ORTHODONTIC TOOTH MOVEMENT IN RESPONSE TO KNOWN FORCE SYSTEMS: CUSPID RETRACTION

by

WARREN GEOFFREY DUFF B.D.S

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF PREVENTIVE DENTAL SCIENCE

WINNIPEG, MANITOBA

December, 1987

ISBN 0-315-44112-7

ORTHODONTIC TOOTH MOVEMENT IN RESPONSE TO KNOWN FORCE SYSTEMS: CUSPID RETRACTION

BY

WARREN GEOFFREY DUFF

A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

ABSTRACT

Knowledge concerning the relationship between tooth movement and known forces is currently based upon inadequate techniques and incomplete data. In order to allow further investigation of this relationship, a technique was developed which combined both in vivo and in vitro phases.

The development of a machine at the University of Manitoba, which is capable of measuring in vitro forces and moments in three dimensions simultaneously, has made it possible to attempt to relate tooth movement to known applied force systems. The machine has been modified so that appliances can be measured under geometric conditions similar to those found in clinical situations. Thus a technique was developed using passive wire templates of in vivo tooth positions as a means of transferring information to the in vitro setting on the above mentioned machine. Quantification of force and moment characteristics could then be assessed using duplicates of the active in vivo appliance.

In conjunction with the above mentioned procedures, a technique was developed, using study casts, to accurately measure the three-dimensional changes in

tooth position as a direct result of applied orthodontic force.

Results from this study indicate;

1. Confidence could be placed in carefully prepared anchorage units as reference points upon which to monitor tooth movement.
2. Changes in linear tooth movement can be assessed to within +/- 0.12mm with 95% confidence.
3. Changes in rotational tooth movement can be assessed to within +/- 3 degrees with 95% confidence.
4. _In vivo_ bracket positions could be accurately transferred to an _in vitro_ setting thus allowing forces and moments to be measured for specific activations of given loops.
5. Loops can be repeatedly duplicated to within 15% to 20% accuracy.
6. The technique, although tedious at some stages, has eliminated a large degree of the variability inherent in earlier studies of this type.
7. When using the technique to evaluate force systems in retraction, some interesting trends in tooth movement became apparent;
   (i) The measured movement of studied teeth tended to reflect clinical expectations.

(ii) Based upon a very small sample size, it is interesting to note that with careful planning, it may be possible to retract cuspid teeth with minimal untoward movements.

8. With minor refinements and repetitive application of this technique it is possible that, over time, more quantitative data will be provided concerning tooth movement in response to known force systems.

DEDICATION

TO MY WIFE JUDY

and

TO MY DAUGHTERS,

SALLY, GEORGIA and ANGELA

The very precious people in my life.

ACKNOWLEDGEMENTS

During the preparation of this thesis, many people have made generous contributions in many varied ways. To all those people I am most grateful.

To my good friend and research advisor Dr. Ken McLachlan, whose keen insight and timely advice made this research project possible.

To Drs. Robert Baker and Denny Smith, who, in their capacity as research committee members gave many valuable suggestions during the writing of this thesis.

To Mr. H.J. Clark of the Civil Engineering Workshop, whose expertise in the construction of precision apparatus was well appreciated.

To my classmates, Dorothy (Dotty) Sonya, and Kris (Rowser) Row whose friendship I shall always treasure. Thanks guys for all the good times, and for the support and encouragement during the not-so-good times.

To the support staff in the Graduate Orthodontic Clinic. I would like to thank you all sincerely for your friendship and help, especially during the clinical aspects of this study.

To all my family and friends both here in Canada and at home in Australia. Thank you all for your support and understanding over the past thirty months.

CONTENTS

Appendices page

LIST of TABLES

Table page

LIST of FIGURES

1. INTRODUCTION

It is apparent that there is very little meaningful information concerning the quantitative nature of tooth movement and applied force systems, available to the orthodontic profession. The few studies that are available in this field have indicated great variability in the magnitudes of forces which are considered desirable for specific tooth movements, such as cuspid retraction. This variability appears to be due to a number of factors, which include;

(i) Individual biological variability.

(ii) The inability to measure applied force systems in three dimensions.

(iii) The use of imprecise methods for measuring tooth position. In addition, the measurement of tooth positional changes has rarely if ever, been assessed in three dimensions.

(iv) The failure to distinguish tipping movements from translatory movements.

(v) The extrapolation of data from other species to draw conclusions regarding the effect of force on tooth movement in humans.

In order to reduce the effect of these variables a suitable technique would have the following ideal requirements;

(a) The use of human subjects undergoing routine orthodontic treatment.

(b) The three-dimensional assessment of tooth positional changes and force systems.

(c) The study of large linear or rotational tooth movements to reduce the effect of measurement error.

With these requirements in mind, a combined *in vivo*, *in vitro* technique was developed to investigate the relationship between tooth movement and known force systems. Assessment of the viability of this technique and recommendations for future research will be discussed.

2. REVIEW of the LITERATURE

2.1. INTRODUCTION:

The relationship between applied force systems and resultant tooth movement has received frequent attention in the literature; however relatively little experimental information is available. The accurate quantification of a force system in all three dimensions of space has generally been an incomplete, if not neglected, task in the few studies which are available in this field. In many cases the data have also proven difficult to interpret. In addition, studies into observed changes in tooth position have indicated a number of problems which have only recently been investigated.

For the purpose of this review, cuspid retraction will be used as a vehicle from which to discuss tooth movement and force systems. Its relevancy to this study will become more obvious in later chapters.

2.2. REVIEW of CUSPID RETRACTION PROCEDURES:

As a necessary part of many orthodontic treatment protocols, the bodily retraction or translation of cuspid teeth is desired. Translation of a tooth implies a uniform pressure distribution over one entire aspect of the root surface and adjacent bone. This pressure distribution in turn provides uniform bone resorption which allows the tooth to move bodily.

Ideally, translation is achieved if a force is applied through the centre of resistance of the tooth. However, forces used in fixed appliance orthodontics are usually applied to the tooth via a bracket attached to the crown of the tooth. The fact that the line of action of a force applied at the bracket does not pass through the centre of resistance of the tooth, poses mechanical problems in the attainment of static equilibrium (Croome,1963).

The application of a distal force at the bracket produces the often undesirable side effects of distal tipping and disto-lingual rotation of the crown.

Translation also implies that a tooth should move in a predictable and controlled manner over the time the force system is applied. In reality, it may be that most retracting devices used today, do not produce true bodily movement as such but rather a series of many small tipping and uprighting movements (Hixon E.and Klein P.,1972).

Many investigators have attempted to design and/or manipulate retraction devices and principles in an effort to produce predictable translation (Buchner,1953;

Burstone et al, 1961; Croome,1963; Broussard et al,1964; Burstone, 1966; Davis,1983; Senior,1985; Gjessing,1985; Orton and McDonald,1985; Burstone, 1985).

Farrant(1976) reviewed the various methods available for cuspid retraction. These methods can be divided into friction and frictionless mechanics. Friction or sliding mechanics makes use of a continuous archwire and a variety of auxiliaries to gain the required retraction force level. Some of the auxiliaries include compression or tension coil springs, latex elastics and extraoral devices. Burstone and Koenig (1976) felt that sliding mechanics have two main disadvantages when translatory tooth movements are attempted: 1) the friction produced may prevent tooth movement, and 2) force magnitudes cannot easily be determined, especially in relation to the forces required to overcome friction.

Frictionless mechanics are based upon the use of a loop in either a continuous or segmented archwire. The sectional arch often used for cuspid retraction consists of a rigid rectangular stainless steel wire segment which extends from the mesial of the cuspid bracket to the distal of the attachment on the first permanent molar. A loop is bent into this archwire in the vicinity of the bicuspid extraction site. The shape of the loop varies according to individual requirements, but in general is approximately 6 to 10 millimetres in height. The retracting force comes from opening the loop and securing it to the molar tooth, either by using hooks and ligature wire or cinching the wire distal to the molar attachment.

In their description of a frictionless retraction spring, Burstone and Koenig (1976) described three primary characteristics which need to be assessed if predictable tooth movement is to be expected. Those characteristics were;

1) The moment to force ratio.
2) The force developed by specified activation of the spring, e.g. the force at yield.
3) The rate of decay of the force, i.e. the force deflection ratio.

Burstone and Koenig (1976) suggested that the moment to force ratio " is the most important characteristic of a retraction spring, since it is this ratio that determines the position to which the tooth will move, i.e. whether the tooth will tip or translate." Burstone (1985) felt that the mechanics of a segmental retraction spring demand the placement of anti-tip and anti-rotation bends in the spring. He has devised a technique whereby wires with varying Moduli of Elasticity are used. This technique was aimed at producing ideal moment to force ratios, ideal force levels and low load deflection characteristics, for more predictable tooth movement.

It has been suggested by many authors that predictable tooth movement can only be attained if all uncontrolled variables can be eliminated. Burstone and Pryputniewicz (1979) commented on the need to be able to measure force systems in three dimensions when predicting tooth movement. In earlier studies, Hanau (1917), Strang (1964), and Waters et al. (1975), similarly pointed out the importance of understanding the force characteristics of a given appliance in relation to predictable tooth movement.

2.3. EVALUATION of FACTORS EFFECTING CUSPID RETRACTION:

The quantification of forces developed by various orthodontic devices has been studied by many reseachers for most of this century. The search for a precise force level required for ideal tooth movement was probably first considered by Schwartz (1932). He suggested that force levels in excess of the capillary blood pressure of the periodontal ligament (i.e. approximately 20-26 grams per square centimetre) should be avoided. Schwartz felt there was an optimum force level which should be used to produce tooth movement. The concept of optimum force seems to imply that a specific tooth movement was predictable. Interestingly, Weinstein (1967) found that forces as low as 2 grams were capable of producing tooth movement. He was investigating the proposal of Smith and Storey (1952), that a threshold value for force existed, below which tooth movement did not occur. An optimal force for distal translation means that a given force produces an equal pressure between the root and the alveolar bone along the entire length of the root. It was expected that this force would produce maximum tooth movement with minimal tissue trauma. Individual biologic variability, such as length and shape of the root, meant that an optimum force value would probably vary from individual to individual and from tooth to tooth (Nikolai, 1975).

The literature reveals an extremely large range of force levels deemed suitable for cuspid translation. Storey and Smith (1952) concluded that 150-250g was required for bodily movement of the cuspid teeth. Reitan (1957) felt that 150g-200g was required for continuous bodily movement of the maxillary cuspid teeth, and 100g-150g for the mandibular cuspids. Reitan also commented that the necessary force would vary according to the length of the root.

Some appliances produced very high force levels. Halderson et al. (1953) noted that a 9mm vertical loop in rectangular wire was capable of producing 800g of force for a 1mm activation. Hixon (1969) reported that the Strang clock spring appliance was capable of producing a force level of 1500g. Sleichter (1971) found that a Stoner closing loop was capable of producing force levels of between 1200g-1500g. Bench et al. (1978) noted that a vertical loop in rectangular wire (018"x 022") could produce 800g-1000g force level in the retraction of cuspid teeth. No activation measurement was given. Ricketts (1979), suggested that forces in the range of 115 g to 150 g be used for the retraction of cuspids.

Since the 1950's, it has generally been accepted that bodily cuspid retraction could be achieved using light forces. Reitan (1960) suggested that a force level of 130g was sufficient for bodily movement of the cuspid. Burstone (1961) suggested that not only was the force level a major factor in producing optimum tooth movement but that a low load deflection ratio would also be a factor in producing specific tooth movements. Paulson et al. (1970), reported that maxillary cuspids could be retracted approximately 1 millimetre per month using a 50g to 75g force on a continuous archwire. The retracting force was achieved by using elastics attached to sliding hooks mesial to the cuspids.

Boester and Johnston (1974) found that force levels of 150g, 240g, and 330g all produced similar movement during cuspid retraction. They also found that a force of 60g produced significantly less movement. Andrews (1975) suggested that 600g be considered ideal for retraction of cuspid teeth.

Thurow (1982) suggested that most teeth would respond favorably to a force in the 25g-100g range. He felt that cuspids required the upper force level due to the larger root area.

The significant point here is that there was not total agreement amongst authors as to the most desirable force level required to achieve cuspid retraction. It seemed that the range of values that have been used for this type of tooth movement may vary by as much as 1000%. Biologic variables such as anatomical, biochemical and histological differences could play a role in the lack of agreement between authors, however, as Levin (1985) concludes,"the lack of accuracy in establishing the force values actually applied, may have contributed to this lack of agreement over optimal force". This tends to imply that sound technology was not available to accurately measure force systems delivered by specific orthodontic appliances.

The significance of the moment to force ratio in achieving specific tooth movements has also received much attention in both past and current research.

