optimum range of force exists which will produce a maximum rate of tooth movement. Above or below this range, there is a decreased rate of tooth movement.

In a group of animals (rats, rabbits and guinea pigs), Storey (40) applied forces ranging from 25-250 grams to tip incisors apart for a period of seven days. Measurements of tooth movement taken directly and from histological preparations showed an increase in rate with an increase in force intensity in rabbits and rats but not in the guinea pigs. As an explanation, the author states that the observed increase in movement did not result from an increased rate of bone resorption but was associated with lateral movement of the premaxillary bones.

In the same year, Storey (41) reported another study on the rate of tooth movement. Two groups of eight guinea pigs each had their incisors moved for fourteen days. In one group the applied tipping load was 100 grams while the other was 25 grams. Daily measurements of displacement were plotted. Within each group daily variation was noted. There was more movement the first day with heavier forces. This movement then ceased until the fourth or fifth day and then recommenced and proceeded at an increased rate. Tooth movement was steadier (no lag phase) with lighter forces. At each of the daily intervals the total displacement was greatest where heavy forces had been applied.

Begg (42), commenting on differential forces, stated that light arch wires and rubber ligature force produce the most rapid movement of anterior teeth with the least disturbance of tooth investing tissues, whereas relatively large forces cause the anterior teeth to resist the pressure so they move only very slowly.

Burstone and Groves (43) attempted to determine threshold and optimum force values for the retraction of human maxillary incisors. Simple tipping forces ranging from 25-150 grams per quadrant were employed. The degree of movement was determined from lateral head films and specially designed calipers for intra-oral use. No threshold values were found. Optimal rates of tooth movement were observed in groups of children where 50-75 grams were applied. Increasing the magnitude of force did not produce any increase in the rate of tooth movement.

In a biomechanical discussion of tooth movement, Burstone (34) reported that lighter forces were more likely to move teeth gradually while heavy forces would demonstrate a marked lag period followed by a period of rapid movement. "In fact over a long time interval the average rate of movement for a heavy continuous force may be greater than those observed for lighter continuous forces."

Lee (44) retracted human maxillary canines with helical loops. The initial force was 450 grams. One of the teeth was moved bodily while the other was tipped. Weekly tooth movement readings were made in relation to a fixed point on the lower arch wire. For both types of tooth movement the optimum force range was 150-260 grams. At this force level the rate of tooth movement for the bodily-moved tooth was .7 millimeters per week and 1.1 millimeters per week for the tipped tooth. Using a planimeter, root surface areas were determined on extracted teeth. A high correlation was found between root area and root length. With this information he was able to calculate the optimal pressure range for bodily movement. It was 165-185 $gm./cm.^2$. Deviation from this optimum resulted in a decrease of the rate of tooth movement.

METHODS AND MATERIALS

Sample

The sample for this study was obtained from those patients awaiting treatment in the Orthodontic Department. The criteria for selection was the presence of protruding maxillary incisors and spacing between these teeth. Five white Caucasian females ranging from eleven and one-half years to fifteen years in age met these criteria.

The left and right maxillary central incisors of each subject were utilized for both the instantaneous and long-term tooth movements.

Instantaneous Tooth Movement

Known forces were applied perpendicular to the labial surface of each maxillary central incisor. From simultaneous displacement recordings of two points on the lingual surface of each tooth, the position of the rotational axis was computed.

Instrumentation.

Two resistance bridge-type transducers were employed to measure tooth displacement. Each consisted of a cantilevered steel beam (.003 inch thick x .25 inch long x .10 inch wide) having two strain gages (SR-4 Bonded wire Type A-19) cemented to opposing surfaces and close to the point of beam fixation (Figure 1). A sliding steel rod (.022 inch) served as the intermediary in the conversion of tooth displacement to beam flexion. The transducers were sealed in an acrylic container (.5 inch x .7 inch x .5 inch) to protect them from moisture and air currents.

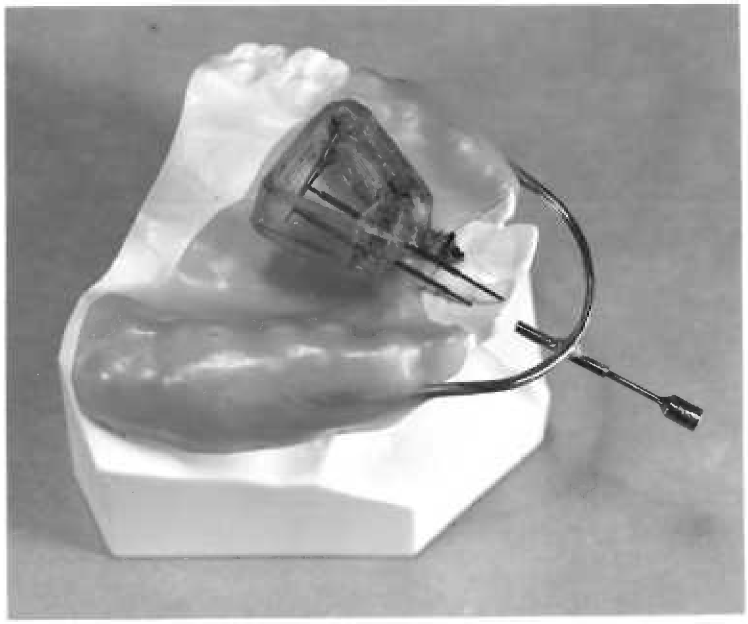


Figure 2. Occlusal Splint with Displacement Transducers and Force-Guiding Rod.

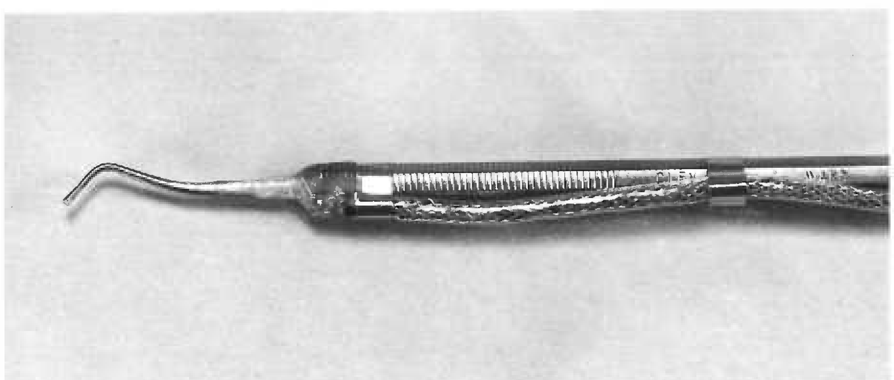


Figure 3. Dynamometer

The two active strain gages of each beam were connected in adjacent arms of a Wheatstone Bridge. The circuit was completed externally by two identical unstressed gages and connected to a strain gage amplifier and graphic recorder (Sanborn strain gage amplifier model 64-500B and Sanborn twin viso two channel recorder model 60-1300). The output of the bridge selected was:

a. Directly proportional to the change in bending load.

b. Twice as large as the output from a single gage.

c. Independent of temperature changes.

d. Independent of axial and torsional loads.

An acrylic overlay splint was made on a maxillary cast for each patient. It covered the entire hard palate and extended over the occlusal surfaces of all teeth excluding the two central incisors and right molars. Before each experimental sequence, the transducer unit was attached to the custom splint with acrylic so that its extruding rods were perpendicular to and in contact with the lingual surface of one central incisor. The rods were positioned midway mesio-distally and inciso-gingivally (Figure 2).

The manually-applied force was measured with an electronic dynamometer constructed from an amalgam condenser (Cleavdent-Ward #1) having two strain gages cemented to its shaft (Figure 3). The bridge circuitry was completed and connected in a manner similar to the displacement transducer.

A steel rod (.040 inch) served to transmit the force from the dynamometer to the tooth. It was orientated perpendicular to its labial surface and in line with the displacement rods mesio-distally and midway between them inciso-gingivally (Figure 2).

<u>Experimental procedures.</u>

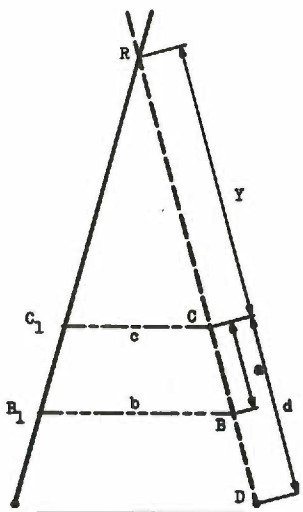
The splint with the displacement transducers was placed in the patient's mouth to check for proper alignment. The lengths of the displacement rods were adjusted so that minimal bending strain was produced in each beam at rest. This minimal flexion was determined visually and by noting the amount of strain recorded. Once the optimum rod lengths were obtained, the splint was fixed to the maxilla with a mixture of fifty percent dental stone and fifty percent plaster, and held under pressure for fifteen minutes to allow for adequate setting. The bridge for each beam was balanced and a base line established on the recorder. It was found, in preliminary trials, that the subjects tended to occlude on the displacement transducer and produce erratic movements. This was eliminated by propping the bite open in the right molar area with a wooden bite block.

At this time the tooth was subjected to a series of fourteen force applications varying in magnitude, position and time. The force was delivered perpendicular to the labial surface of the crown and midway mesiodistally. The applications were divided into two main groups. In the first series, the force was increased from zero grams over a three-to-eight-second period until the five hundred gram level was reached and then released immediately. Five applications were made to the middle of the crown inciso-gingivally (via the sliding rod) and two each were to points one millimeter from the gingival margin and incisal edge respectively. The second series involved the application of a force which was increased from zero grams to a certain value and then maintained for sixty seconds. In each of these five cases, the force was delivered to the middle of the crown inciso-gingivally. The force levels held constant were 100 grams, 200 grams, 300 grams, 400 grams and 500 grams. During the experimental sequence the force levels were vocally relayed by an assistant monitoring the recorders. A time interval varying from five to sixty seconds was allowed between each of the fourteen applications. This represented the period it took the tooth to return to its initial position as established earlier on the recorder. At the conclusion of these procedures, the splint was removed from the patient's mouth. The average time that the splint was present in the oral cavity was ninety minutes. Both the left and right incisors of each patient were subjected to these force applications. A duplicate run was carried out on the left incisor of one patient (#5) to determine the nature of the variation due to transducer placement and time.

Calibration and error estimation.

Before and after each experimental sequence, the dynamometer was calibrated twice with a 100 gram weight. The maximum measurement error was found to be 2.5%. Due to the design of the instrument, a further error arose whenever the force was not applied perpendicular to the long axis of its tip. At the extreme suspected angular deviation, the error in force determination was ± 5%.