Kusy and Tulloch (1986), described observed tooth movement as being dependent on two components of the force system. The force itself translates the tooth in a direction parallel to the line of force. The resultant moment rotates the tooth around the centre of resistance.

Burstone and Pryputniewicz (1980), Christiansen and Burstone (1969), and Yoshikawa (1981) all concluded that the type of movement exhibited by a tooth was determined by the ratio between the magnitude of the couple and the force applied at the bracket. Smith and Burstone (1984) stated that small changes in this ratio could have major effects on observed clinical tooth movement. Chaconas et al. (1974) also noted that the most critical part in the ability of a spring to produce translation was the moment to force ratio, not the absolute value of each.

Yang and Baldwin (1974) investigated various springs in an effort to define an ideal retraction device. Springs with varying numbers of helices were compared with an open vertical loop. Although the vertical loop had a constant moment to force ratio throughout its activations, the loop with helices placed gave a lower load deflection ratio, and possibly a higher moment to force ratio. They implied that the latter would better enable the clinician to control root and crown movement during retraction. Very little mention was made regarding the obvious flexibility of these loops, especially in respect to control in the bucco-lingual dimension. This would seem to have important connotations regarding control of disto-lingual rotations during retraction, and in the effect of masticatory forces on the loop during deactivation.

Biological variables have been implicated as a major factor in determining rates of tooth movement. Burstone (1985) quotes;

"During study of the rate of tooth movement one is impressed with the great variation in response to relatively identical force systems".

He explains that three phases of tooth movement occur, i.e. the initial, lag and post lag phases, and that the rate of tooth movement, as a function of force, was different for the various stages. This information tends to imply that the observed rate of tooth movement was directly related to the cellular components of the system, which were ultimately dependent upon time and stress magnitude. Burstone does acknowledge however that at lower force levels, subsequent increases would enhance the rate of tooth movement. At higher magnitudes however, increases were more likely to delay tooth movement due to hyalinization of the periodontal ligament.

2.4. FORCE MAGNITUDE--TOOTH MOVEMENT CORRELATION STUDIES:

The following is a review of studies in which an attempt was made to correlate clinical tooth movement, force magnitude and time. It should be remembered that the majority of these studies were designed to investigate the existence of an exact force range for specific tooth movements. It appears that prior to 1950 there were no tooth translation studies in which an attempt was made to control the variables of force, time and space. In fact Oppenheim (1944) and Gottlieb (1946) expressed the commonly held belief that it was pointless to study the effect of force quantitatively because of the wide variation in the biological response of different patients.

Storey and Smith (1952), were probably the first researchers to attempt to correlate tooth movement with known force systems. They used patients who required the retraction of lower cuspid teeth into first bicuspid extraction sites. Retraction springs were designed to deliver either heavy (400g-600g) or light

(175g- 300g) forces. These loads were precalibrated for each spring using load deflection curves. Reference marks were placed on the appliances corresponding to the deflections for various known loads. A heavy spring was placed on one side of the mouth and a light spring on the other. Anchor units consisted of the second bicuspid and first molar teeth. To compare the amount of tooth movement between each side, a fixed point was created in the upper jaw using a detachable arm which fitted into a buccal tube soldered to a rectangular archwire on the upper teeth. Tooth positional changes and changes in the deflection of the springs were recorded weekly. The measurements were regarded as being accurate to 0.25 millimetre. The load developed by the spring could be determined at any given time from the load deflection curve.

From this study, Storey and Smith concluded that there was an optimum range of force values which should be used to produce a maximum rate of movement of the cuspid teeth with only negligible movement of the anchor teeth. They found that this range of force extends from 150g to 250g. Interestingly they also found that the cuspid teeth always moved by tipping around the apical one third of the root. When forces were used within this optimum range it was found that the cuspid teeth moved approximately 0.1 millimetres per day. This was considered to be the maximal rate of tooth movement. Radiographs were used to determine the amount of cuspid tooth movement.

In contrast to the views of Oppenheim and Gottlieb, Storey and Smith believed that when an attempt was made to standardize techniques and control factors such as force magnitude and time, the response of teeth was similar for all patients.

Lee (1965), used experimental apparatus similar to that used by Storey and Smith in a study of patients requiring maxillary cuspid retraction. A fixed point on the mandibular archwire was used as a reference point. A helical torsion spring was used which produced about 450g of force. Within the same patient, one cuspid was moved bodily and the other tipped. Measurements were accurate to 0.1 millimetre. Lee found that the optimum force level for maximum tooth movement fell between 150g and 260g. After further work, he actually felt there was no significant difference in the rate of tooth movement between either side. He concluded that true bodily movement was not occurring but rather a jiggling motion of the tooth.

As part of a larger study Utley (1968), using cats as subjects, compared the distance and rate of tooth movement using orthodontic forces of different magnitudes. The forces used were determined by precalibrating stretched latex elastics and ranged from 40g to 560g. Tooth movement calculations were made by comparing and superimposing radiographic tracings of right and left maxillary jaw sections. They concluded that the maxillary cuspids within the same animal moved equal distances regardless of force magnitude. They also concluded that the rates of cuspid movement were not related to force magnitudes.

In a study investigating the plausibility of optimum force, Hixon et al. (1969) used precalibrated retraction springs to monitor force levels clinically. Forces were varied from 64g to 1515g. Force levels were measured twice weekly. Three tantalum implants were placed on each side of the maxilla and mandible to provide fixed reference points from which changes in tooth position could be measured. To ascertain tooth positional changes, a vertical line was scribed through anatomical landmarks on the teeth, such as the pulp chamber, from an initial radiograph. Superimposition of subsequent radiographs using the tantalum implants allowed detection of changes in tooth position. Plaster casts were also made bi-weekly to further assess cuspid position. They found that all of the cuspid teeth and many of the posterior teeth had tipped into the extraction site once applied forces exceeded 1000g. It was also evident that the cuspid teeth rotated disto-lingually. These results were in direct contrast to their initial intention of bodily movement. They concluded that the rotary and tipping components of canine retraction are inherently large and that in order to overcome these tendencies large compensatory bends are required.

Hixon et al. felt they had uncovered many unanswered questions concerning force and rate of tooth movement. These included;

(i) What was the magnitude of variation between patients?

(ii) Were there differences in response which were related to age?

(iii) Were there differences between intermittent and continuous forces?

(iv) Was there a difference between bodily movement and tipping followed by uprighting?

Most importantly however they stated;

"Before any of these problems can be resolved, mechanical variables must first be controlled so that the biological variables can be separated for study".

In an effort to further investigate the relationship between force and the rate of tooth movement, Hixon et al. (1970) attempted to develop a mechanical system which would allow only translation.

In this study, six children who required cuspid retraction were used. Rigid .045 inch tubes were soldered to the buccal and lingual aspects of the anchor units. Soldered wires from the cuspid attachments would then be free to slide through the tubes during retraction, and ultimately prevent tipping. Elastic traction used on both the buccal and lingual aspects reduced the rotation problem, however the apparatus was unable to eliminate tipping of the teeth completely. The method used for assessment of tooth positional changes was similar to that used in their 1969 study. The results of this study (1970) indicated that the flexion of most arch wires would allow tipping to occur once a distalizing force was applied. They also noticed that tooth movement occurred in two distinct stages. An initial period of movement when the periodontal ligament was compressed, followed by a period of constant tooth movement two weeks later. Using the data in which translation of the cuspid teeth was actually achieved, they concluded that variations in the initiation as well as the overall rate of tooth movement was probably not due to the magnitude of the force but rather the variation in metabolic response.

In a clinical study involving cuspid retraction using segmental loops, Sleichter (1971) attempted to compare tooth movement using light (150g to 200g) and heavy (1200g to 1500g) forces. Tooth movement was assessed using lateral cephalographs and periapical radiographs. Sleichter commented on the many difficulties encountered when attempting to measure the distance between teeth which were in the process of tipping and rotating. However he did conclude that gross tipping of the teeth was in evidence, especially in the mandibular arch. He also noted that a reduction in space of up to 0.5 millimetre per week could be anticipated with any force from 150g to 1500g. Sleichter did concede that it seemed unnecessary to use heavy forces if light forces produced an equal rate of tooth movement.

Pryputniewicz and Burstone (1979) used holography to study the effect of time and force magnitude on orthodontic tooth movement. Their study however looked at loading the maxillary central incisors of three adult subjects with known force systems, and so was basically designed to investigate minute displacements in tooth position over a short time. Although this technique is not fully developed, it does have the potential to offer many valuable improvements in this field of study. It is a non-invasive technique, highly accurate and measurements can be made in three dimensions. It does appear however that it is not suitable for the measurement of large tooth displacements.

Paulson et al. (1970) reported that one of the major problems to be encountered in tooth movement studies was the lack of stable landmarks. These researchers investigated the use of laminography to assess tooth movement. Six patients requiring maxillary cuspid retraction were used. Plaster models and a conventional lateral cephalogram were used to determine the vertical plane through which the laminagraphs would be taken. Two laminagraphs were taken, one at the beginning of treatment and the other after the teeth were retracted. Superimposition of the laminagraphs was achieved using anatomic landmarks such as borders of the maxillary sinus and the maxillary tuberosity. Changes in tooth position were recorded to the nearest 0.5 millimetre. No attempt was made to document the angular changes of the teeth during retraction. They used a continuous archwire (.016 inch stainless steel) and latex elastics which produced force values of between 50g and 75g. They found there was a difference in the amount of cuspid movement of between 2.5 millimetres and 6.0 millimetres over a time period of between 2.5 months and 8.25 months. From these results they concluded that the observed variation was due to individual biologic differences.

In a study investigating the translation of premolars in dogs, Fortin (1971) concluded that true bodily movement was possible if the appropriate moment to force ratio is applied to the tooth. He also concluded from histologic evidence that a force of 450g should be considered optimal for human cuspid translation. Fortin felt that this 450g force should be considered a light force, and, to permit maximum tooth movement, the appliance should not be reactivated in less than 6 to 8 weeks. His results also suggested that younger patients would show a greater response than adults.

Mitchell et al. (1973) investigated the concept of differential force using domestic cats. They used a fixed appliance which, when activated, would produce translation. Tooth positional changes were assessed using plaster casts and comparing these with the actual fixed specimens after treatment. A reference point was determined geometrically on the plaster casts. They concluded that the effects of individual variation, age, constancy of forces and the type of tooth movement are just a few factors which require assessment before magnitudes of forces can be considered as a single factor in determining tooth movement.

In a study investigating tooth movement and frictional mechanics, Huffman and Way (1983) devised a method to accurately measure the changes in tooth position. Both upper and lower cuspids were retracted using a force of 200g along a round stainless steel continuous archwire. An acrylic jig with horizontal and vertical spurs was fitted so that the incisors were capped and the tip of the second bicuspids was lightly covered with acrylic.

At each visit the jig was fitted to the patients teeth to assess cuspid position. Distal movement was determined by comparing the distal wing of the cuspid bracket with the vertical spurs. Tipping of the cuspid was assessed by placing a specially machined metal section with a vertical scribed line, into the cuspid bracket. A small "T" bevel was then lined up with the horizontal spurs on the jig and the angle made with the scribed line recorded. Interestingly, they found that at no time during the treatment was there any difficulty fitting the jigs, from which they implied minimal anchorage loss. Measurements of changes in tooth position were taken at two week intervals over a ten week period.

Although the aim of this study was to compare the control offered by .016inch and .020 inch stainless steel archwires in the retraction of cuspid teeth, the method of assessing tooth position is of particular interest for a number of reasons. It obviates the need for serial cephalometric radiographs, which are not only of questionable value in accurately assessing tooth position but also expose the patient to unnecessary radiation. In addition to this, the use of the acrylic jig acts as a reasonably stable reference plane upon which to assess tooth positional changes and simultaneously can aid in assessing anchorage loss.

2.5. A REVIEW of TECHNIQUES used to ASSESS TOOTH POSITION:

As early as 1924, methods were being developed to measure tooth position in three dimensions. Simons (1924) developed the symmetrograph which used three scales set at right angles to each other to define points on the occlusal surfaces of teeth. Various modifications were made to this technique over the following years until 1972 when Van Der Linden et al. developed the Optocom which was basically a travelling microscope with sighting lines to define the position of a given point. The data collected from this instrument was transmitted to a converter and ultimately to a teletype to be punched out on paper tape. It should be noted that in this technique, the first two dimensions were measured with the cast in the same position. However to measure the third dimension the cast must be reoriented, and this was a possible source of error.

Various other techniques such a stereophotogrammetry (Berkowitz and Pruzansky, 1968) and as previously mentioned, holography (Pryputniewicz and Burstone, 1979) have also been investigated.

The use of a new instrument called a Reflex Metrograph was assessed by Takada et al (1983) for its applicability in the three-dimensional assessment of dental casts. By using a semi-reflecting mirror and a light source carried on a three-dimensional slide system, marked points on a dental cast could be identified and their coordinates digitized for sampling by a computer.

Using a light source of 0.3 millimetres in diameter, and similarly sized marks on the measured teeth, Takada and co workers found that specific points could be identified to an accuracy of plus or minus 0.1 millimetre using the Reflex Metrograph.

Jones et al. (1980), stressed the difficulty in obtaining a stable base to act as a frame of reference when measuring changes in tooth position. They also noted that, if a change in tooth position was to be measured, then exactly the same points would have to be recorded on both plaster casts, relative to a common frame of reference. They suggested using precise anatomic detail on some teeth and/or using small acrylic templates with holes to identify the same position on a tooth on different casts. Jones and co-workers also felt that relating measurements from plaster models to those from radiographs in an effort to produce a reference plane had limited applications.

More recently, Richmond (1987) assessed the use of the Reflex Metrograph in recording the three-dimensional relationship of the teeth with the dental arches. Although no attempt was made to describe a technique to measure tooth positional changes, it was interesting to note that Richmond found the error of this instrument to be less than 0.27 millimetre.

2.6. CONCLUSIONS:

Although it is apparent that some research has been undertaken to identify ideal mechanics in relation to specific tooth movement, complete understanding of the principles involved can only be gained if a three-dimensional assessment is made.

Similarly, true translation of a tooth can only be assessed if data is collected regarding that movement in the three planes of space. It is obvious from the literature that a great range of force values are thought suitable for cuspid retraction. It is also apparent that very little correlation exists between observed rates of tooth movement and force magnitude. This has led researchers such as Burstone (1985) to conclude that observed variations in tooth movement as a consequence of similar force systems are due to individual biologic variability.

If one takes into account that 1) most relevant studies are basically two-dimensional and 2) most studies used seemingly inadequate methods for assessing force characteristics of a given appliance, then it is not unreasonable to conclude that the great variations seen in studies of this type could be due more to technique inadequacies than to biological variation.

Quinn and Yoshikawa (1985) noted there were four major problems which complicated studies of force magnitude and tooth movement. They were;

(a) The investigator's inability to control the type of tooth movement caused by their appliances.

(b) The possibility of biasing the data if it is not collected in coordination with appliance activation. This bias is due to the non-linear, time-dependent course of tooth movement.

(c) In any collection of data regarding tooth positional changes, large measurement errors are present.

(d) The large variation in rate of tooth movement has made statistically significant findings difficult to interpret.

Techniques now available may aid the researcher in attempting to control some of the variables in this type of study. The quantification of the three-dimensional force and moment characteristics of a given appliance can now be achieved, Paquien (1978) and Lack (1980).

The recent development of the Reflex Metrograph has made it possible to accurately assess the three-dimensional position of specific teeth, but only _in vitro_. Some problems still exist, especially in regard to the establishment of stable reference planes and the orientation of subsequent casts in a longitudinal study.

It does seem that, before definitive statements can be made concerning tooth movement and its relation to force systems, more stringent controls and more accurate data collection must be placed on as many accessible variables as possible.

The purpose of the present study was to develop and assess techniques whereby the relationship between known force systems and resultant tooth movement could be investigated.

3. MATERIALS and METHODS.

3.1. INTRODUCTION:

To investigate the tooth movement resulting from orthodontic forces a technique was developed which combines _in vivo_ and _in vitro_ phases. In the _in vivo_ phase, tooth movements are determined and, in the _in vitro_ phase, forces and moments delivered by the orthodontic appliance are determined.

For this study, a small sample (5) of patients was selected who required the retraction of at least one maxillary cuspid tooth. The aim of the clinical part of the study was to achieve translation or bodily retraction of the cuspid teeth. Segmental arches with loops were designed and applied in each case. Each loop used in each patient was duplicated and the duplicate was activated _in vitro_, in a method similar to that being used in the mouth. Thus, from the duplicate loops it was possible to determine the initial forces and moments delivered by the _in vivo_ loop.

This information was then combined with the measured changes in tooth position recorded over a period of time. It was hoped that some information would be gained regarding the predictability of tooth movement in response to known force systems.

As a consequence of the foregoing, this chapter is divided into the in vivo and in vitro sections. However, some overlap in the procedures is necessary to adequately describe the procedures in the technique.

3.2. DESCRIPTION of IN VIVO PHASE:

Five patients were selected for this study through normal clinical screening procedures at the University of Manitoba, Faculty of Dentistry, Graduate Orthodontic programme. Two of the patients were ultimately not used in the study due to experimentally significant anchorage loss in one and time constraints in the other. These patients were to undergo typical multibanded orthodontic treatment but were specially selected because maxillary cuspid retraction could be done as the first step in their treatment. The retraction of maxillary cuspid teeth was selected in this study for a number of reasons;

1. The large tooth movements such as that observed in cuspid retraction would enable detection and measurement of tooth positional changes more easily, and simultaneously reduce the effect of errors due to tooth mobility and measurement procedures.

2. Many patients require maxillary cuspid retraction as part of a routine treatment protocol.

3. Cuspid retraction using segmental mechanics is a mechanically determinate system.

The appliances used for this study were "A" Company stainless steel bands on the bicuspids and molars, and Ormco brackets on the cuspids. The bands and brackets were in an .018 x .025 inch setup with "pretorqued slots". In order to provide maximum anchorage of the posterior segments throughout the study, a Nance holding appliance was placed in each of the five patients. In addition, the bicuspids and molars were joined using a passive rectangular wire segment (.017 X .025 inch stainless steel) on each side. Two of the patients also had their second permanent molars banded and incorporated into the anchorage unit.

Once the anchorage units were established, the patients were left for a minimum of four weeks to allow for some biologic stabilization of the anchor teeth.

The selection of specific loops for each case was made after considering certain in vivo and in vitro factors. The in vitro criteria which aided in loop selection will be considered in a later section. For this study vertical and "L" loops were used.

The length of the loops was determined according to the position of the height of the centre of resistance of the cuspid tooth. As described in the literature review, it is desirable to have a force acting through the centre of resistance of a tooth if translatory movement is to be expected. The height of the centre of resistance was determined by estimating the length of the cuspid tooth from lateral cephalometric radiographs and knowing that the centre of resistance of a single rooted tooth is thought to be approximately one third to one half of the root length apical to the alveolar crest (Burstone and Pryputniewicz, 1980). The height of the loop must also take into account the anatomic considerations of the patient, such as vestibular depth and prominence of cuspid eminence. The actual loop types and dimensions used for each patient can be seen in Figure 3.1. All loops were constructed of .018 X .018 inch stainless steel wire (Ormco). Note from Fig.3.1 that only the loops from three patients are described.

At the time of loop construction, insertion and activation, a series of steps were followed to enable the in vitro part of the study to continue:

(i) After the specific loop design was decided for each patient, a template was drawn on metric graph paper. Loops were then bent and accurately adapted to this two-dimensional template. Two identical loops were made for each tooth. They are referred to as the master and duplicate loops. Both these loops were then adapted accurately at the chairside, so that they fitted the molar auxiliary tube and the cuspid bracket passively, and simultaneously met patient comfort requirements. The master loop was used for the in vivo part of the study, and the duplicate loop was identified and stored. To activate the master loop, a ligature wire was tied around the molar attachment and ligated to a crimped hook or soldered post, placed immediately distal to the loop. Figures 3.2 and 3.3, represent a typical vertical loop used in this study.

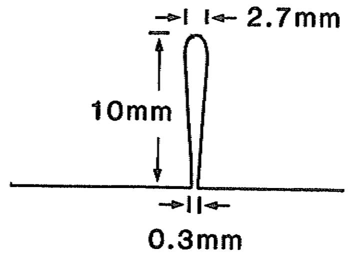
No anti-rotation or anti-tipping bends were placed in the arch segments at any time, to ensure that only the force and moment characteristics generated from a distal activation of the loop were recorded.

(ii) As part of this study it was necessary to develop a template of the in vivo tooth positions which would enable transfer of these positions to an in vitro situation.

The following are graphic representations of the loops used in the patients selected for this study.

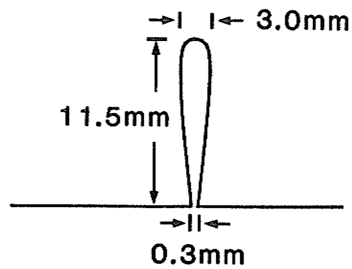
A. <u>Patient JH</u>

Open Vertical Loop



B. <u>Patient CK</u>

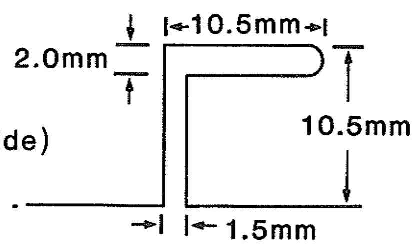
Open Vertical Loop



C. <u>Patient TW</u>

L Loops

(Right side)



(Left side)

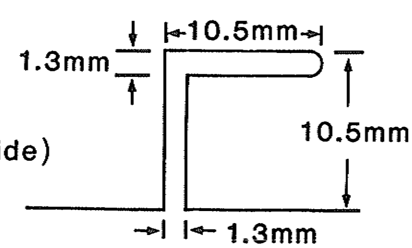


Figure 3.1

Although this template is constructed at chairside, it will be described more fully in the next section.

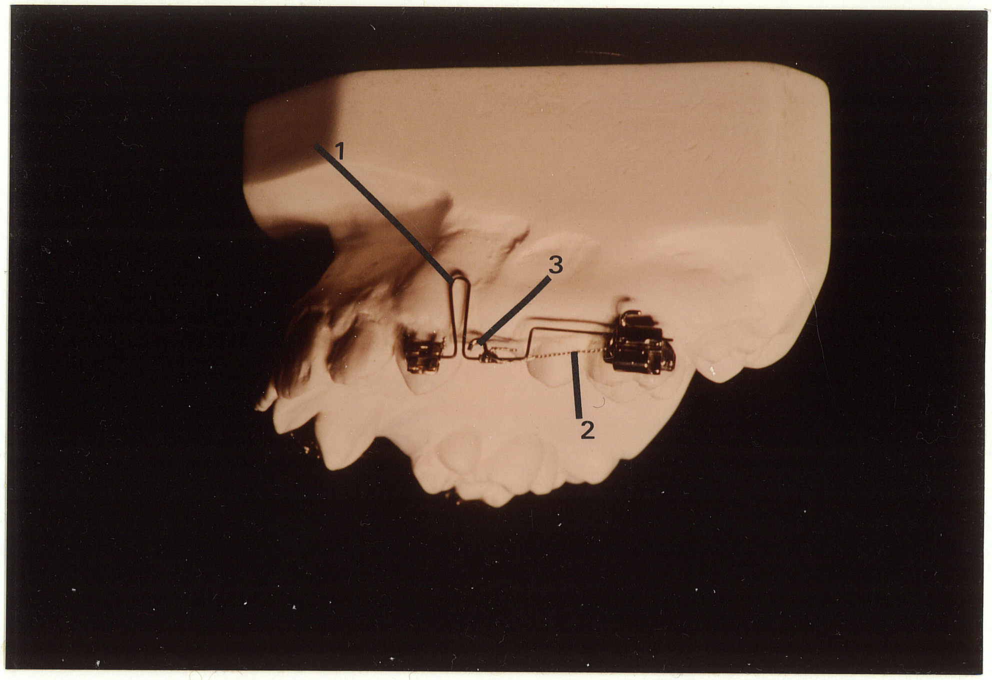
(iii) Alginate impressions (Jeltrate Plus, Caulk Dentsply) were taken at every visit and casts poured in orthodontic plaster (Columbus Dental). These casts were carefully identified and stored.