The displacement transducer was calibrated at the termination of the experimental sequence. Using a dial micrometer, each beam was calibrated over the same range as it was stressed in the mouth. This was determined by flexing the beam with the micrometer until the values on the recorder reached the original resting state. Readings taken at the minimal attenuation setting were accurate to the nearest ± .0001 inch. This value doubled at the maximum attenuation. Since the rods were parallel to each other, they could not both be perpendicular to the lingual surface of the crown. This introduced a measurement error found to be ± 1.5% at the extremes of ± 10° from the perpendicular which was the maximum angular deviation suspected.



$$X = \frac{a}{\frac{b}{c} - 1} + d$$

LEGEND

X - distance from rotational axis R to incisal edge D

Y - distance from rotational axis R to rod C

a - distance between rod B and rod C

b - distance point B moves to point B_1

c - distance point C moves to point C_1

d - distance from rod C to incisal edge D

DERIVATION

$$\frac{Y}{c} = \frac{Y + a}{b}$$

$$Y = \frac{a}{\frac{b}{c} - 1}$$

$$X = Y + d$$

$$X = \frac{a}{\frac{b}{c} - 1} + d$$

Figure 4. Geometric Determination of the Rotational Axis Position.

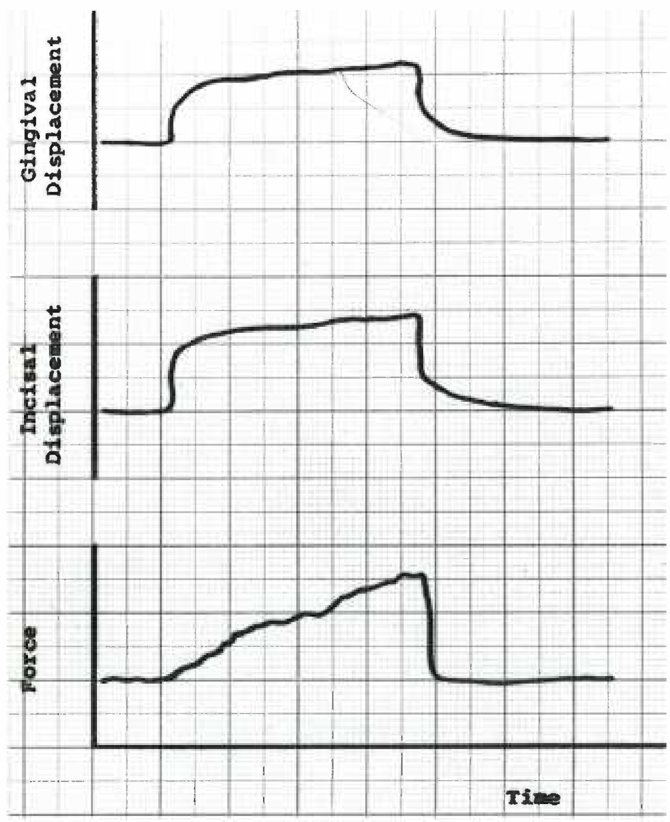


Figure 5. Graphic Recordings of Incisal and Gingival Displacement, Force and Time.

The resistive force developed in the flexed beam was determined with a measuring microscope and known weights. It was found to be .53 grams/ .001 inch. The maximum displacement expected was .01 inch.

Axis location.

The line about which a rigid body rotates when a perpendicular force is applied can be located geometrically (Figure 4). The distances "b" and "c" traversed by the two displacement rods were calculated from the graphic recording at the 50, 100, 150, 200, 250, 300, 400 and 500 gram force levels for each experimental test (Figure 5). It was not possible to determine the axis reliably below forces of 50 grams because the displacement curves were rising too sharply here. From a series of ten measurements, the perpendicular distance "a" between the centers of the two parallel rods was found to be 5.798 mm. in the displacement transducer used on the first subject and 3.983 mm. in all other cases. After cementing the splint in the mouth, the distance "d", between the gingival displacement rod and the incisal edge was measured with dividers and millimeter rule. Using the derived equation of Figure 4, the position of the rotational axis "X" in relation to the incisal edge was determined for each force value.

Determination of incisor tooth lengths.

In order to compare and combine all the data from the determination of the rotational axes in each tooth, it was decided to represent these computed values as percentages of total tooth length and of supported root length. This would reduce between-tooth variation.

A radiographic technique utilizing cephalograms and apical ratiographs was devised to supply the necessary data. A lateral head film was taken of each patient after aligning the orbitale pointer of the cephalometric head positioner. On the cephalogram, a line was drawn perpendicular to the long axis of the superimposed maxillary central incisors. The angle it formed with the Frankfort plane (porion-orbitale) was measured. The subject was then replaced in the head positioner. Frankfort horizontal was re-established with the orbital pointer. The cone of an intra oral x-ray unit was rotated until it formed the same angle with the horizontal as determined above. This cone angulation insured a beam of radiation perpendicular to the long axis of the incisors. A periapical radiograph of the two incisors was taken using the paralleling technique and a Rinn-XCP anterior instrument. The magnification factor was established after measuring the anode-to-tooth and tooth-to-film distances. The true length of each incisor was then found by correcting the measured radiographic lengths for magnification.

To assess the accuracy of this procedure a skull was subjected to ten trials. The computed values were then compared to the actual value after a central incisor was removed. The computed values differed by 0.6% (.1 mm.).

As a further test of reliability, this procedure was carried out three times on a prosthetic patient awaiting full mouth extractions. The computed values of the left and right incisors differed by 0.5% (.1 mm.) when compared to the actual values on extraction.

To obtain the length of the supported root, the gingival sulcus depths and clinical crown heights were measured. The sum of these two were subtracted from the total tooth length to give the desired dimension.

Long-Term Tooth Movements

Long-term tooth movements were carried out over a period of twenty-eight days. A fixed orthodontic appliance delivered tipping forces to the labial surfaces of the left and right maxillary central incisors. At

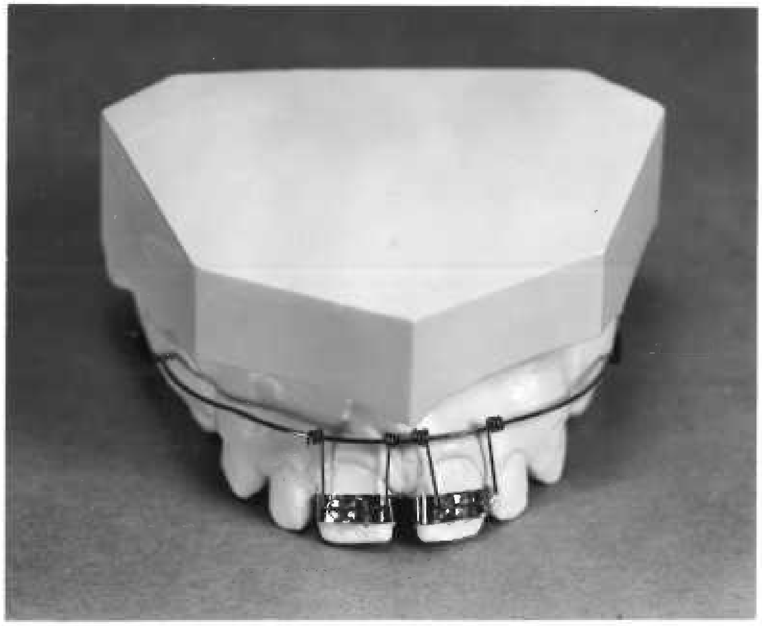


Figure 6. Orthodontic Appliance Employed to Deliver Tipping Forces.

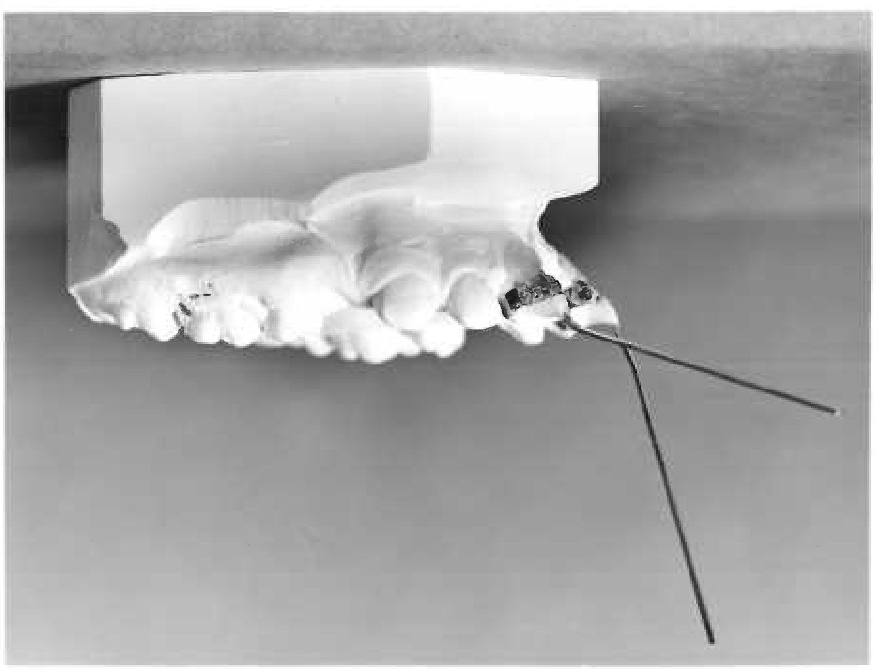


Figure 7. Tooth Markers.

seven-day intervals the axis of rotation and magnitude of incisal displacement were determined for each tooth.

Appliance design.

A high labial archwire (.022" x .028") with auxiliary springs was constructed to deliver the force (Figure 6). The maxillary first molars and central incisors were fitted with preformed bands having molar tubes (.022" x .028") and extra wide edgewise brackets (.022" x .028") attached respectively. The spring over the left incisor was fashioned from .014" stainless steel wire while that over the right incisor from .010" wire.

Force determination.

A mechanical force gage (Dontrix) was used to quantitate the forces produced by each spring when it was placed. An additional measurement was obtained at the time of the subject's return for appliance adjustment and another after the spring had been reactivated. A steel wire (.010") was threaded around the spring arm and attached to the gage. The gage was pulled in a line perpendicular to the labial surface of the tooth. At the instant the spring lost contact with the tooth, a reading was taken.

The gage was calibrated in the laboratory using known weights (20-200 grams). From ten series of weight applications, it was found that the gage was accurate to an average of ± 4 grams.

Axis location.

A radiographic technique utilizing metal tooth markers was employed to locate the rotational axes.

The tooth marker had a four inch vertical arm (.065 inch) (Figure 7). This was fixed to the incisor bracket by ligating its horizontal arm (.022" x .028"). To stabilize this attachment, two acrylic pods were placed around the end of the vertical rod and in contact with the tooth's labial surface.