3.3. DESCRIPTION of IN VITRO PHASE:

As described earlier, two basic designs of loops were considered for this study, the vertical and "L" loop. In the context of this study it was felt desirable for the loops to have the following characteristics;

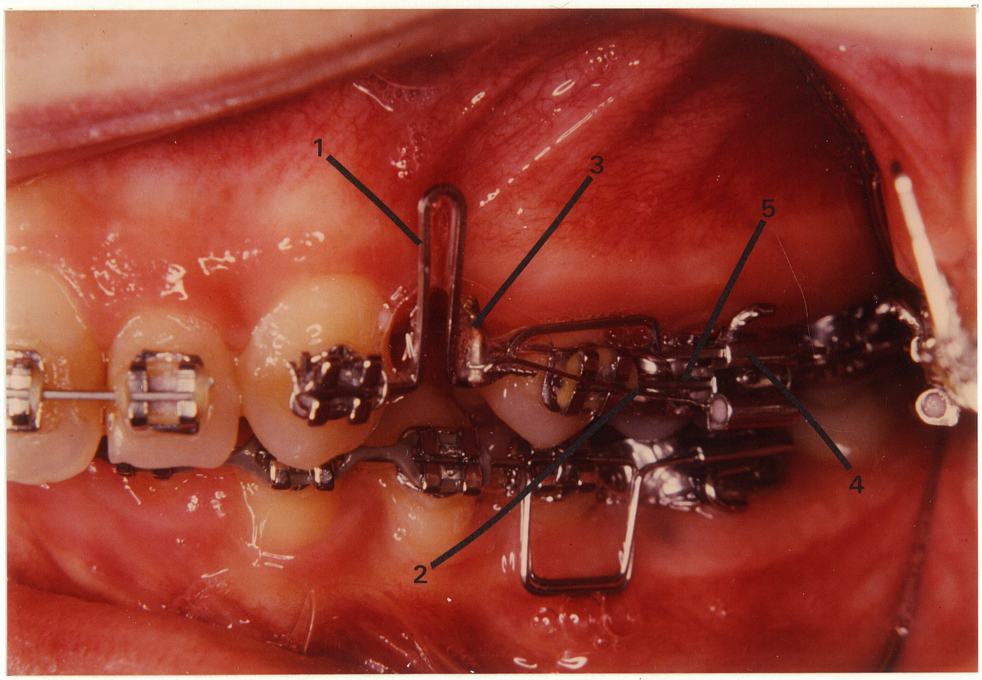
(a) The loop should have a height approaching the height of the centre of resistance of the cuspid tooth wherever possible. The estimation of this height has been described earlier.

(b) The loop should offer a retraction force value between 100g and 250g for a concomitant loop activation of between 1 millimetre and 2 millimetres.



1. Passive vertical loop.
2. Tie back ligature.
3. Crimped tie back hook.

Figure. 3.2. View of typical vertical loop *in vitro*.



1. Active vertical loop.
2. Tie back ligature.
3. Soldered tie back hook.
4. Auxiliary tube.
5. Passive wire anchor segment.

Figure 3.3. View of typical vertical loop *in vivo*.

(c) The loop should offer a constant moment to force ratio. For this reason, and in addition to those reasons described earlier, the loops were made without placement of compensating bends.

(d) It is desirable that the loop should be rigid enough in all dimensions to resist the effects of mastication and other patient interferences. This rigidity will be considered later, when assessing the ability of the loop to resist the expected disto- lingual rotatory effect often observed in cuspid teeth during retraction.

(e) The ends of the loop should fit the brackets and tubes as accurately as possible. This precision of fit was considered desirable, as effects produced by activation of the loop would be accurately transferred to the teeth.

(f) It should be possible for the loop to be activated accurately. This is required so that activation duplication can be achieved in both parts of the study. For the purposes of this study, a Boley gauge was used to measure the amount of loop activation. The position between the legs of the loop at their closest point was used in each case to measure the amount of activation. To standardise this part of the technique, a set 1mm activation was used in all but a few cases.

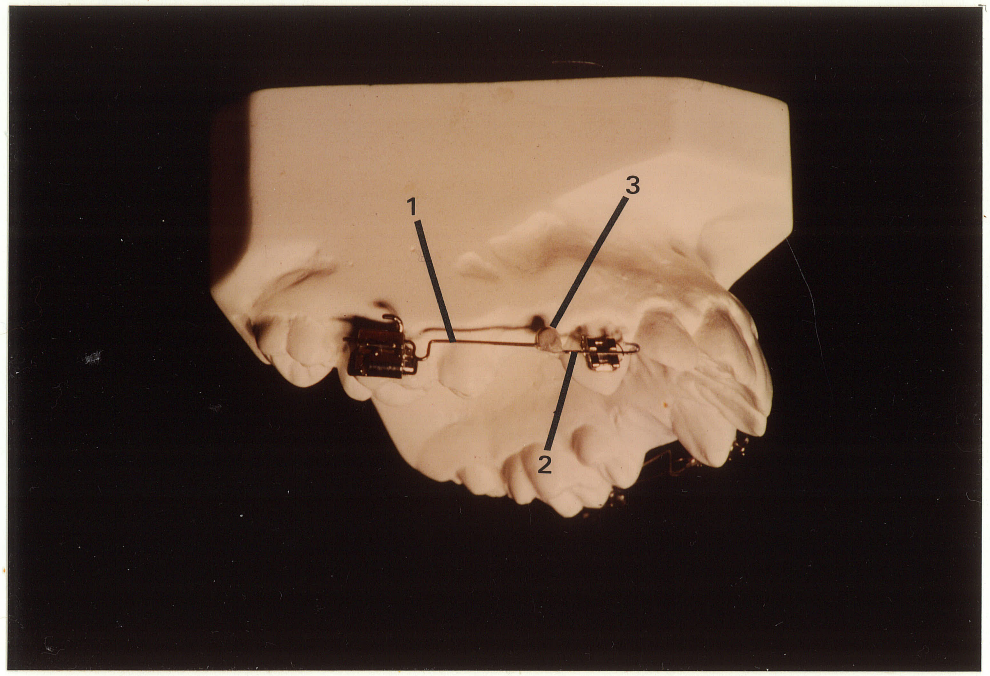
The moment to force ratio of a loop plays an important role in determining the type of tooth movement that will result due to activation of the loop. In order to produce translation, a simple distalizing force should act at the bracket. A separate study was undertaken to investigate two important factors in loop design and placement which may help to idealise the moment to force ratio required for a specific tooth movement, such as translation. This aspect of the study was based upon the work of Lack (1980), and the results aided in the assessment of loop type, design, interbracket position and degree of activation required for each patient in order to produce cuspid translation. The procedures and results of this study are described in Appendix A, but essentially two parameters were explored, namely;

1. Varying the height of the loop in relation to the height of the centre of resistance of the tooth and,
2. Varying the interbracket positional placement of the loop.

The results indicated that a more favorable moment to force ratio for our desired objective could be achieved when the apex of the loop was extended apically to the centre of resistance of the tooth, and when it was positioned immediately distal to the cuspid bracket. These requirements could not be met in regard to loop height, due to anatomical restrictions in the patient. However with this information, the moment to force ratio could be identified and made as close to the ideal as possible.

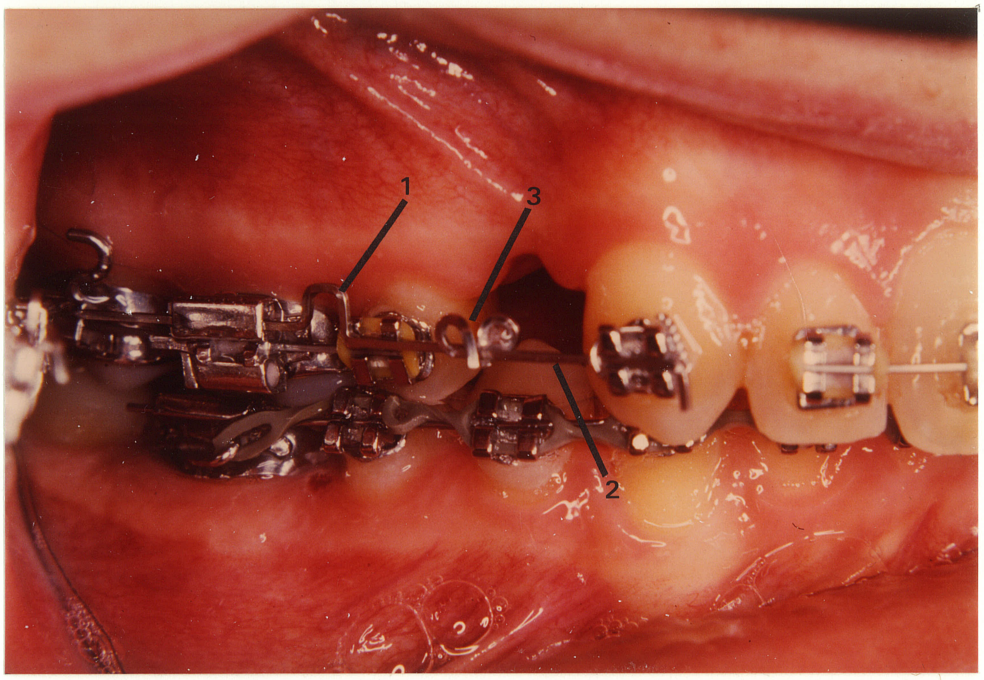
3.4 IN VITRO SIMULATION of TOOTH POSITION:

In order to simulate in vivo tooth positions on the measuring apparatus, a technique was developed to produce a passive template of the actual in vivo bracket positions, which could be transferred to the measuring apparatus. At each visit, two separate sections of .018 X .018 inch stainless steel wire were adapted, one to fit the cuspid bracket and the other the auxiliary molar tube. A small half-helix was bent into the anterior section of wire, and placed against the mesial wing of the cuspid bracket prior to ligation. This step produced an accurate stop, which not only prevented the anterior section of wire from sliding distally, but allowed the ligature wire to pass freely around the mesial wing of the bracket. The anterior wire section was ligated to the cuspid bracket, to prevent that section of wire from sliding mesially. Thus the position of the cuspid bracket was accurately related to the wire. A small gable bend was placed in the posterior section of wire, mesial to and against the molar tube. This was done to prevent that piece of wire from sliding distally through the molar tube, as well as accurately locating the molar attachment to the posterior section of wire. In the region of the first bicuspid extraction site, small helices were placed in the ends of both sections of wire. These helices were approximated closely, with care being taken to ensure passivity, i.e. no contact between the two sections of wire. Finally, a rapid curing acrylic resin was applied to the wires in the region of the helices, to join the two sections of wire. Fig 3.4, offers a schematic representation of the foregoing procedures. Fig. 3.5, shows a typical wire template in the <u>in vivo</u> situation.



1. Posterior section of passive template.
2. Anterior section of passive template.
3. Helices joined with acrylic resin.

Figure 3.4. View of passive wire template *in vitro*.



1. Posterior section of passive template.
2. Anterior section of passive template.
3. Helices prior to joining with acrylic resin.

Figure 3.5. View of passive wire template in vivo.

After approximately 10 minutes, the joined sections of wire were carefully removed from the patient's mouth. Prior to removal, the template, was checked to ensure the correct tooth relationships had been recorded. This passive wire template was identified and then taken to the laboratory, where it was used to position the replicas of the bracket and molar tube on the measuring apparatus. This procedure was simplified by using a specially designed frame which could fit over the existing measuring apparatus (see Appendix B).

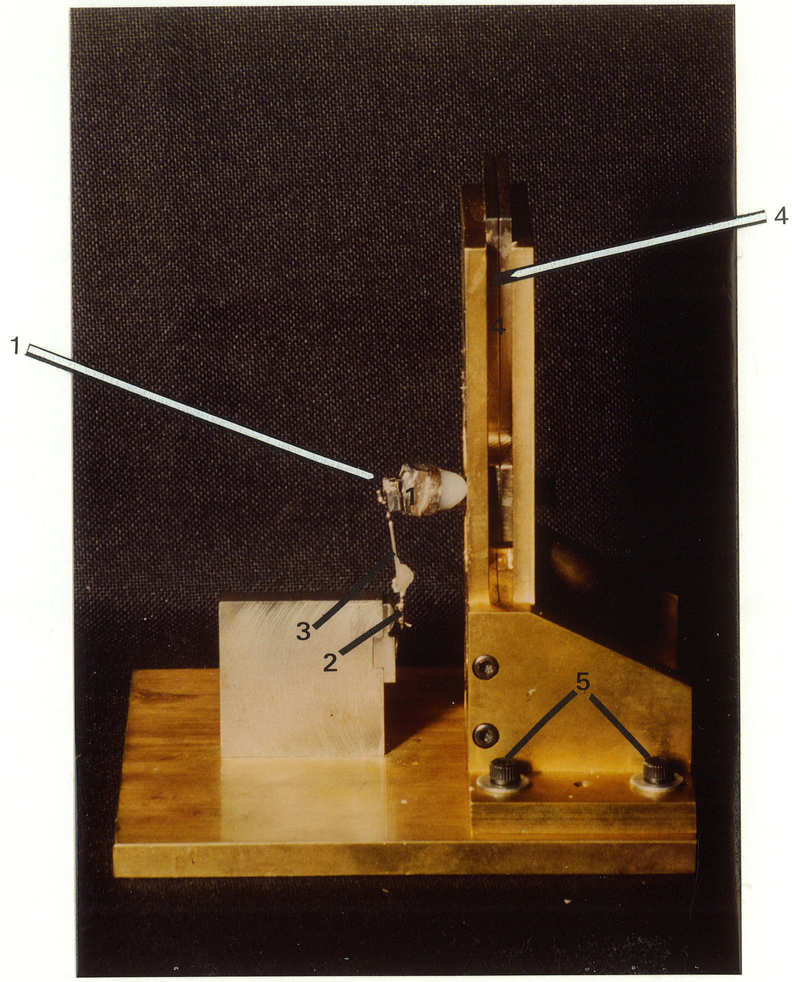
The piece of apparatus representing the cuspid tooth was positioned in the frame, in the exact relative position it would eventually take on the measuring apparatus. An .018 X .025 inch bracket was bonded to this machine tooth. The molar machine "tooth" was represented by a screw with a removable machined end. The machined end was contoured to approximate the buccal surface of an upper first molar tooth. This machine "tooth" can be adjusted in three dimensions.