Initially, before any force application, two lateral head films were taken of each patient with the tooth markers in place. At subsequent seven-day intervals, the force producing appliance was removed, and a head film was taken with the markers retied.

A tracing of the long axes of the overlapped maxillary central incisors and of both tooth markers was made from the initial film. After superimposing this tracing on successive films, the new marker positions were marked. Cranial landmarks (Sella Turcica, Nasion and Pterygomaxillary fissure) and maxillary implants were used as reference points for film superimposition. Three tantalum-tungsten implants (1 mm. long and .022 inch diameter) were implanted as described by Thorburn (2).

With the data obtained from each head film, the axis of rotation was located in the following manner:

$$X = \sqrt{a^2 + \left(\frac{b \cos\frac{1}{2}\alpha}{\sin\alpha}\right)^2 - \frac{2ab \cos\frac{1}{2}\sin(\frac{1}{2}\alpha + \beta)}{\sin\alpha}} - c$$

Where X - The distance from the axis of rotation to the incisal edge.

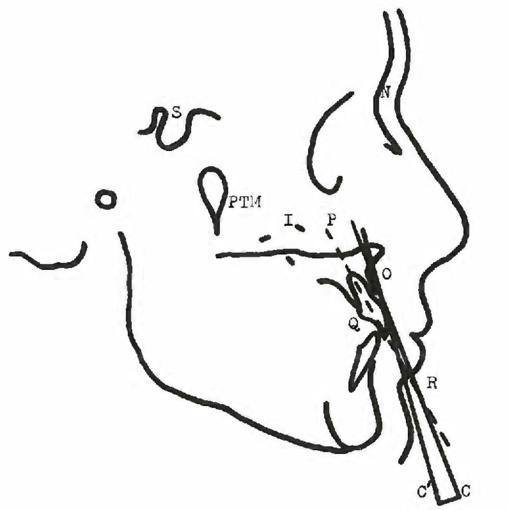
a - The distance from the free end of the tooth marker to its point of intersection with the long axis of the tooth.

b - The distance between the initial and successive positions of the marker measured at the free end.

c - The distance from the incisal edge to the intersection point of the tooth and its marker.

LEGEND

S --- Sella Turcica
N --- Nasion
PTM - Pterygomaxillary Fissure
I --- Implants
OC -- Initial marker position
OC′ -- Subsequent marker position
PQ -- Initial tooth position



$$X = \sqrt{a^2 + \left[\frac{b\cos\frac{1}{2}\alpha}{\sin\alpha}\right]^2 - \frac{2ab\cos\frac{1}{2}\alpha\sin(\frac{1}{2}\alpha + \beta)}{\sin\alpha}} - c$$

Where X is the locus of the Rotational Axis in millimeters from the incisal edge and $a = CR$; $b = CC'$; $c = QR$; $\alpha = \angle COC'$; $\beta = \angle OCC'$.

Figure 8. Determination of the Rotational Axis Position.

α - The angle formed by the initial and successive marker positions.

β - The angle formed by the initial marker and the line joining its free end to the successive marker (Figure 8).

The magnification factor in the mid-sagittal plane, which was utilized in the above calculations was found to be 92.4 ± .1% in a series of ten films of a millimeter rule.

Since there were two initial head films for each patient, the position of the rotational axis was computed twice for each weekly interval. Using these duplicate values, the Standard Error of the Measure of X as calculated with the formula S.E.M. = $\sqrt{\frac{d^2}{2N}}$ was 13 mm. This represented the total error in locating the axis of rotation from head positioning, marker positioning, radiographic exposure, processing, and unknown factors.

<u>Incisal edge displacement.</u>

At weekly intervals duplicate determinations of incisal edge displacement were made from the marker tracings. These values were calculated in the following manner: $D = 2.X.\text{Sin}\frac{1}{2}\alpha$ where

D - The displacement at the incisal edge.

X - The distance from the rotational axis to the incisal edge.

α - The angle formed between the initial and successive marker positions.

It should be noted that D represents the <u>total</u> amount of movement from day one to the time the second film being compared was taken.

The Standard Error of the Measure of D was computed as before and found to be .47 millimeters.

RESULTS

Instantaneous Tooth Movement

Influence of tipping force magnitude on rotational axis.

Absolute values of rotational axis position, in relation to the incisal edge, were calculated for each maxillary central incisor at eight force levels ranging from 50 to 500 grams, (Appendix C). In order to better compare the data from each tooth, a reduction of the between-tooth variation due to the tooth dimensions was indicated. The greatest reduction occurred when the absolute axis position was expressed as a percentage of total tooth length rather than root length.

For ease of presentation, the six to fifteen axes computed at each force interval for each tooth were averaged. These values are entered in Table 1 as a percentage of tooth length beginning from the incisal edge.

Table 1. Mean Axis Position of Each Tooth at Different Magnitudes of Force, Applied to the Crown Midway Inciso-Gingivally.

Subject	Tooth	50 gm	100 gm	150 gm	200 gm	250 gm	300 gm	400 gm	500 gm
1	L	43.1	57.0	62.5	65.8	67.0	69.4	73.5	80.4
	Rt	43.9	46.8	49.1	50.4	52.0	53.3	55.5	56.7
2	L	38.2	49.9	53.7	61.8	61.6	52.3	66.4	64.9
3	L	38.6	49.3	56.2	59.0	59.4	61.6	60.8	61.4
	Rt	32.4	38.8	44.9	41.1	45.6	45.4	47.5	47.3
4	L	54.7	67.9	69.1	69.8	69.4	70.7	69.9	69.3
	Rt	39.9	43.8	45.2	44.4	46.4	48.6	52.9	59.6
5	L	45.8	49.9	50.6	51.9	52.2	53.9	56.3	57.9
	Rt	64.3	96.2	102.2	108.7	118.4	131.0	168.7	153.7

Due to an oversight, there were no force applications to the mid-crown of subject #2's right incisor.

For each of the nine teeth, the axis of rotation appears to have moved further from the incisal edge as the magnitude of force was increased from 50 to 500 grams. In order to statistically test whether these were significant changes in rotational axis position, a Regression type analysis was selected. Not only would this statistical tool measure the relationship between force magnitude and axis position, but also it would provide an equation describing this relationship. From plots of the individual tooth raw data, eighteen likely regression models were selected for computer analysis. The regression model which best fit the data was:

$$\text{Log } Y = A + B \text{ Log } X + C(\text{Log } X)^2$$

where

Y - represents the rotational axis expressed as a percentage of tooth length from the incisal edge.

X - represents the magnitude of tipping force.

A - represents the intercept value.

B, C, - represent the regression coefficients.

Table 2 records the computed coefficients of correlation, coefficients of determination, intercept values and regression coefficients for each tooth.

Table 2. Regression Analysis Relating Axis Position and Magnitude of Force Applied to the Crown Midway Inciso-Gingivally. N = number of observations.

Subject	Tooth	N	R*	R^2	A	B	C
1	L	61	.6589	.4341	-1.8917	+1.2915	-0.2488
	Rt	68	.7519	.5654	-0.4867	+0.0035	+0.0268
2	L	16	.8575	.7353	-1.7238	+1.0967	-0.1964
3	L	72	.6997	.4896	-1.8708	+1.2959	-0.2498
	Rt	67	.7095	.5034	-1.6830	+1.0218	-0.1926
4	L	65	.6731	.4531	-1.4060	+1.0433	-0.2168
	Rt	67	.7305	.5336	+0.0058	-0.4600	+0.1352
5	L	94	.6265	.4038	-0.4798	+0.0767	+0.0040
	Rt	94	.5477	.3000	-0.8393	+0.3871	-0.0049

* Each R value significant at .9995.

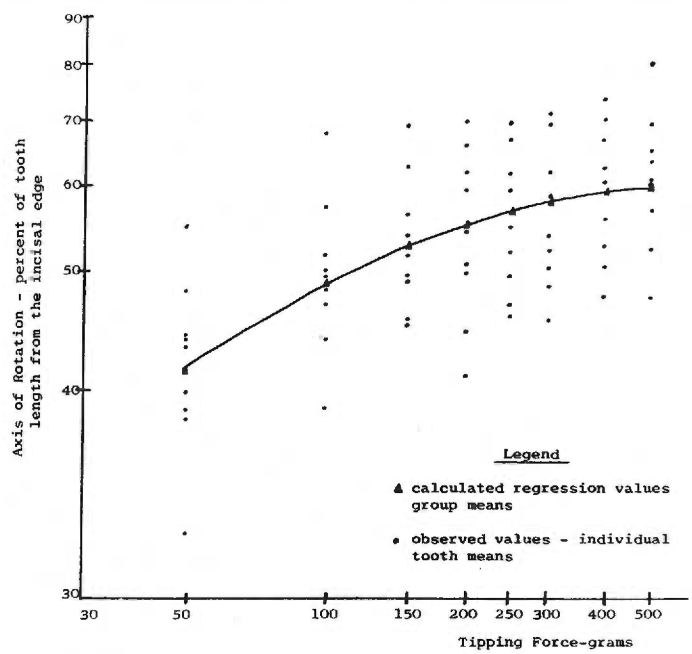


Figure 9. The Effect of Tipping Force Magnitude on the Location of the Rotational Axis.

Since each coefficient of correlation was statistically significant, the shift in axis position at each of the eight force levels was real. In other words, the position of the rotational axis is related to the magnitude of a tipping force. The rotational axis moves toward the root apex as the intensity of forces increases.

In figure 9, this relationship is demonstrated graphically. The plotted curve, described by $\text{Log } Y = -1.1129 + 0.649 \text{ Log } X - 0.1025 (\text{Log } X)^2$, was computed by averaging the intercept and regression values of all teeth. The individual tooth axis means listed in Table 1 are also plotted. The data obtained from the right incisor of patient #5 was excluded here because the calculated axes values were very much different from those of the left incisor as well as all other teeth and particularly because this tooth was adjacent to a recent extraction site.

Effect of site of force application on rotational axis.

Force was delivered to the labial surface of each crown in the middle, gingival, and incisal areas. There were only two series of force applications in the latter two areas. The observed rotational axis values for each tooth are entered in Appendix C. These do not reveal any pattern relating rotational axis position and site of force application.

To test this data statistically, it was decided to compare the individual-tooth regression models determined for each site of force delivery. The models related force magnitude and axis location as before. Calculated regression coefficients for the incisal and gingival force applications were not statistically significant. Most probably, this was a result of the small sample sizes. Since no comparisons could be made between the regression models, the effect of the site of force application on axis position could not be determined.

<u>Influence of force magnitude and time on rotational axis.</u>

In appendix D, the axes positions observed at five time-points where a constant force level was maintained are recorded. The times were 0, 15, 30, 45 and 60 seconds.