Then the passive template was tied into the cuspid bracket arrangement, which was securely fixed to the frame. The machined end of the molar "tooth" was then bonded to the adjustable screw, in such a way that it took the alignment and orientation of the template. Once the epoxy resin was completely set, and the screw secured in position, an .018 X .025 inch bondable tube-slot assembly was carefully slid onto the free end of the template wire down to the position of the molar gable bend. The molar tube assembly was then bonded to the now firmly attached machined end on the adjustment screw. In this manner, the two bonded brackets would now replicate the relative bracket positions, in vivo. This assembly was then transferred to the original measuring apparatus. Figs 3.6, 3.7 and 3.8 photographically represent the above mentioned steps.

Once the above arrangement was secured on the measuring machine, the passive wire template was removed and the duplicate loop secured to the in vitro "teeth", in the same manner as that used clinically.

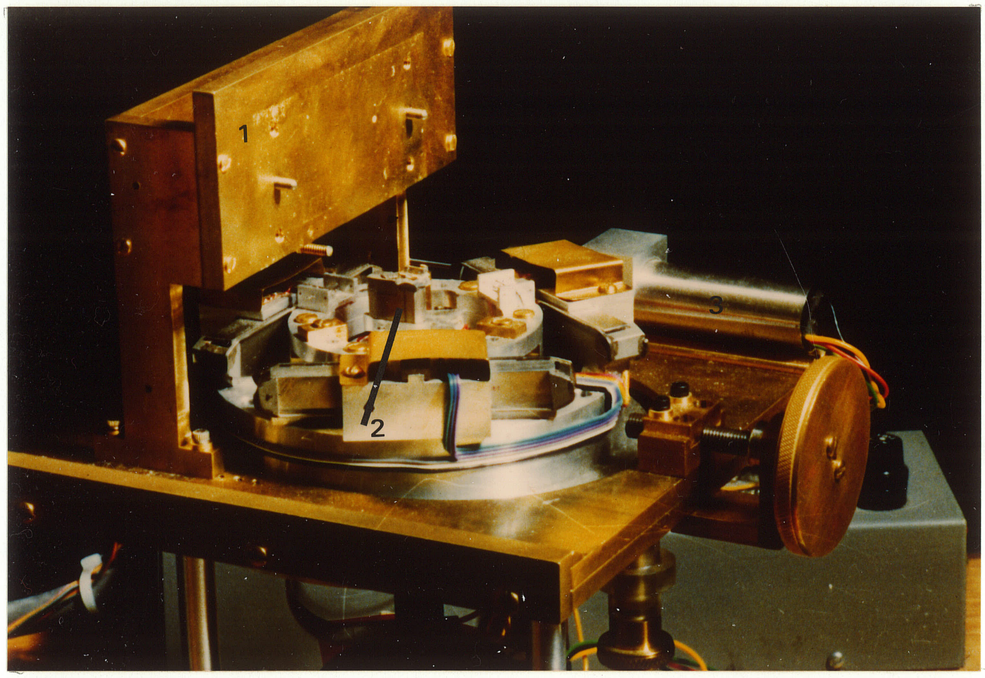
The aforementioned steps were repeated for every activation of each loop, and a new wire template was made at each clinical visit. This technique permitted the in vitro apparatus to be repositioned in a way that represented the changed tooth positions. The duplicate loop was then tied into the machine and activated in a manner which simulated the in vivo procedure.

Once the duplicate loop was tied in and a zero reading taken on the machine, it was activated to exactly the same degree as that used in vivo. As previously mentioned, this can be assumed to be 1mm, unless otherwise stated.



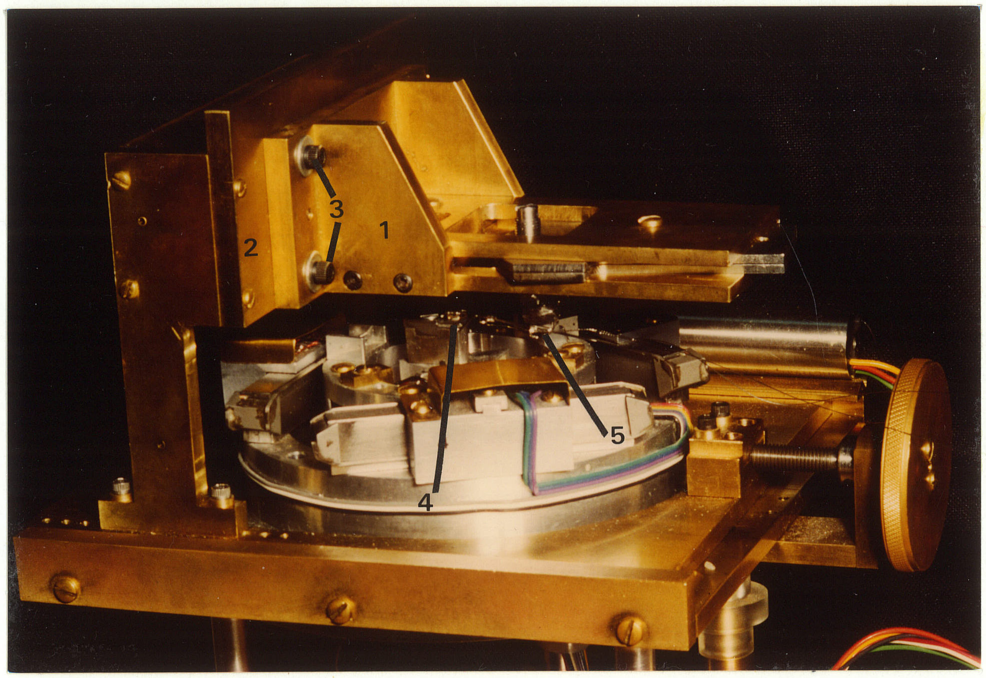
1. Molar tube bonded to adjustable screw.
2. Cuspid bracket bonded to removable metal section.
3. Template representing <u>in vivo</u> bracket positions.
4. Adjustable metal plates.
5. Securing screws.

Figure 3.6. Bracket positioning transfer jig.



1. Frame to secure transfer jig.
2. Centre of measuring instrument.
3. Linear voltage displacement transducer.

Figure 3.7. Measuring apparatus with modified frame.



1. Transfer jig.
2. Support frame.
3. Securing screws.
4. Cuspid bracket secured to centre of measuring instrument.
5. Molar tube.

Figure 3.8. Transfer jig attached to frame on measuring apparatus.

Data was then collected regarding the force and moment characteristics for that loop, for the specific activation and tooth relationships.

To quantify the repeatability in the duplication of loops, a separate study was carried out. When determining the types of loops to be used in this study it was desired that one requirement be that they completely deactivate after a reasonable period of time i.e. about four weeks. Also as mentioned earlier, it was desired that the loops had a constant moment to force ratio. In order to evaluate the operator's ability to duplicate loops, ten vertical and ten "L" loops were tested. Each set of loops was carefully bent to a drawn template with typical <u>in vivo</u> dimensions. The range of variation in the primary force and moment characteristics of the duplicated loops at identical activation intervals, was assessed. In this way, any discrepancies in loop geometry would become evident. Each loop was tested individually on the measuring apparatus described in Appendix B.

The testing procedures were identical for each loop. An initial zero reading was taken from the machine prior to securing the loop into the "machine teeth". The method for securing each loop was similar to that described by Hirvonen (1983). Once the loop was secured, a second reading was taken. This step was taken to negate the effects of ligating, which could otherwise lead to spurious results during the collection of data. The loops were then activated at 0.5mm increments up to 2mm and then returned to zero.

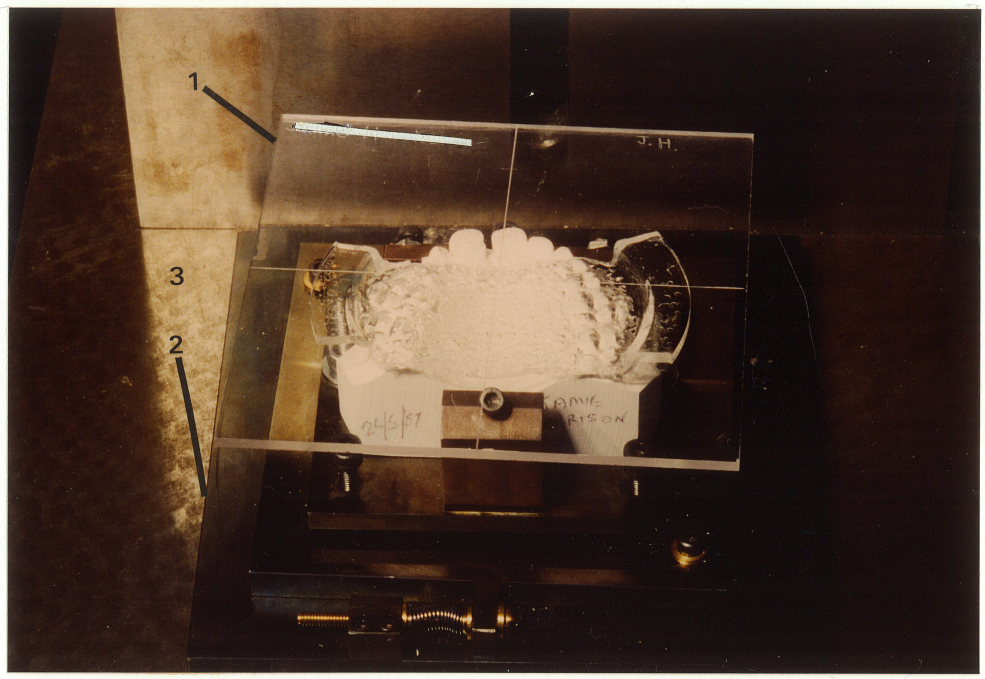
Collected data was transferred to the IBM personal computer for analysis. Mean values for the distalizing force and resultant mesio-distal couple were compiled for each activation of each loop. Results from this study indicated that for each loop type, a constant moment to force ratio was evident throughout the entire range of activation. For the ten vertical loops, a 1mm activation produced force levels which were all within a 10% range of the mean value for force (including one standard deviation). In a similar fashion, the moment values were within a 20% range of the mean value for moments. Results for the "L" loops indicated even smaller ranges of force and moment values. It should be remembered that this variation also included the maximum error derived from the measuring machine. This study indicated that simple loops could be duplicated with a sufficient degree of accuracy.

3.5. MEASUREMENT of CHANGES in TOOTH POSITION:

An important aspect of this study was the development of a technique which would enable the quantification of changes in tooth position. Although the Reflex Metrograph would appear to remove much of the tedious and time consuming aspects of cast measurement, its expense made it unavailable for use in this study. Thus the need for development of an alternative method.

Stable anchor units were considered desirable, not only to aid in achieving the type of tooth movement required, but also to attempt to give some reference points upon which tooth movement could be measured.

At the first appointment, which was approximately one month after anchorage consolidation, an alginate impression was made of the maxillary arch and poured in orthodontic plaster following manufacturers' recommended directions. Using this cast, a reference orientation splint was constructed. This involved making a rigid acrylic splint which covered only the cusp tips of the anchor teeth. All other teeth were fully relieved. The splint was then trimmed and fixed to a piece of square rigid acrylic(12.5X12.5cm) which was 3mm in thickness. Perpendicular lines were then scribed upon this square section of acrylic. See Fig. 3.9.



1. Acrylic orientation splint.
2. Adjustable baseplate assembly.
3. Machined metal table.

Figure 3.9. Plaster cast in baseplate assembly with orientation splint.

shows the orientation splint in place on the maxillary cast.

The splint was used for the following purposes;

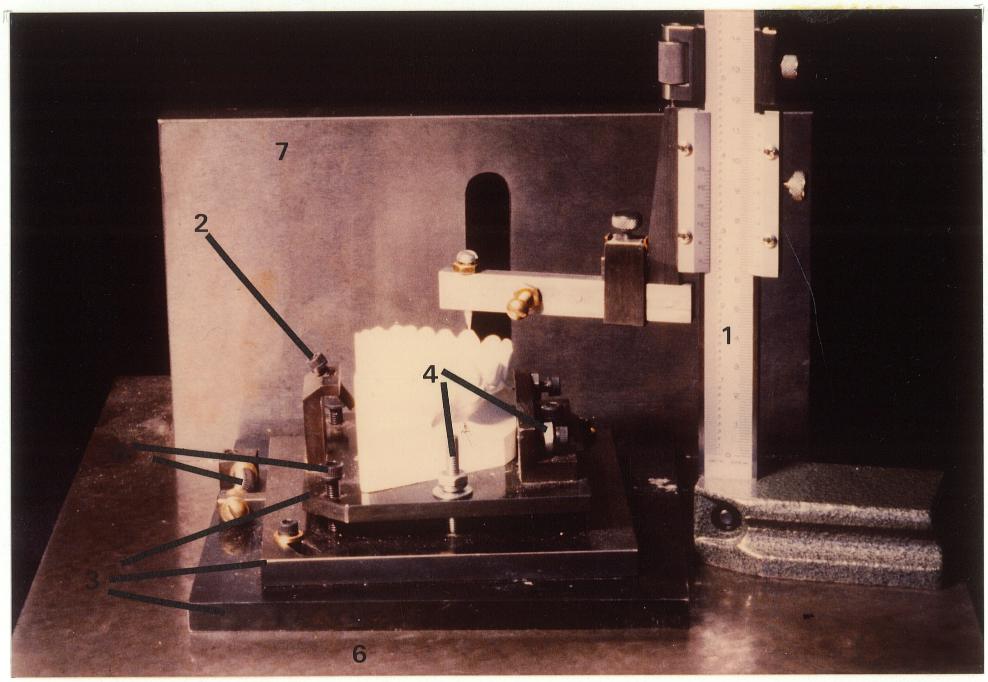
(1) To orient the plaster casts on the measuring apparatus.

(2) The accuracy of fit of the splint on subsequent casts would indicate the degree of anchorage control that had been attained and this in turn would help determine the degree of confidence to be placed in the reference teeth.

The cast measuring apparatus consisted of three machined metal baseplates, related and secured in such a way as to allow full adjustment in three dimensions. The series of baseplates were used upon a precisely machined metal table in association with a fixed perpendicular side plate. See Fig. 3.10.

The casts to be measured were trimmed to fit the baseplates, and a securing screw was adjusted to hold the plaster cast firmly. See Fig. 3.10.

In order that changes in tooth position could be measured, it was necessary to choose suitable reference points on the teeth involved. Four points were chosen on each molar anchor tooth, and three or four on the bicuspids. Four points were also identified on the cuspid teeth. These points were widely spaced on each



1. Vernier height gauge.
2. Screw to secure cast.
3. Adjustable baseplate assembly.
4. Securing screws.
5. Adjustment screws.
6. Machined metal table.
7. Perpendicular metal back plate.

Figure 3.10. Apparatus used for measuring tooth position

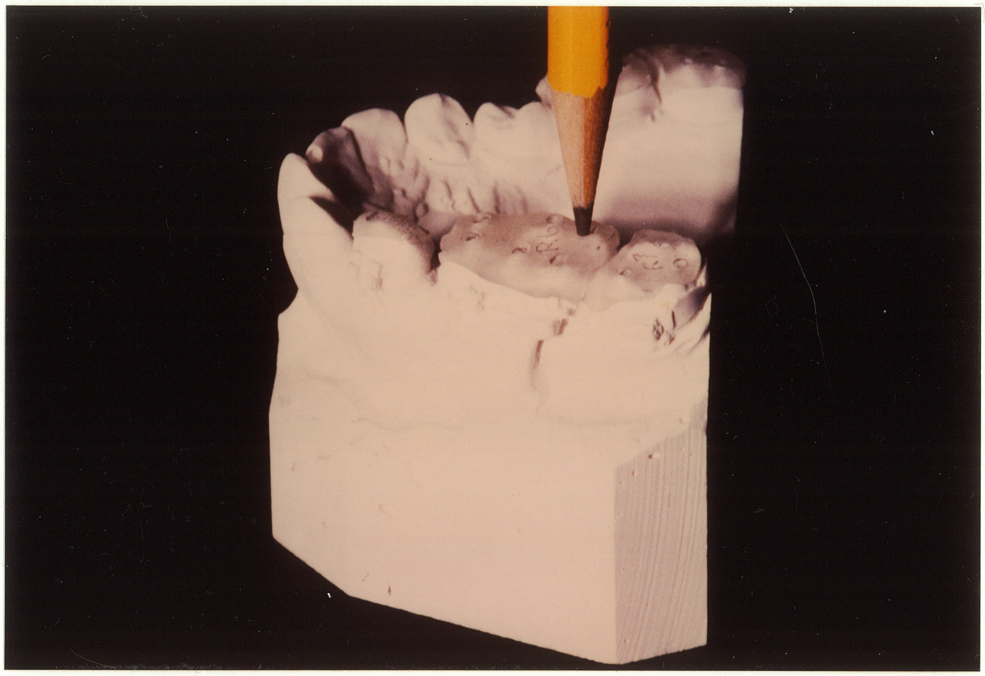


Figure 3.11. Plaster cast with acrylic templates and marking pencil in position.

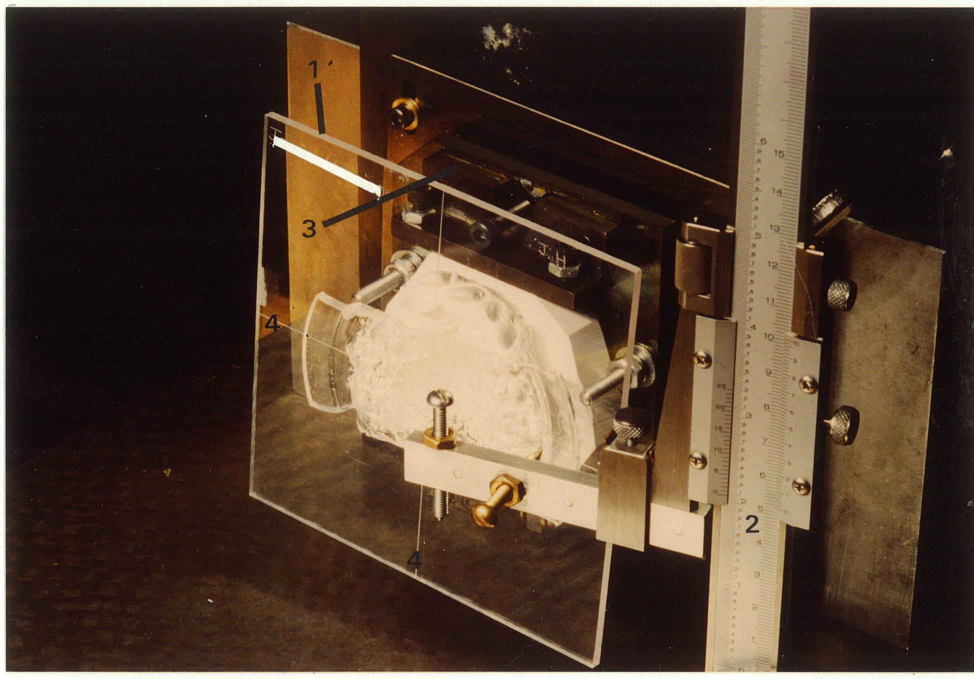
tooth to further reduce the effect of measurement error.

The reference points were duplicated on subsequent casts by using sectional acrylic overlays, into which small holes were drilled at the appropriate reference point sites. By placing these acrylic overlays onto the reference and studied teeth, small marks could be placed on the plaster using a sharp lead pencil. See Fig. 3.11. Once the reference points were marked, the cast was placed in the adjustable baseplate apparatus. At this time the Vernier height gauge, capable of measuring to .01 millimetres was used to take measurements of the reference points. Initially, three or four widely separated points were selected in the occluso-gingival direction and their heights equalised by means of three adjusting screws on the baseplate apparatus (see Fig.3.10). This step reduced measurement errors which could arise from malalignment of the cast in the sagittal and transverse planes. Following this, a measurement was taken of all marked points on the cast in the occluso-gingival dimension.

The orientation splint was then placed onto the cast and the whole assembly including the baseplates, was fixed against the perpendicular metal backplate (see Fig. 3.12). In order to allow duplication of this position for subsequent casts, the horizontal scribed line on the orientation splint was made parallel to the metal base table. This technique also provided a stable axis from which tooth movement could be measured. A series of adjustment screws on the baseplate assembly allowed easy manipulation during this procedure. Measurements were again taken of all the reference points. These measurements were of tooth positions in the sagittal, or antero-posterior direction.

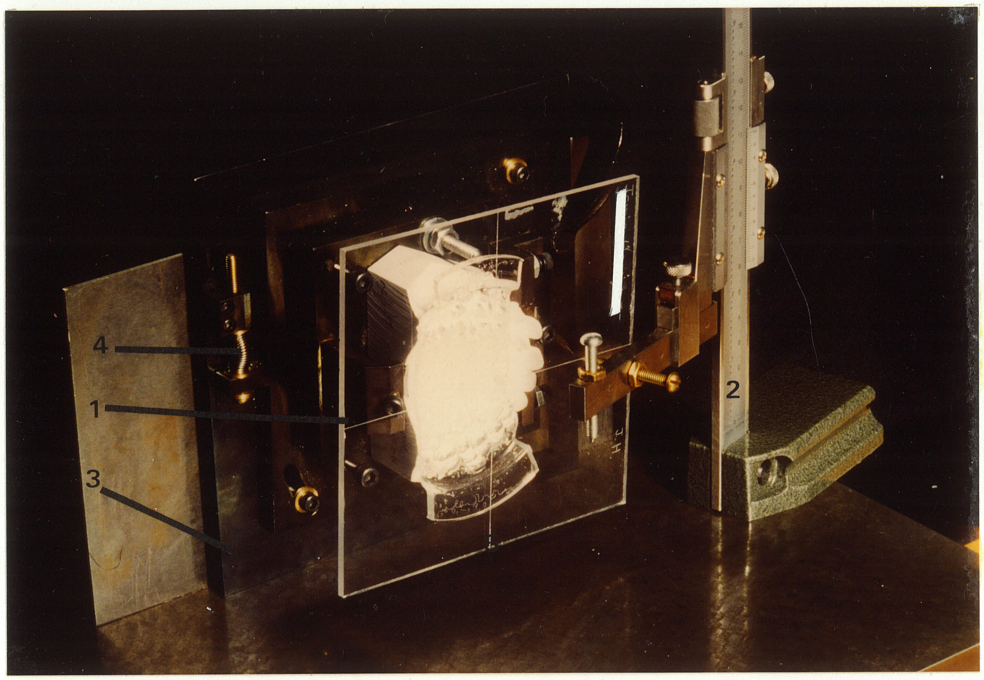
Finally, the whole baseplate cast assembly was turned through 90 degrees on the perpendicular backplate (see Fig. 3.13). This rotation was double checked by measuring the newly oriented horizontal scribed line on the splint in the previously mentioned manner. This, once again, ensured that the sagittal plane of the cast was lying parallel to the metal table. Measurements of the reference points were again recorded. These measurements represented the transverse relationships of the teeth.

The data collected in the above manner, permitted a quantitative three-dimensional description of the position of each point on each tooth to be made. By taking the coordinates of the same points on subsequent casts as treatment progressed, all six (three linear, three rotational) tooth movements were recorded.



1. Orientation splint.
2. Vernier height gauge.
3. Adjustable baseplate assembly.
4. Cross-scribed lines on orientation splint.

Figure 3.12. Cast positioned for measuring reference points in antero-posterior plane.



1. Orientation splint.
2. Vernier height gauge.
3. Adjustable baseplate assembly.
4. Adjustment screw.
5. Cross-scribed lines on orientation splint.

Figure 3.13. Cast positioned for measuring reference points in transverse plane.

Before the collected data on tooth position could be used, a reference axis had to be established. This was achieved initially by taking an average of all measurements on the anchor teeth in each of the specific dimensions. Because the casts were actually made parallel to the machined baseplate, this average value represented the centre of an orthogonal axis system which was also parallel to the machined baseplate. In a similar fashion, an average was taken of the four points on the cuspid tooth/teeth. By subtracting the value given to the reference axis from the average value derived for the cuspid tooth on subsequent casts, the linear movement of the cuspid could be determined, i.e.; intrusion vs extrusion, distoversion vs mesioversion and buccoversion vs linguoversion.