In order to evaluate the effects of time and magnitude of force application on axis position, the data was treated statistically utilizing the Analysis of Variance (Table 3). Since there were no 45- and 60-second time points for subject 1-Rt, all the values from this tooth were excluded.

Table 3. Analysis of Variance Used to Test the Effects of Time and Magnitude of Force Application on the Position of the Rotational Axis.

Source	Sum of Squares	df	Mean Square	F
Subject	9,333.11	9		
Force	1,717.92	4	429.5	7.68*
Time	106.00	4	26.5	.47
F X T	1,733.50	16	108.3	1.94
Error	12,067.99	216	55.9	
Total	24,958.52	249		

* Statistically significant at .95.

This analysis revealed that time did not have a significant effect on rotational axis position; however, force magnitude did have a significant effect.

Long-Term Tooth Movement

<u>Influence of force magnitude and time on rotational axis.</u>

All the weekly force values produced by each spring, both before and after reactivation, were averaged and entered in Table 4.

Table 4. Mean Tipping Force (Grams) Applied to Each Tooth Over a Twenty-Eight Day Period.

Subject	Right Incisor	Left Incisor
1	56	150
2	65	134
3	62	196
4	50	165
5	40	104
$\bar{x}$	55	150

The replicated weekly values of the rotational axis for each tooth are recorded in appendix E. In order to determine if time and magnitude of force affected the position of the rotational axis, the data was treated statistically utilizing the Analysis of Variance (Table 5). To simplify the procedure, force magnitude was defined as being either "light" (40-65 grams) or "heavy" (100-200 grams). Because of illness, four second-week entries were absent from the data of subject #3; therefore, the "Total" degrees of freedom were reduced by four and the "Error" by two.

Table 5. Analysis of Variance Used to Test the Effects of Time and Magnitude of Force Application on the Position of the Rotational Axis.

Source	Sum of Squares	df	Mean Square	F
Subject	20,506.6	4		
Force	6,275.2	1	6,275.2	19.9 **
Time	69.1	3	23.0	0.1
F X T	195.5	3	65.2	0.2
Error	8,212.1	26	315.5	
Sampling	8,202.4	38		
Total	43,462.9	75		

** Statistically significant at .9995.

The analysis revealed that time did not have a significant effect on the axis of rotation whereas force magnitude did. Heavier forces produced axes significantly further from the incisal edge than lighter ones.

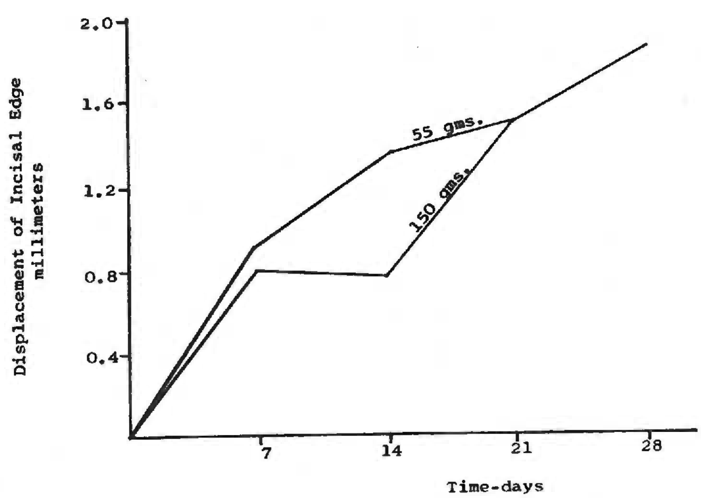


Figure 10. The Effect of Force and Time on Tooth Displacement.

One should realize that such an analysis describes the entire group as a whole. Individually, no differences appear to exist between the axes produced by heavy and light forces in subjects #2 and #5 (Table 6).

Since one could not demonstrate that time did have a significant effect on axis position, the weekly values of the rotational axis were averaged for each tooth (Table 6).

Table 6. Mean Rotational Axis Position Observed During Twenty-Eight Day Experimental Period (measured in millimeters from incisal edge).

Subject	Axis Light Force	Axis Heavy Force
1	12.3	41.8
2	13.1	11.7
3	38.4	77.8
4	24.0	42.7
5	22.6	22.7

Effect of force magnitude on rate of incisal edge displacement.

The technique employed for the determination of rotational axes also furnished data which could be used to relate force magnitude and rate of tooth movement. Replicated weekly values of incisal edge displacement for each tooth are listed in appendix E. The data for all the left and right incisors were averaged and presented graphically in figure 10. Force magnitude could not be shown to have a significant effect on the amount of incisal displacement at the first, third, and fourth weekly intervals. The difference at two weeks was statistically significant. A review of the data revealed that the recorded displacement of tooth #2-right was very much smaller at two weeks than it was a week earlier. This could arise by either the tooth moving in a direction opposite to that of the force or, more likely, by an error in displacement determination for this tooth. Excluding the values from subject #2, no significant differences could be

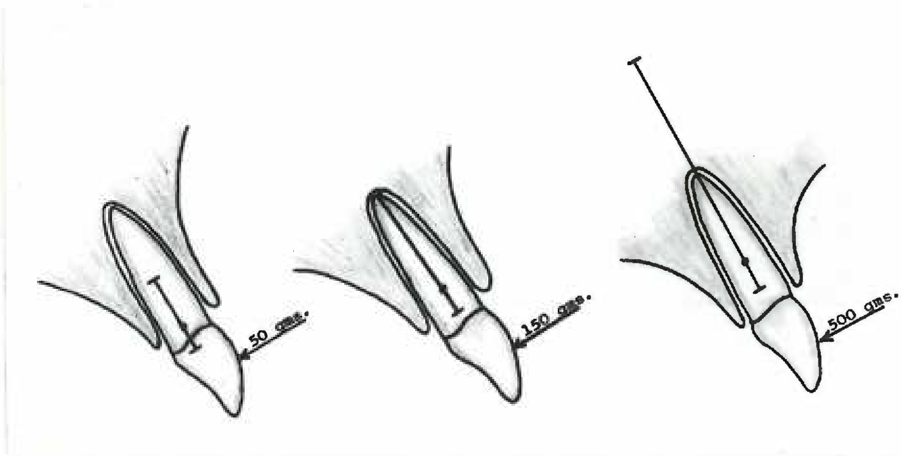


Figure 11. The Mean and Range of the Rotational Axis Positions Produced During Instantaneous Tooth Movement.

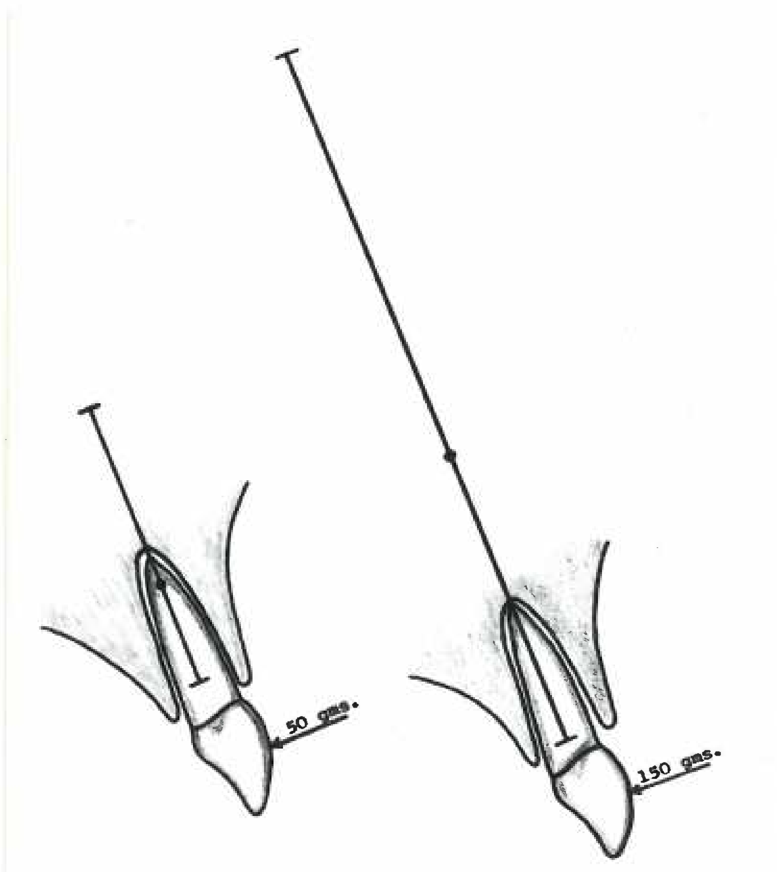


Figure 12. The Mean and Range of the Rotational Axis Positions Produced during Long-Term Tooth Movement.

found at any weekly interval between axis positions produced by heavy and light force applications.

Comparison of Axes Produced During Instantaneous and Long-Term Tooth Movement

Table 7 records the mean axis position produced during instantaneous movement for each tooth at either the 50 or 150 gram force level. These values represent the mean forces applied over the twenty-eight day experimental period. The mean axis position observed for each tooth during this latter time interval are also entered.

Table 7. Mean Rotational Axis Position Observed During Instantaneous and Long-Term Tooth Movements (expressed as millimeters from incisal edge).

Subject	Crown Height mm.	Root Length mm.	Light Force Inst. Axis mm.	Light Force L. T. Axis mm.	Heavy Force Inst. Axis mm.	Heavy Force L. T. Axis mm.
1	9.95	13.26	10.0	12.3	14.3	41.8
2	10.45	16.47	10.3	13.1	14.5	11.7
3	10.80	19.15	10.7	38.4	16.8	77.8
4	10.65	12.84	9.4	24.0	16.2	42.7
5	10.65	11.71	14.3	22.6	11.3	22.7
$\bar{x}$	10.42	14.69	10.9	22.1	14.6	39.3

The group means revealed that the location of the rotational axis produced by instantaneous and long-term movements was not the same at either the 50 or 150 gram force levels. With long-term movement, axes were further from the incisal edge (except subjects #2 and #5) and even beyond the root apex; however, the relationship of rotational axis position and force magnitude were similar for both instantaneous and long-term movement. Under both conditions, heavier forces produced axes further from the incisal edge than did lighter ones (Figures 11, 12).

DISCUSSION

Axis of Rotation

The majority of our present-day concepts of the nature of rotational axes arise from the early histologic investigations of long-term tooth movement. The prime purpose of these studies was to describe morphologic changes in the supporting tissues and not axes of rotation. These findings, though incidental, stimulated a great deal of philosophical discussion. Conclusions reached concerning the location of an axis and the effect of force on this location varied widely. This may be explained largely by differences in the experimental design of each study. These differences included: a) type of experimental animal, b) permanent or deciduous dentitions, c) specific teeth, d) intensity of force application, e) position and direction of force application, f) type of force (continuous, intermittent, bodily, tipping), g) duration of force application and h) method of axis position determination. Also, the conclusions were based on observations made from the experimental movement of only one or two teeth.