In addition to the above, each of the points on the cuspid teeth could be related to the reference axis. Opposite pairs of points on the cuspid could be related to each of the three axes to determine movements such as tipping, rotation and rolling of the crown. Derived data was plotted as a function of time to aid in interpretation.

Of course it was necessary to investigate the measurement error involved in identifying a given reference point on a tooth. To this end a separate experiment was performed in which thirty separate measurements were taken of a point in three mutually perpendicular dimensions. This experiment was done using the Vernier height gauge and the same procedures as were used in data collection. The results indicated that intra-observer measurement error was 0.12 mm. These results agreed with values reported by Sonya (1987), in a parallel study.

In order that more meaningful conclusions could be made concerning cuspid movement, it was felt that some understanding of changes in the reference anchor teeth would be helpful. One method of achieving this was to compare movement of the anchor teeth against other hard and soft tissue positions. It has long been known however that there were few, if indeed any, stable landmarks in the oral cavity. Many teeth may move in a minor way after only one or two teeth are moved orthodontically. Soft tissue landmarks such as palatal rugae may be distorted by impression making, and/or tooth movement.

Various methods were investigated in an attempt to describe any significant changes in the position of the reference anchor teeth. An Orthoscan (Unitek) camera which enables the operator to obtain photographs on a 1:1 ratio was initially used intra-orally. It was found however that due to poor photographic contrast and lack of anatomical detail, these photographs were inadequate for the purposes of this study.

The use of the above camera on plaster casts was also investigated. This technique provided greater detail of both hard and soft tissues. Detailed tracings were made of these photographs. The tracing of the original plaster cast was then superimposed upon the tracing of the last plaster cast using a "best fit" technique. Lack of precision in this technique dictated that it was only used to determine gross tooth movements in the sagittal and transverse planes during the course of treatment. In this way we could not only determine whether the measured results correlated with generalised observed changes in tooth position, but also whether significant changes in the reference (anchor) teeth had occurred.

In the case of cuspid retraction, assessment of relative change between the two anchorage sides was considered of limited value, owing to the potentially unstable position of all other landmarks. A procedure was developed to determine the degree of relative change between these anchorage units, even though the orientation splint was considered well-fitting on all casts.

An axis system was developed from the average of all measured points from the anchor teeth of one side.

Selected points from the contralateral anchor teeth were then measured to this axis. These measurements were then compared using the initial cast and the final cast. The procedure was repeated for each side. In this way it was hoped that any significant movement of the anchor teeth relative to each other could be detected. In this way, the degree of movement of the teeth under an otherwise well-fitting splint could be detected. Although the use of the orientation splint ensured maintenance of relative anchor tooth position, provided it fitted all subsequent casts accurately, some change in the anchor unit as a whole was possible. To check this, the intra-oral photographs were used (as mentioned previously), as well as making a comparison of posterior tooth position, both in vivo and in vitro.

It should be remembered that these steps were carried out only to aid in determining which teeth were more stable, and ultimately would give the best possible estimation of cuspid tooth movement.

In summary, this research project involved the following procedures:

1. Design, placement and activation of a cuspid retraction loop in a number of clinical cases.

2. Development of a passive template to replicate in vivo bracket positions on a specially modified measuring apparatus.
3. Duplication of the design, placement and activation of the active loop to measure force and moment characteristics of each loop and for each activation, in vitro.
4. Three-dimensional force and moment measurement in vitro.
5. Measurement of actual three-dimensional tooth position changes using plaster casts.
6. Correlation of the in vivo and in vitro data to investigate tooth movement in response to force systems delivered by specific cuspid retraction loops.

4. RESULTS

4.1 Introduction

As mentioned in Chapter 3, of the initial five subjects selected, three have been included for review in analyzing the effectiveness of this technique in relating force systems and tooth movement. The three patients used were J.H, C.K and T.W. This meant that data was available and analyzed for four cuspid teeth during retraction.

The results presented for linear tooth movement have been plotted in millimetres as a function of time. It should be noted from the time scale, that activations were not made in equal time increments. The results obtained for tipping and rotatory movements have been plotted in degrees of rotation, also as a function of time. Tooth movements are plotted in part A of the following figures.

The results from loop analysis are plotted in parts B and C of the following figures. Forces and moments are measured in grams (g) and gram millimetres (g-mm) respectively.

4.2 Combined Results from Tooth Movement and Loop Analysis.

4.2.1 Patient J.H

Tooth movement in this patient was followed for approximately seven months, over which time seven 1 millimetre activations of the vertical loop were made. Figure 4.1, shows the linear tooth movement obtained for patient J.H. It should be noted that between the fourth and fifth activation the loop was not active for about half of that time. This was due to the loss of the ligature tie back between appointments.

The results showed that the primary objective of cuspid distalization has been achieved with about 5.5 mm of distal movement being evident. Distal movement averaged approximately 0.8 mm per month.

Figure 4.1, also indicates secondary tooth movements. It appears that the tooth has extruded approximately 1.15 mm over the total time frame. However, during the course of treatment, the tooth actually intruded 1 mm between the second and third activation. The cuspid also moved buccally during the retraction by approximately 2.5 mm.

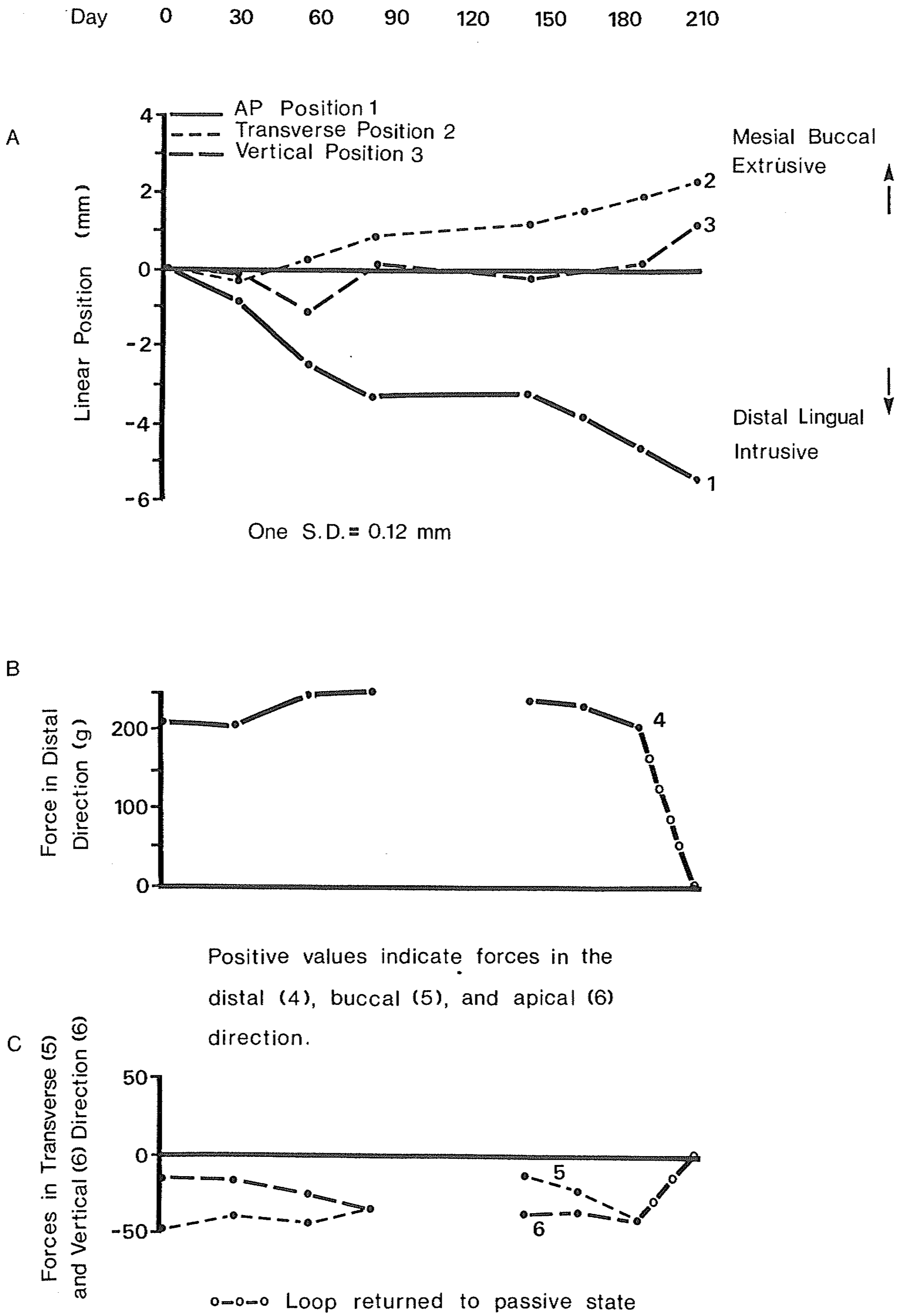


FIG 4.1 Patient JH

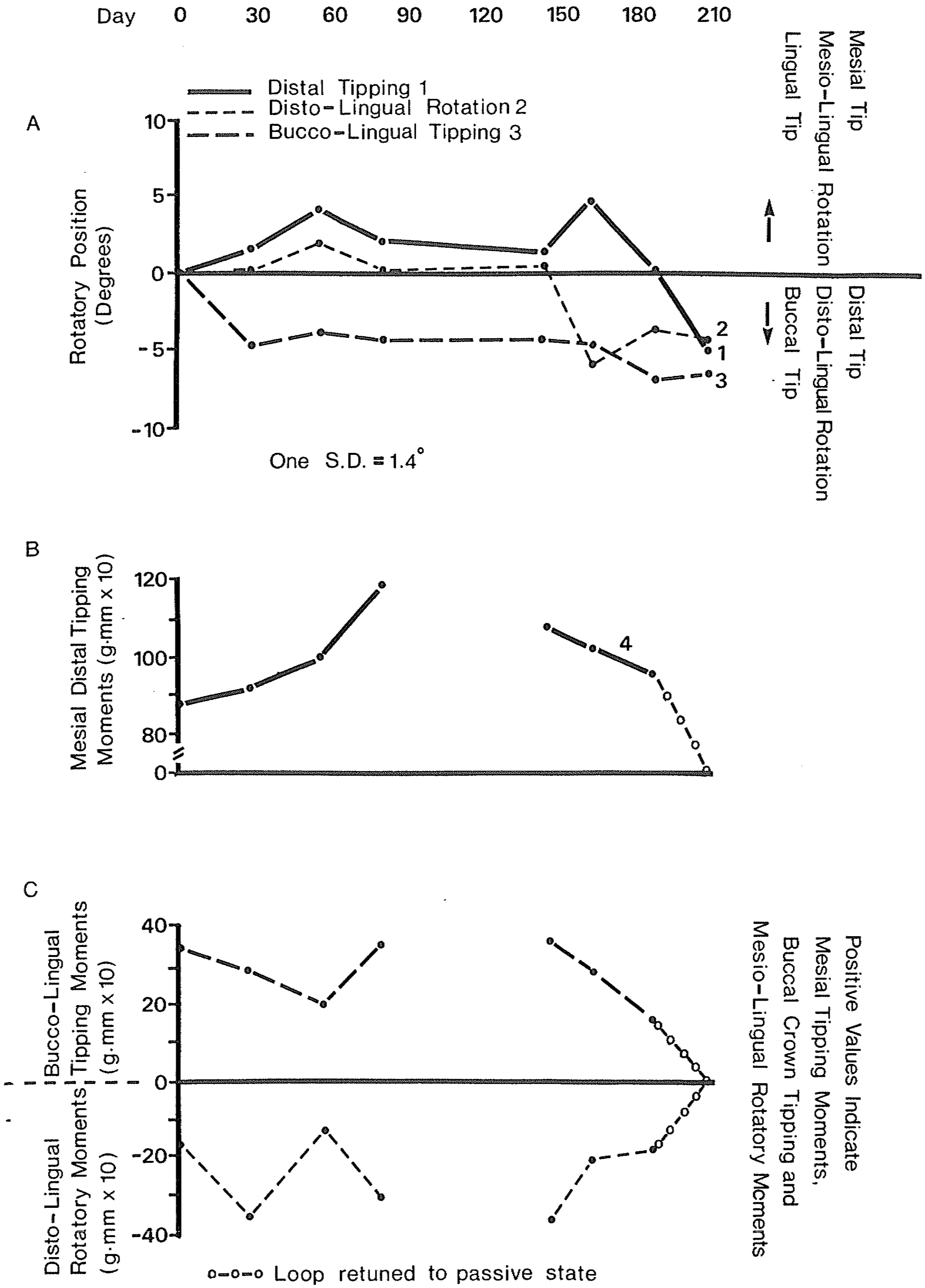


FIG. 4.2 Patient JH

Figure 4.1, provides plots of the force characteristics in each of the three dimensions at each activation of the loop. The distalizing force for this particular loop ranged from 190g to 250g, with all but one activation being over 200g. The forces in the other two dimensions were within a 50g range.