An additional source of information on rotational axes is found in the mathematical and mechanical models developed to describe instantaneous movement of teeth within their sockets. In an attempt to measure or explain biologic phenomena with physical analogues, certain assumptions must be made regarding the physical properties of the living tissues being analyzed, such as the physical nature of a tooth's attachment apparatus. Variation in initial assumptions has been responsible for the different models derived to date; however, all have assumed that the alveolar socket is a rigid body and that only the tooth moves when force is applied to it.

A review of the literature reveals that no clear distinction has ever been made between instantaneous and long-term tooth movement. Often, the conclusions reached from the study of one have been extended and applied to describe the other. During the course of this investigation some very pertinent questions arose: 1) Are the resultant positions of the rotational axes produced by instantaneous and long-term movement the same? 2) If these positions are different, can they be related in any manner? 3) Are these positions influenced by the magnitude of tipping forces in the same manner? 4) Are these positions influenced by the duration of force application in the same manner?

The findings of this study provided the answers for all but the second question. The position of the rotational axis resulting when a tipping force is applied instantaneously is not the same as when the same force is delivered over a long period of time. Instantaneous tipping movements produce axes in the cervical and middle root thirds; whereas, long-term movements yield axes in the root's apical third and even beyond its apex. Force magnitude does effect a change in both cases and in the same manner. The greater the load, the further the axis is from the incisal edge. In either of the two types of movement, the position of the rotational axis could not be shown to change with time.

The second question could not be answered as readily as the others. The author believes that a relationship does exist between the rotational axes produced by both instantaneous and long-term tooth movements. In support of this concept, a hypothetical model is advanced. It is based largely on the findings of this investigation.

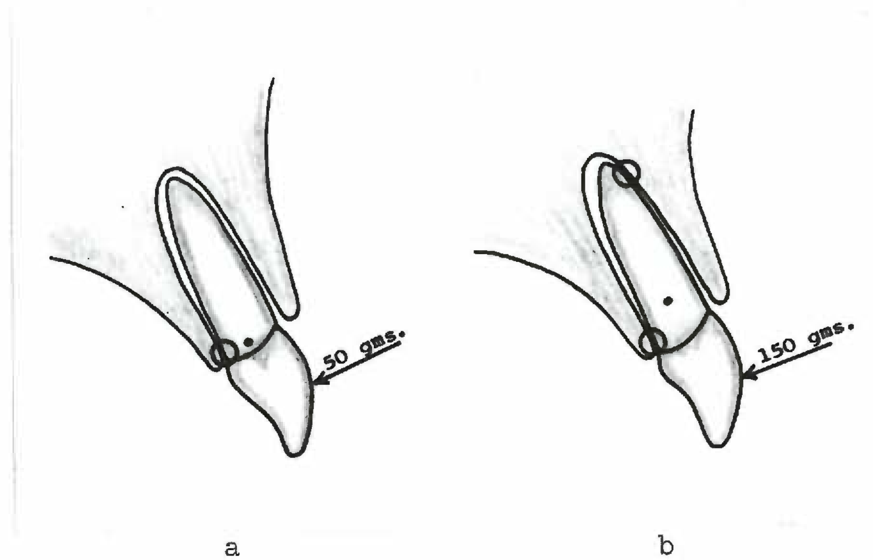


Figure 13. Mean Positions of the Rotational Axis Arising During Instantaneous Tooth Movement.
• - Mean Axis Position   o - Area of Maximum Pressure

During the application of a tipping force, the greatest increment of tooth movement takes place instantaneously. This can be seen on all the recorded tooth displacement curves (Figure 5). With the force-delivering system employed in this study, about seventy-five percent of the total tooth movement took place below the fifty gram force level. The nature of the initial segment of the displacement curves made it impossible to determine the exact magnitude of this movement. Since the positions of the rotational axes could not be calculated below fifty grams, the type of initial motion also was unknown. Probably, both tipping and bodily components were involved.

Areas resistant to motion must arise very rapidly in the periodontal membrane after a force is applied, since a sharp decline in the rate of tooth displacement is noted almost instantaneously on recordings. The theoretical model (Figure 13a) places this first major resistive area at the alveolar crest region opposite the side of force application. Not only could this area decrease the rate of motion but it would also act as a fulcrum point for the tooth to rotate about. At fifty gram loads the rotational axes were found to lie at this level. With an increase in force the crown would be displaced further, while the root apex would deviate in an opposite direction. Thus a new area of resistance would develop at the base of the alveolus (Figure 13b). The resultant axis, at this time, would lie somewhere between these two fulcra. In other words, the initial axis site would shift in an apical direction. This shift was observed when the force magnitude was increased from fifty grams upward.

The attempt to interpret the findings of the instantaneous movements further and to apply the theoretical model to the long-term observations led to the following hypothesis: The axis of rotation, as determined in this study, is the resultant of not only the rotational movement of the tooth within its socket but also of the bending of alveolar and/or maxillary basal bone.

A review of the literature revealed some investigations which would tend to support this hypothesis.

In 1954 Muhlemann and Zander (32) studied tooth mobility when varying tipping forces were applied to the incisor teeth of young monkeys. A mechanical strain gage was employed to measure tooth displacement. When this same gage was applied directly to the labio-marginal alveolar bone and known tipping loads applied both labially and lingually to the crown, elastic deformation of bone was registered whenever the force exceeded 100 grams. This bone displacement accounted for nearly half the measured tooth displacement at this level. The authors concluded that "physiological tooth mobility is due to intra-alveolar displacement of the root, bone distortion and tissue compression. The magnitude of the force decides whether the crown excursion is associated with root displacement or with root displacement and bone distortion. Differences in the thickness of the alveolar plate and age of the animal affect the elastic response of the bone."

Bassett and Becker (45) found that when mammalian and amphibian bones were stressed with 15-30 gram bending forces the bones deformed. This distortion generated an electric potential whose amplitude was dependent on the rate and magnitude of the loading. Its polarity was determined by the direction of bending.

Epker and Frost (46) analyzed the relationship between physical loads on bones and the resultant biologic responses. Physical analogues, diagrams of known features of bone and of known patterns of cellular activity were the basis of the analysis. Their findings revealed that load-induced changes in the curvature of the surfaces of bone correlated consistently with known patterns of bone resorption and formation. They postulated that "strain generally is a major biomechanical factor which influences cell behavior patterns in live bone."

Picton (47), using electronic transducers, detected and measured displacement of the alveolar margins of fifteen teeth in two adult monkeys. Controlled horizontal and intrusive thrusts were applied manually. Bone displacement started in response to forces appreciably less than 100 grams and occurred in a linear manner with forces up to one kilogram. Horizontal forces of more than 50 grams tended to cause the labial and lingual alveolar plate to be displaced in the same direction as the applied force. He stated that, "intrusive forces caused dilation of the socket."

Since bone appears to deform elastically under relatively small bending loads, the combination of forces resulting from the two highly-stressed areas of the periodontal membrane and alveolus seen in Figure 13b may be of sufficient magnitude to induce bone-bending. The probability of this occurence increases with greater loading. Most likely, the effects of bone-bending on the initial recorded rotational axes are very small but rise rapidly as force intensity is increased. In instantaneous movement, the area from which the bending originates is most probably within the basal bone or at the junction of alveolar and basal bone; therefore, with loads greater than 50-100 grams, the resultant axis would shift from its initial position to a new one located further from the incisal edge.

As stated earlier, this hypothetical model can also be employed to describe the long-term movements and their relation to instantaneous tooth

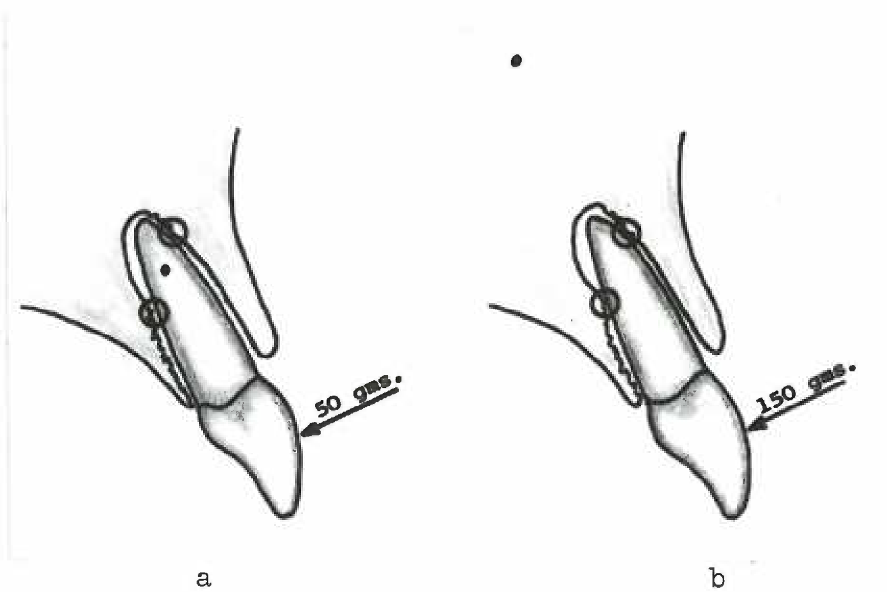


Figure 14. Mean Positions of the Rotational Axis Arising During Long-Term Tooth Movement.
• - Mean Axis Position o - Area of Maximum Pressure

movement. Forces of fifty grams, when applied for extended time periods, will initiate osteoclastic bone resorption in areas where sufficient pressure is being developed. From the model (Figure 13a) this resorption would occur at the alveolar crest region opposite the side of force application and immediately apical to it. As seen in figure 14a, this would shift the main resistive area so that the fulcrum point would lay apical to its initial position. In this study, the position of the rotational axis produced by instantaneous movement did shift apically when the same 50 gram force was applied over a long period of time. With loads greater than 50-100 grams, bone-bending results. Since the bending stresses are mainly in the apical areas of the alveolus (Figure 14b), the originating site of bone deformation would probably lie within the basal bone. This assumption could explain how the resultant axis of rotation at loads of 150 grams were observed beyond the root apex.

One must realize that this hypothetical model is based on certain assumptions. These are: a) The initial area which resists tooth motion is located in the periodontal membrane at the level of the alveolar crest and opposite the side of force application. b) The initial resistive area acts as a fulcrum about which the tooth rotates. c) The stresses developed within the alveolus by tipping forces greater than 50-100 grams are of sufficient magnitude to cause bone deformation or bone-bending. Further investigation in the areas of bone physics and instantaneous tooth movement at low force levels is required before these assumptions can be adequately validated.

Rate of Tooth Movement

One of the primary aims of orthodontics is to move teeth as quickly as possible to their predetermined positions with minimal tissue damage and discomfort to the patient. Establishment of optimal force values, if they exist, would be desirable; however, as was seen in the review of the literature, investigations to date in this area have been highly controversial.

When the adjacent incisor teeth of each subject were tipped by either a "light" (40-65 gram) or "heavy" (100-200 gram) tipping force for twenty-eight days, the degree of tooth movement at any of four weekly intervals was independent of the magnitude of the tipping force. The factors which appeared to have the most influence on the amount of tooth movement were time and individual biologic response.

SUMMARY AND CONCLUSIONS

The purpose of this investigation was to determine the position of the rotational axis as it is related to the magnitude, position, and duration of applied tipping forces. Rotational axes of maxillary central incisors were determined when these teeth were tipped lingually for periods of seconds and also over a twenty-eight day interval in the same five females.

Manually-produced tipping forces were applied to the labial crown surface of each tooth midway inciso-gingivally. Electronic transducers were employed to measure the instantaneous displacement of two points on the lingual crown surface and the magnitude of the force being delivered. One thousand one hundred fifteen rotational axis positions were calculated at eight force levels ranging from 50-500 grams. Statistical evaluation of the individual tooth data revealed that the position of the rotational axis was positively correlated to the magnitude of the applied tipping force ($R = .52-.86$). From a combination of the individual data, a regression model was constructed to describe this relationship. At the lower force values the axis was located in the root near its junction with the crown. With an increase in force, the axes migrated apically to assume a position near the junction of the cervical and middle root thirds at the maximum load.

In addition to mid-crown applications, the force was also delivered to the gingival and incisal areas. In the latter cases the calculated correlation coefficients were not statistically significant. Since no comparisons could be made between the regression equations relating magnitude of force and axis position for the different areas of force delivery, the effect of the site of force application on the location of the rotational axis could not be determined. Using an analysis of variance, the duration of force application (1-60 seconds) could not be demonstrated to have a significant effect on axis position.

Fixed orthodontic appliances were employed to tip these same teeth for a period of twenty-eight days. Heavy forces (100-200 grams) were delivered to the left incisors while light forces (40-65 grams) were applied to the right ones. Metal tooth markers combined with a radiographic technique, involving the superimposition of lateral head films, were used for the weekly determinations of axis location and rate of tooth movement. Statistical analysis revealed that the magnitude of the tipping force had a significant effect on axis position. Axes produced by the lighter forces were in the root while those resulting from the heavier forces were found to be beyond the apex. Time did not have a significant effect on axis position. At each of the four weekly intervals the amount of tooth movement, measured at the incisal edge, was found to be independent of force magnitude.

A hypothetical model, based on the assumption that bone will deform under stress, was developed to describe the findings and to relate the rotational axes produced by instantaneous and long-term tipping movements.

BIBLIOGRAPHY

1. Guerini, V. History of dentistry, ed. 1. New York, Lea and Febiger, 1909, p. 80-87.

2. Thorburn, B. The instrumentation for placing intraosseous metallic implants and their reliability. Orthodontic certificate project, University of Oregon Dental School, 1965.

3. Sandstedt, C. Einige Beiträge Zur Theorie der Zahnregulierung. Nordisk Tandlakaretidskrift. 5:236, 1904; 6:1, 1905.

4. Oppenheim, A. Tissue changes particularly of the bone, incident to tooth movement. Am. Ortho. 3:57, 1911.

5. Johnson, A. L., Appleton, J. L., and Rittershofer, L. S. Tissue changes involved in tooth movement. Int. J. Ortho., OS, Rad. 12:889, 1926.

6. Bodecker, C. Tissue changes involved in tooth movement. Int. J. Ortho., OS, Rad. 12:896, 1926.

7. Schwarz, A. M. Tissue changes incidental to orthodontic tooth movement. Int. J. Ortho. 18:331, 1932.

8. Schwarz, A. M. Uber die Bewegung belasteter Zähne. Ztschr. f. Stomatal. 26:40, 1928.

9. Orban, B. Biologic problems in orthodontia. J. Amer. Dent. Assoc. 23:1849, 1936.

10. Herzberg, B. L. Bone changes and orthodontic tooth movement. J. Amer. Dent. Assoc. 19:1777, 1932.

11. Oppenheim, A. The crisis in orthodontia. Int. J. Ortho. 20:250, 1934.

12. Oppenheim, A. Biologic orthodontic therapy and reality. Angle Orthodont. 6:69, 1936.

13. Stuteville, O. H. The movement of teeth subjected to pressure. Chi. Den. Soc. Bul. 14:20, 1933.

14. Stuteville, O. H. A summary review of tissue changes incident to tooth movement. Angle Orthodont. 8:1, 1938.

15. Frey, H. Tissue changes caused by orthodontic treatment. Brit. Dent. J. 84:52, 1948.

16. Moyers, R., and Bauer, J. The periodontal response to various tooth movement. Amer. J. Orthodont. 36:572, 1950.

17. Storey, E. Bone changes associated with tooth movement--a radiographic study. Aust. J. Dent. 57:57, 1953.

18. Reitan, K. The tissue reaction as related to the age factor. Dent. Rec. 74:271, 1954.

19. Reitan, K. Tissue behavior during orthodontic tooth movement. Amer. J. Orthodont. 46:881, 1960.

20. Massler, M. Change in the lamina dura during tooth movement. Amer. J. Orthodont. 40:364, 1954.

21. Huettner, R. J. and Whitman, C. L. Tissue changes occurring in the macaque rhesus monkey during orthodontic tooth movement. Amer. J. Orthodont. 44:328, 1958.

22. Kulis, L. H. The relation between force magnitude and the center of rotation in the maxillary incisors. Thesis, Indiana University, School of Dentistry, 1962.

23. Atta, A. E. Force magnitude and center of rotation, histologic study in the rhesus monkey. Thesis, Indiana University, School of Dentistry, 1964.

24. Fish, G. D. Some engineering principles of possible interest to orthodontists. Dent. Cos. 59:881, 1917.

25. Case, C. S. Dental orthopedia and correction of Cleft Palate, ed. 2. Chicago, C.S. Case Co., 1921.

26. Schwarz, A. M. Movement of teeth under traumatic stress. Dent. Items of Interest. 42:96, 1930.

27. Synge, J. L. The tightness of teeth, considered as a problem concerning the equilibrium of a thin incompressible elastic membrane. Phil. Trans. Royal Society of London. Series A, 231:435, 1933.

28. Gabel, A. B. A new theory on the mechanics of tooth support. Dent. Cos. 76:677, 1934.

29. Hay, G. E. The equilibrium of thin compressible membrane with application to the periodontal membrane. Can. J. of Res. Sec. A, 17:123, 1939.

30. Thurow, R. C. The periodontal membrane in function. Angle Orthodont. 15:18, 1945.

31. Bien, S. M. Forces used to effect distal movement of teeth. Amer. J. Orthodont. 37:508, 1951.

32. Muhlemann, H. R., and Zander, H. A. Tooth mobility -- the mechanism of tooth mobility. J.Periodont. 25:128, 1954.

33. Wheatley, A. E. Orthodontics. Dent. Techn. 13:17, 1960.

34. Burstone, C. J. The biomechanics of tooth movement. In Kraus, B., and Riedel, R. Vistas in orthodontics, Philadelphia, Lea and Febiger, 1962.

35. Jarabak, J. B., and Fizzel, J. B. Techniques and treatment with the light wire appliance, ed. 1. St. Louis, C. V. Mosby Co., 1963.

36. Haack, D. C., and Weinstein, S. Geometry and mechanics as related to tooth movement studied by means of two-dimensional model. J. Amer. Dent. Assoc. 66:157, 1963.

37. Christianson, R. L. Tooth mobility and instantaneous centers of rotation. Thesis, Indiana University, School of Dentistry, 1964.

38. Reitan, K. The initial tissue reaction incident to orthodontic tooth movement. Acta Odont. Scand. Supl. 6, 1951.

39. Storey, E., and Smith, R. Force in orthodontics and its relation to tooth movement. Aust. J. Dent. 56:11, 1952.

40. Storey, E. Bone changes associated with tooth movement. Aust. J. Dent. 59:147, 1955.

41. Storey, E. Bone changes associated with tooth movement. Aust. J. Dent. 59:209, 1955.

42. Begg, P. R. Differential force in orthodontic treatment. Amer. J. Orthodont. 42:481, 1956.

43. Burstone, C. J., and Groves, M. H. Threshold and optium force values for maxillary anterior tooth movement. J. Dent. Res. 39:695, 1960, abstract.

44. Lee, B. Relationship between tooth movement rate and estimated pressure applied. J. Dent. Res. 44:1053, 1965, abstract.

45. Bassett, C. A., and Becker, R. O. Generation of electrical potentials by bone in response to mechanical stress. Science. 137:1063, 1962.

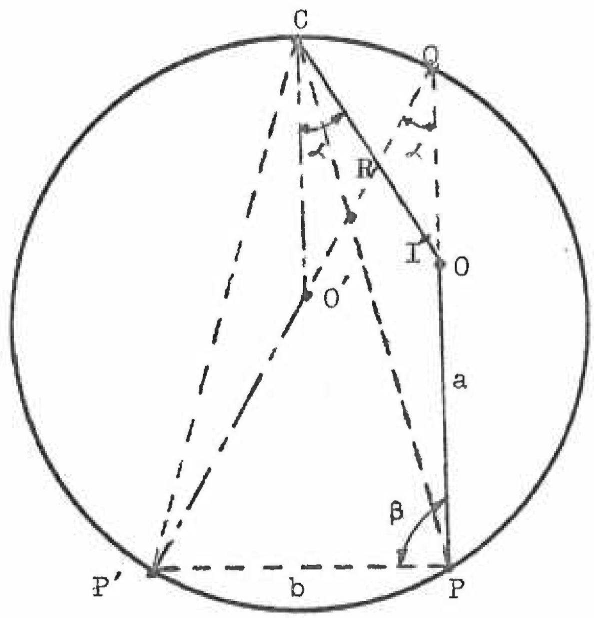
46. Epker, B. N., and Frost, H. M. Correlation of bone resorption and formation with the physical behavior of loaded bone. J. Dent. Res. 44:33, 1965.

47. Picton, D. C. On the part played by the socket in tooth support. Arch. Oral Biol. 10:945, 1965.

APPENDICIES

APPENDIX A

Derivation of Equation Used in the Determination of the Rotational Axis



C is the locus of the rotational axis;

O is the intersection of the marker with the long axis of the tooth;

P is the free end of the marker;

I is the incisal edge;

$O'P'$ is the "new position" of the marker after tooth movement;

Q is the intercept of OP and $O'P'$;

α is the angle of rotation;

$\beta = \angle P'PO$; $a = PO$; $b = PP'$; $c = IO$; $Y = OC = O'C$.

α, β, a and b are all known quantities.

$\angle COP = \angle CO'P'$; $\angle COQ = \angle CO'Q$

$\angle ORQ = \angle O'RC$

$\therefore \angle OQO' = \angle OCO' = \alpha$

$\angle OCP = \angle OC'P'$

$\angle PCP' = \angle OCO' - \angle OCP + \angle O'CP' = \angle OCO' = \alpha$

Consider the circle which circumscribes the $\Delta\ PP'Q$:

arc $PP' = 2\alpha$ because the angle α has its vertex located on the circumference of the circle.

Any other angle α spaning the same arc must also have its vertex on the circumference of this circle.

$\angle PCP' = \alpha$ Therefore point C must be located on the circumference of the circle.

arc $PP' = 2\alpha$

$PC = P'C$, therefore arc PC = arc $P'C = \frac{360° - 2\alpha}{2} = 180° - \alpha$

arc $P'Q = 2\beta$

arc CQ = arc $P'Q$ - arc $PC = 2\beta + \alpha - 180°$

$P'C = 2r\text{Sin}\,(90° - \frac{1}{2}\alpha)$ as the length of a cord $= 2r\text{Sin}\frac{1}{2}\,\theta$

$PP' = b = 2r\text{Sin}\,\alpha$

$$r = \frac{b}{2\text{Sin}\,\alpha}$$

$$\therefore P'C = \frac{b\text{Sin}\,(90° - \frac{1}{2}\alpha)}{\text{Sin}\,\alpha}$$

In $\triangle CO'P'$, the following elements are known: a, $P'C$ and $\angle CP'O' = \frac{1}{2}\text{arc}CQ$ $= \frac{1}{2}\alpha + \beta - 90°$

In a triangle where two side a and b and their included angle θ are known, the opposite side c is equal to $\sqrt{a^2 + b^2 - 2ab\cos\theta}$

Therefore the value Y, representing the distance from the rotational axis C to point O can be determined as follows:

$$Y = \sqrt{a^2 + \left(\frac{b\sin(90° - \frac{1}{2}\alpha)}{\sin\alpha}\right)^2 - \frac{2ab\sin(90° - \frac{1}{2}\alpha)}{\sin\alpha}\cos(\tfrac{1}{2}\alpha + \beta - 90°)}$$

$$= \sqrt{a^2 + \left(\frac{b\cos\frac{1}{2}\alpha}{\sin\alpha}\right)^2 - 2ab\,\frac{\cos\frac{1}{2}\alpha\,\sin(\frac{1}{2}\alpha + \beta)}{\sin\alpha}}$$

X represents the distance from the incisal edge I to the rotational axis C.

X = Y - OI

X = Y - C.

APPENDIX B

Maxillary Central Incisor Dimensions *

Subject	Tooth Length mm.	Root Length mm.	Crown Height mm.
1	22.81	13.26	9.55
2	26.92	16.47	10.45
3	29.95	19.15	10.80
4	23.49	12.84	10.65
5	22.31	11.71	10.65

* Mean of values for left and right incisor

APPENDIX C

Instantaneous Movement
Rotational Axes and Force Magnitude
(axis expressed in millimeters from incisal edge)

Subject	50 gm.	100 gm.	150 gm.	200 gm.	250 gm.	300 gm.	400 gm.	500 gm.
1 Rt	9.37	10.35	10.78	11.03	11.34	11.44	10.79	11.03
	10.42	10.84	11.31	11.44	12.98	13.49	14.17	15.03
	10.42	10.50	11.61	11.68	11.90	12.57	12.35	13.45
	10.23	10.50	10.80	10.88	11.06	11.31	13.62	13.93
	10.18	10.20	10.63	11.07	12.46	12.87	13.93	11.25
	10.30	10.52	11.37	12.38	12.27	14.00	12.42	
	9.47	11.25	10.71	12.96	11.79	11.79	11.35	
	10.60	11.96	11.87	11.62	11.09	10.76		
	9.96	11.00	11.62	10.86	11.79	11.23		
	9.21	9.98		11.04	10.76			
		10.34			11.23			
1 L	17.03	16.70	17.40	18.25	16.34	19.18	20.28	20.28
	6.39	13.82	19.74	19.18	19.18	17.03	21.68	24.88
	5.46	10.43	11.09	11.96	11.62	13.45	13.45	16.03
	11.40	12.09	14.25	16.68	15.93	15.99	17.40	22.58
	11.30	13.63	13.28	12.50	12.78	18.68	18.23	13.10
	10.03	11.63	12.08	14.43	18.25	12.78	13.10	13.13
	9.08	14.03	13.63	12.93	13.28	13.73	13.28	
	11.83	12.94	12.63	14.25	14.93			
	5.82	11.85						
2 L	10.16	10.16	13.45	17.81	15.46	10.73	17.05	16.68
	10.37	16.69	15.46	15.46	17.71	17.42	18.70	18.25
3 L	11.20	17.41	16.34	17.41	18.25	17.82	14.93	16.34
	10.58	8.55	13.45	16.35	16.03	16.68	16.68	17.41
	8.24	15.46	17.41	18.24	17.81	20.28	19.72	16.35
	10.92	12.28	17.40	18.24	16.68	20.28	19.71	17.81
	16.34	14.47	15.19	18.69	18.69	18.24	17.40	18.24
	8.53	16.34	16.35	17.41	14.93	15.72	14.68	19.70
	16.68	13.45	14.93	14.93	16.68	18.71	18.68	23.93
	10.15	16.68	15.18	17.04	20.28	19.70	23.93	
		12.48	18.23	18.68	20.85	21.55		
		19.18	23.92	19.71				
		16.04						

* force applied midway inciso-gingivally.

Subject	50 gm.	100 gm.	150 gm.	200 gm.	250 gm.	300 gm.	400 gm.	500 gm.
3 Rt	9.22	10.67	11.72	14.46	13.28	14.03	14.68	14.24
	10.51	11.97	12.78	12.50	13.28	13.82	14.24	14.24
	9.26	13.27	13.63	13.82	13.82	13.46	13.63	14.23
	8.02	12.36	13.46	12.63	13.43	14.03	14.25	14.25
	5.42	9.40	20.28	12.63	13.82	12.94	14.03	14.92
	15.48	12.63	9.61	10.68	14.24	13.10	14.94	13.11
	10.50	9.72	13.83	14.03	13.83	13.83	13.83	
	10.37	13.28	13.46	13.63	13.66	13.66		
	8.96	12.96	12.23	14.69				
4 Rt	8.84	9.19	9.51	6.89	10.50	10.78	15.95	15.95
	10.29	10.08	10.35	10.72	11.08	11.28	11.35	12.09
	9.32	10.50	10.90	11.07	11.22	11.75	12.11	17.99
	8.86	11.01	11.21	11.36	11.50	10.40	12.50	12.61
	8.84	9.73	10.01	10.13	10.26	11.08	10.62	11.22
	9.42	10.01	10.96	11.44	11.44	11.02	11.23	14.10
	8.79	9.92	10.41	10.36	10.36	12.29	13.23	
	9.19	10.29	10.61	10.26	11.08			
	9.41	10.84	11.51	11.67				
	12.73	11.22						
4 L	10.72	15.23	14.63	14.83	15.03	14.28	13.68	13.36
	12.62	15.68	14.83	15.03	15.23	16.73	15.93	15.03
	10.95	15.48	16.19	15.21	15.46	15.67	15.93	17.34
	13.63	14.83	14.46	16.18	16.18	16.45	16.45	15.68
	11.92	16.19	18.04	18.41	18.41	18.41	17.36	17.70
	14.44	16.45	16.75	17.03	17.36	15.46	16.48	18.43
	14.46	17.68	16.75	17.04	15.03	19.27	18.43	
	12.20	15.24	15.71	15.96	17.69			
	14.83	16.76	18.81	17.96				
5 Rt	11.08	11.44	10.66	11.84	12.73	13.65	32.78	43.09
	11.51	10.90	11.59	13.23	24.97	26.97	42.46	19.69
	12.11	13.10	22.58	25.89	29.40	41.84	15.69	21.30
	16.46	20.74	22.58	29.40	18.41	16.46	17.36	36.58
	18.83	36.60	17.03	16.18	20.20	18.41	39.06	34.46
	10.91	14.64	20.20	16.18	39.06	36.58	34.40	39.13
	9.06	17.03	30.86	24.93	28.08	32.46	34.38	45.78
	21.30	26.86	30.88	25.88	32.48	26.93	50.18	
	20.71	24.09	25.86	25.86	34.40	39.08	72.38	
	13.63	20.72	30.88	32.48	39.08	55.73		
	13.79	24.08	36.58	42.10	11.83	13.35		
	20.71	27.48	12.96	12.01				
	10.72	12.85	25.86	39.08				
	15.02	26.91	20.69					
	9.47	34.39						

* force applied midway inciso-gingivally.

Subject	50 gm.	100 gm.	150 gm.	200 gm.	250 gm.	300 gm.	400 gm.	500 gm.
5 L a	13.47	13.12	11.33	12.25	10.12	14.61	15.74	13.72
	10.42	11.16	13.73	14.13	12.51	14.13	13.98	14.93
	12.23	13.34	13.01	13.11	13.22	12.60	13.59	14.13
	11.87	12.60	11.46	13.12	11.72	13.85	15.13	13.58
	10.54	11.78	10.62	10.90	11.58	13.98	13.72	14.93
	9.68	10.38	11.46	11.60	11.22	13.35	13.46	14.28
	10.58	11.22	11.93	12.33	11.46	11.72	14.13	13.46
	10.10	10.90	10.62	11.78	11.51	11.86	13.02	
	10.23	10.76	11.78	12.49	13.73	11.58	11.93	
	10.42	11.46	11.65	11.65	14.61	11.86		
	10.26	10.90	11.46	11.78	13.11	11.93		
	10.42	10.67	10.38	10.54				
	9.97	10.63	11.11	12.01				
	10.38	10.81						
	9.80	12.17						
5 L b	8.76	11.52	10.81	10.96	11.79	12.17	11.78	10.23
	9.72	11.76	11.33	11.52	11.51	11.16	10.54	13.11
	10.85	11.40	10.91	11.28	10.46	10.67	11.61	11.40
	9.97	10.27	10.90	10.72	10.96	11.02	11.52	11.11
	7.91	10.46	10.46	10.67	12.01	11.72	10.94	12.89
	10.13	10.58	11.28	10.67	11.16	11.27	11.78	12.33
	10.00	10.46	10.94	10.90	10.46	11.06	12.16	10.67
	8.98	10.90	10.72	10.07	11.26	11.00	9.69	
	9.11	9.69	10.65	12.08	9.41	10.03	11.40	
	8.46	10.46	9.69	10.03	10.40	10.63		
	7.90	9.97	10.71	10.27	11.85	12.33		
	11.22	10.81	10.91	11.58				
	9.10	10.27	13.63	13.22				
	12.79	13.12						
	10.71	12.24						

* force applied midway inciso-gingivally.

Subject	50 gm.	100 gm.	150 gm.	200 gm.	250 gm.	300 gm.	400 gm.	500 gm.
1 L	5.36	9.41	9.36	12.49	12.36	12.63	11.96	13.10
	8.53	9.66	12.49	11.97	13.45	13.83	14.03	13.83
2 Rt	11.73	14.46	18.28	15.78	15.18	14.93	18.28	17.38
	16.38	18.68	18.28	17.08	19.68	18.28	18.68	20.28
	13.28	20.88	19.68	19.18	20.28	19.68	20.28	20.28
	22.28	21.58	18.28	21.58	22.28	24.98	24.88	23.08
	21.58	20.88	22.28	23.08	21.58	22.28	23.08	22.28
	18.28	20.28	22.28	24.98	21.58	21.58	21.58	24.88
	20.28	20.88	20.88	20.28	23.08	21.58	22.28	
	13.45	18.68	20.78	22.28	20.88	23.08		
	24.78	23.08	23.08	23.08				
	9.12	23.08						
2 L	12.96	18.70	15.46	15.46	20.29	19.73	19.20	20.90
	11.40	15.46	18.26	15.73	19.73	19.20	21.58	18.71
	10.59	19.20	18.23	18.23	20.30	23.08	21.57	20.92
	15.46	12.78	15.46	18.26	17.73	20.30	19.71	19.20
	12.36	15.46	18.26	15.73	14.03	17.05	16.68	16.68
	11.21	17.81	17.42	19.20	23.08	23.08	18.25	20.72
	13.11	18.26	25.07	20.28	19.18	18.71	20.28	
	11.41	19.21	17.81	17.05	21.57	21.57		
	13.11	13.63	20.28	20.28				
	15.46	15.46						
3 Rt	11.60	16.36	14.03	15.18	15.18	15.46	15.46	14.68
	9.36	11.01	14.03	13.45	14.46	14.46	14.68	14.68
3 L	12.22	17.42	17.83	20.30	19.72	19.21	23.93	23.93
	14.68	17.81	19.71	20.88	22.30	23.93	25.98	25.98
4 Rt	9.20	11.02	11.92	12.97	13.95	14.11	14.11	15.03
		9.74	10.46	10.67	10.96	11.02	11.44	11.84
4 L	15.96	15.92	15.03	15.46	14.63	14.83	14.28	15.02
	10.66	12.51	13.10	14.10	14.28	14.82	14.11	14.28
5 L a	10.80	11.06	12.09	12.35	11.78	11.71	12.41	12.70
	9.56	11.00	11.71	11.71	12.08	11.78	11.71	12.01
5 L b	10.42	10.30	10.42	11.16	10.90	11.00	11.00	11.22
	10.27	10.16	10.30	10.67	10.76	10.86	11.28	11.01
5 Rt	16.46	17.03	18.41	20.18	20.18	20.18	23.30	28.40
	11.28	14.63	17.36	18.91	17.36	17.36	18.41	18.70

* force applied 1 mm. from marginal gingiva.

Subject	50 gm.	100 gm.	150 gm.	200 gm.	250 gm.	300 gm.	400 gm.	500 gm.
1 L	6.17	8.74	8.92	10.28	9.45	9.56	10.93	10.77
2 Rt	8.60 14.03	12.08 17.78	14.92 15.48	17.38 15.48	20.88 17.38	20.28 20.28	19.68 21.58	19.68 24.88
2 L	7.26 6.31	13.10 7.60	18.25 9.51	16.68 15.46	17.42 17.41	17.42 15.46	16.68 17.05	15.46 15.46
3 Rt	6.27	13.63 16.68	11.51 14.05	11.97 14.03	13.45 15.18	14.45 13.64	14.45 15.18	15.46 14.68
3 L	10.44 9.15	16.05 13.46	18.26 17.83	22.30 18.72	25.87 17.05	27.04 15.76	28.40 23.08	28.40 22.30
4 Rt	11.02 8.06	14.10 10.00	12.97 10.84	15.94 11.36	16.03 11.29	16.09 11.29	15.94 11.67	19.68 13.87
4 L	14.28 10.31	15.93 15.93	16.73 18.03	16.46 15.03	15.03 14.10	17.05 14.46	19.68 13.79	18.04 13.22
5 L a	11.22 11.76	11.40 11.22	12.25 11.93	12.25 13.12	12.42 13.99	12.33 13.59	13.46 13.85	13.72 13.36
5 L b	10.46 9.52	11.52 10.90	13.46 11.58	13.34 11.39	13.46 11.64	13.71 11.05	13.46 11.78	13.59 11.78
5 Rt	11.09 16.46	11.09 34.18	11.37 30.18	12.11 34.18	13.79 39.58	13.23 36.59	14.11 34.18	14.46 45.78

* force applied 1 mm. from incisal edge.

APPENDIX D

Instantaneous Movement

Rotational Axes and Time
(millimeters from incisal edge)

Tooth	Force gm.	0 sec.	15 sec.	30 sec.	45 sec.	60 sec.	Tooth	Force gm.	0 sec.	15 sec.	30 sec.	45 sec.	60 sec.
1 Rt	100	10.71	11.22	13.62			3 Rt	100	12.63	12.98	11.86	10.59	9.89
	200	11.24	13.14	14.58				200	10.68	12.50	11.41	11.21	11.31
	300	11.31	13.47	13.93				300	14.03	13.46	14.46	12.08	13.10
	400	13.62	14.07	15.30				400	14.94	14.03	13.38	12.78	11.97
	500	13.93	15.27	15.37				500	13.11	12.10	11.85	10.75	10.75
1 L	100	16.08	14.94	19.73	19.73	22.30	3 L	100	16.34	16.36	16.36	15.19	16.34
	200	12.78	17.41	33.38	38.18	33.38		200	17.41	17.03	17.04	18.25	16.70
	300	18.32	19.19	19.73	22.28	22.28		300	15.46	15.46	15.46	14.68	13.28
	400	13.10	13.28	16.34	14.23	9.50		400	14.68	23.05	18.70	15.18	15.18
	500	12.66	14.23	15.19	14.23	12.79		500	19.70	19.19	19.70	23.93	19.72
2 Rt	100	20.08	24.78	21.58	23.95	24.06	4 Rt	100	10.01	10.73	11.36	11.76	12.11
	200	25.00	24.98	23.93	27.10	24.98		200	11.44	12.63	13.50	13.23	13.50
	300	21.58	23.08	24.88	23.08	24.88		300	11.08	12.01	13.23	14.11	14.87
	400	21.58	23.92	21.58	21.60	19.28		400	11.23	13.00	15.93	15.93	14.87
	500	24.88	27.38	25.93	27.38	27.38		500	14.10	23.28	29.38	32.58	39.18
2 L	100	17.81	17.43	19.20	25.95	25.95	4 L	100	13.94	14.27	14.27	14.27	14.27
	200	19.20	17.03	16.70	18.26	17.03		200	17.03	15.93	15.48	17.68	16.45
	300	23.08	21.58	20.90	18.70	21.58		300	17.36	16.75	16.75	17.68	16.45
	400	18.25	20.29	19.71	23.06	19.71		400	16.38	18.03	18.41	18.41	18.41
	500	19.71	21.57	20.93	20.93	19.21		500	18.43	19.71	19.71	18.41	18.81

Tooth	Force gm.	0 sec.	15 sec.	30 sec.	45 sec.	60 sec.
5 Rt	100	16.06	16.26	14.89	14.86	14.89
	200	25.82	42.02	22.92	37.15	24.09
	300	13.49	16.42	20.01	19.62	20.20
	400	72.38	50.20	36.58	24.93	25.88
	500	54.33	52.38	77.84	92.28	60.78
5 L a	100	13.13	13.47	15.47	13.79	14.13
	200	12.13	14.00	14.23	13.78	13.74
	300	13.27	15.08	15.34	15.59	16.62
	400	13.84	13.93	14.92	15.38	15.34
	500	13.09	14.99	15.45	15.92	15.65
5 L b	100	11.89	13.38	14.22	14.88	14.95
	200	12.10	13.26	13.68	14.61	15.02
	300	12.25	12.51	13.03	13.30	13.29
	400	11.59	12.35	13.26	13.25	13.45
	500	10.45	11.07	12.47	12.74	13.16

APPENDIX E

Weekly Locations of the Rotational Axes
(millimeters* from incisal edge)

Subject	Tooth	LEFT INCISOR								RIGHT INCISOR							
	Week	W1		W2		W3		W4		W1		W2		W3		W4	
	Film	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2
1		34.5	22.6	34.4	67.6	45.2	39.0	43.5	47.3	11.4	3.9	12.0	13.4	14.6	7.4	15.4	20.2
2		5.2	5.4	1.0	1.9	30.1	18.7	17.6	9.7	10.6	11.5	14.9	23.3	7.0	8.9	9.6	17.8
3		110.2	49.2	103.9	66.6	114.4	64.5	86.1	53.3	29.9	69.6	27.2	49.1	23.1	36.2	27.8	44.4
4		28.5	70.3	39.0	54.0	23.8	43.5	41.4	41.4	23.3	17.5	21.4	30.0	25.5	15.6	40.0	18.5
5		27.0	22.7	**	**	20.5	19.8	17.8	23.9	26.4	19.2	**	**	26.5	26.3	18.0	18.5

* corrected for magnification

** no data - patient sick

APPENDIX F

Weekly Tooth Displacement
(millimeters* at incisal edge)

Subject	Tooth / Week / Film	LEFT INCISOR								RIGHT INCISOR							
	Week	W1		W2		W3		W4		W1		W2		W3		W4	
	Film	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2
1		0.60	0.64	0.60	0.59	1.18	1.20	1.57	1.49	0.50	0.22	0.87	0.87	1.27	0.65	1.34	1.59
2		0.23	0.24	0.04	0.08	2.10	1.31	1.24	0.80	0.74	0.74	1.08	1.55	0.55	0.70	1.23	1.50
3		1.35	1.29	1.00	1.16	1.53	1.80	2.10	1.95	1.77	1.82	1.90	2.57	2.02	2.02	2.43	2.71
4		0.70	0.86	1.02	0.94	0.83	1.11	1.44	1.44	1.34	0.89	1.12	1.38	1.63	1.06	1.61	0.81
5		0.82	1.94	**	**	2.93	1.90	2.44	5.25	1.28	0.71	**	**	2.87	3.12	3.61	2.74

* not corrected for magnification

** no data - patient sick