The plots in Figure 4.2, show the rotatory and tipping movements of the cuspid in patient J.H. It appears that the tooth alternated between tipping mesially and distally within a +/- 5 degree range. The related moment values seen in Figure 4.2, indicate that between 880 g-mm and 1180 g-mm was present at the bracket at the seven activations. It can be seen that the moment values in Figure 4.2, are positive. Positive moment values in this situation indicate a tendency for the tooth to tip mesially. This arises because the force system is measured at the bracket and the geometry of the activated loop leads to a counteracting moment. This concept will be explained further in the next chapter.

Figure 4.2, shows that reasonable control was achieved concerning rotation around the long axis of the tooth. Minimal disto-lingual rotation had occurred up to the fifth activation, at which time, a 5.5 degree disto-lingual rotation was observed. From this point, minimal change then occurred over the last two activations. The range of disto-lingual movement was approximately 7.5 degrees.

In regard to bucco-lingual tipping, it can be seen that 7.5 degrees of buccal crown tip occurred over the seven activations. As with the linear movement, it is interesting to note that between the fourth and fifth activations, minimal change in tooth position occurred. This was the interval over which time the tie back ligature was lost. Figure 4.2, shows that the moment values for the other two dimensions were low in value and had minimal variation.

4.2.2 Patient C.K.

Tooth movement in this patient was followed for approximately six months over which time six 1 mm activations of the vertical loop were achieved. It can be seen from Figure 4.3 that the primary objective of cuspid distalization was achieved with 3.7mm of distal movement occurring. This movement averaged 0.6mm per month. Figure 4.3, shows the recorded values for distally directed force. From this plot it can be seen that with the exception of the second activation, all other force values were reasonably constant at between 100g to 120g.

For movement in the other two dimensions, Figure 4.3, indicates that the cuspid moved buccally in a progressive fashion approximately 2.6mm. Also it is evident that negligible movement in the vertical dimension occurred.

The force values shown in Figure 4.3, tend to indicate that a progressive increase in buccally directed force occurred over the treatment time. The increase being in the order of approximately 40g. The measured vertical forces were relatively constant at 50g, and of an intrusive nature.

Figure 4.4, is the plot of tipping and rotatory movements for patient C.K. It is apparent from this graph, that the cuspid underwent various tipping movements during the course of treatment. Interestingly, it appears that for the first two activations the tooth tipped 7 degrees mesially from its original position. Between the third and fourth activation the tooth tipped distally, back to its original position. This pattern of movement was repeated over the following activations with the final position showing the tooth tipped 5 degrees distally. Figure 4.4, shows that the related moments for this tipping, with the exception of the second activation, were within a 300 g-mm range.

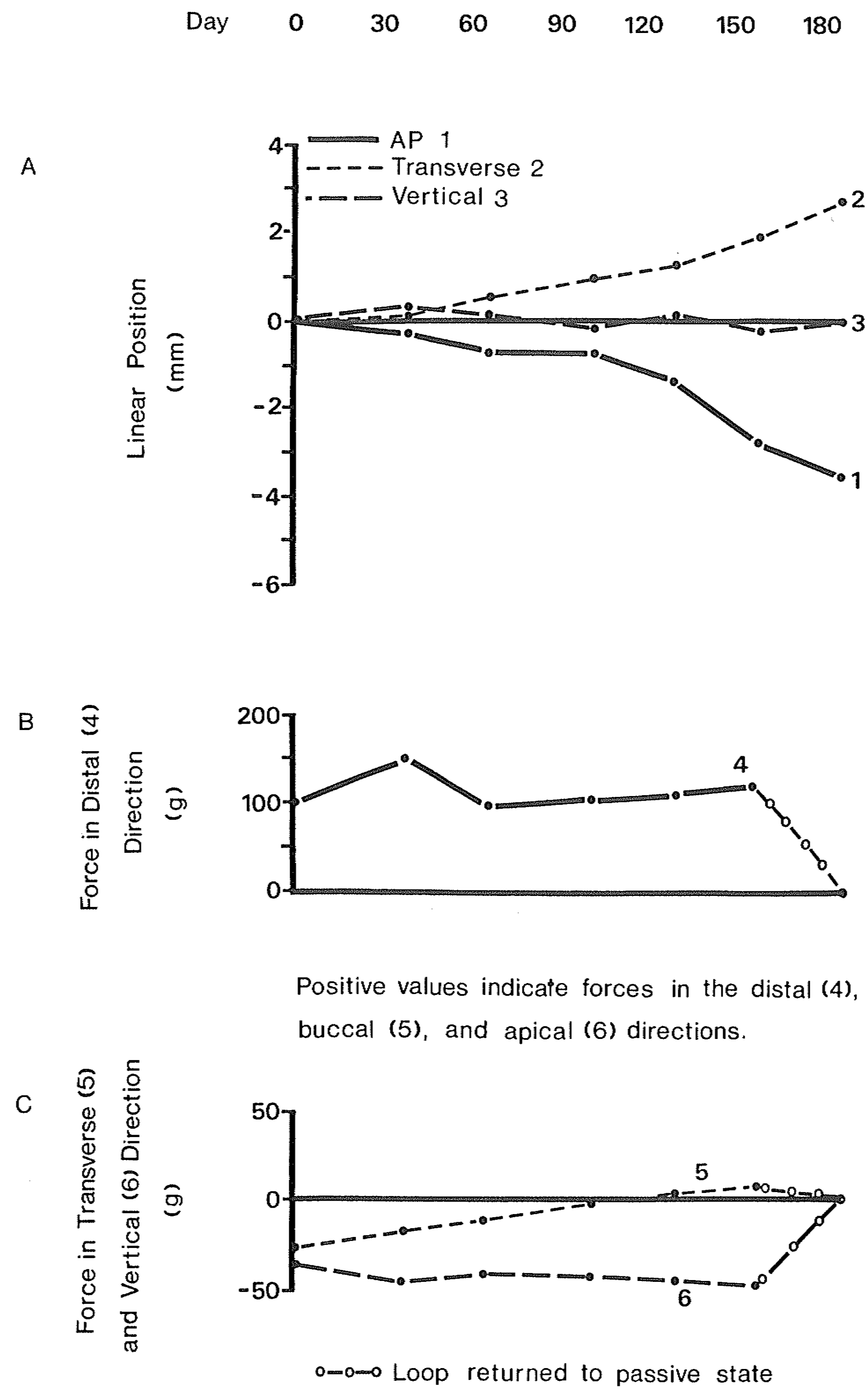


FIG. 4.3 Patient CK

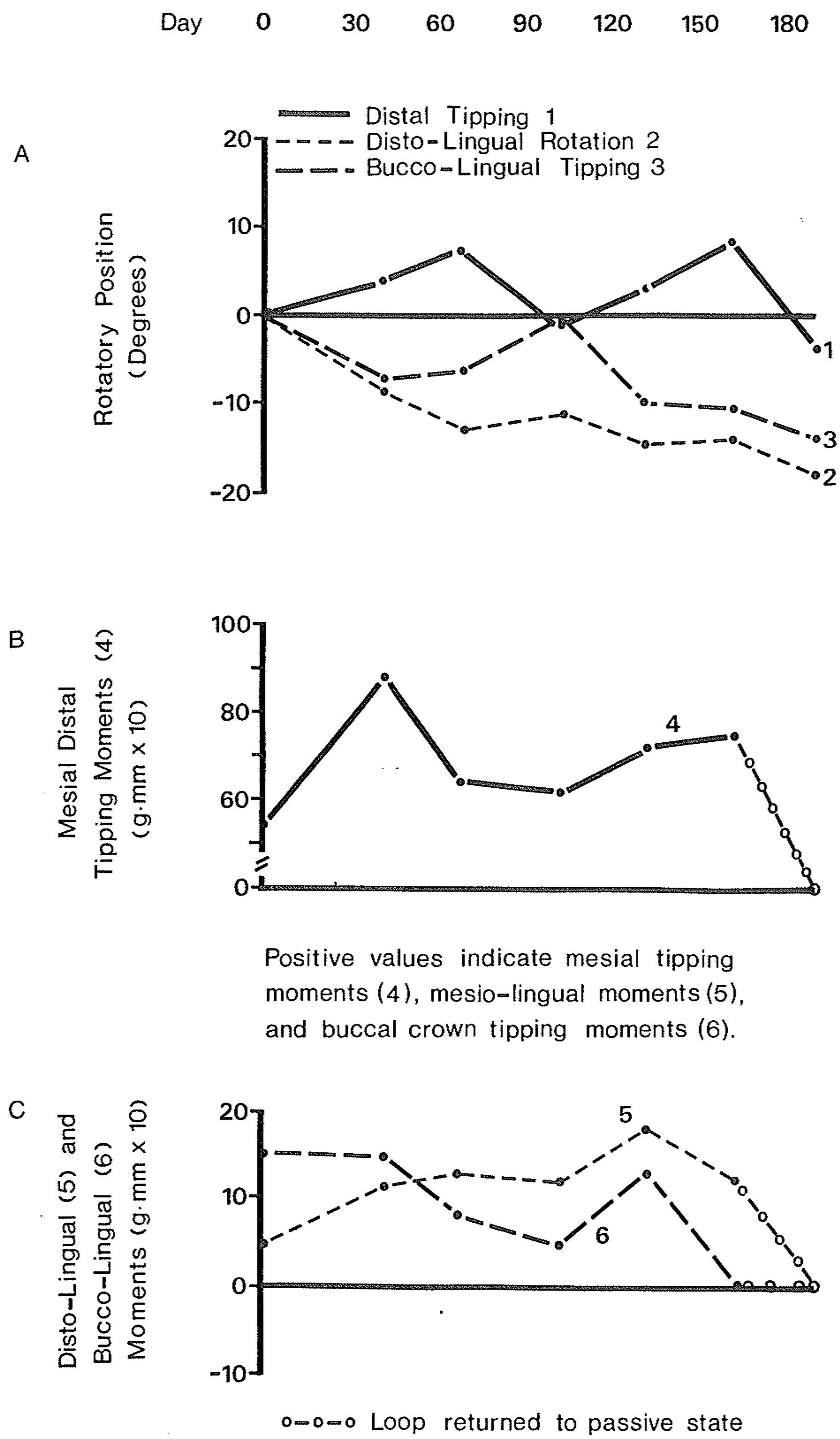


FIG. 4.4 Patient CK

From Figure 4.4, it can be seen that the tooth ended up being rotated 18 degrees disto-lingually from its original position. The same plot shows 15 degrees of buccal crown tip during the same period. The relationship between these two seemingly large changes, and a possible explanation is discussed in the next chapter. Figure 4.4, indicates that the moments related to disto-lingual rotation and buccal crown tip were all below 150 g-mm and fairly constant.

4.2.3 Patient T.W (Right cuspid).

Movement of the right cuspid tooth was followed for approximately five months, over which time five 1mm activations of the "L" loop were achieved. Figure 4.5, indicates that the cuspid moved distally 2.2mm over the measured time frame with an average tooth movement of approximately 0.4mm per month. It should be noted that the tie back ligature had fractured some time between the fifth and sixth activations. This plot also indicates that there was a progressive tendency for the tooth to move buccally 1.5 mm, and also to extrude 1.5mm.

Figure 4.5, indicates that a fairly constant force of 80g was used during retraction. The forces in the transverse and vertical direction were low and consistent.

From Figure 4.6, it appears the tooth underwent an initial distal tipping of approximately 5 degrees. This position was maintained, even though some minor uprighting and tipping occurred during the retraction process. The maximum amount of tipping was 8 degrees from the original orientation.

The above figure also indicates that the tooth rotated disto-lingually 6 degrees during the first activation. From that point on its orientation was reasonably well maintained with the exception that during the last activation, another 3.5 degrees of disto-lingual rotation occurred. This ultimately totalled 9.5 degrees of rotation from the original tooth position.

The tooth showed an initial buccal crown tip of 5 degrees, which was maintained throughout the remaining activations within a +/- 1.5 degree range. The cuspid was ultimately tipped buccally 3.5 degrees from its original position.

From Figure 4.6, it can be seen that the moments produced by the appliance in the mesio-distal plane ranged from 660 g-mm to 700 g-mm. The moments produced in the other two planes are plotted in Figure 4.6. These values fall within a +/- 150 g-mm range.

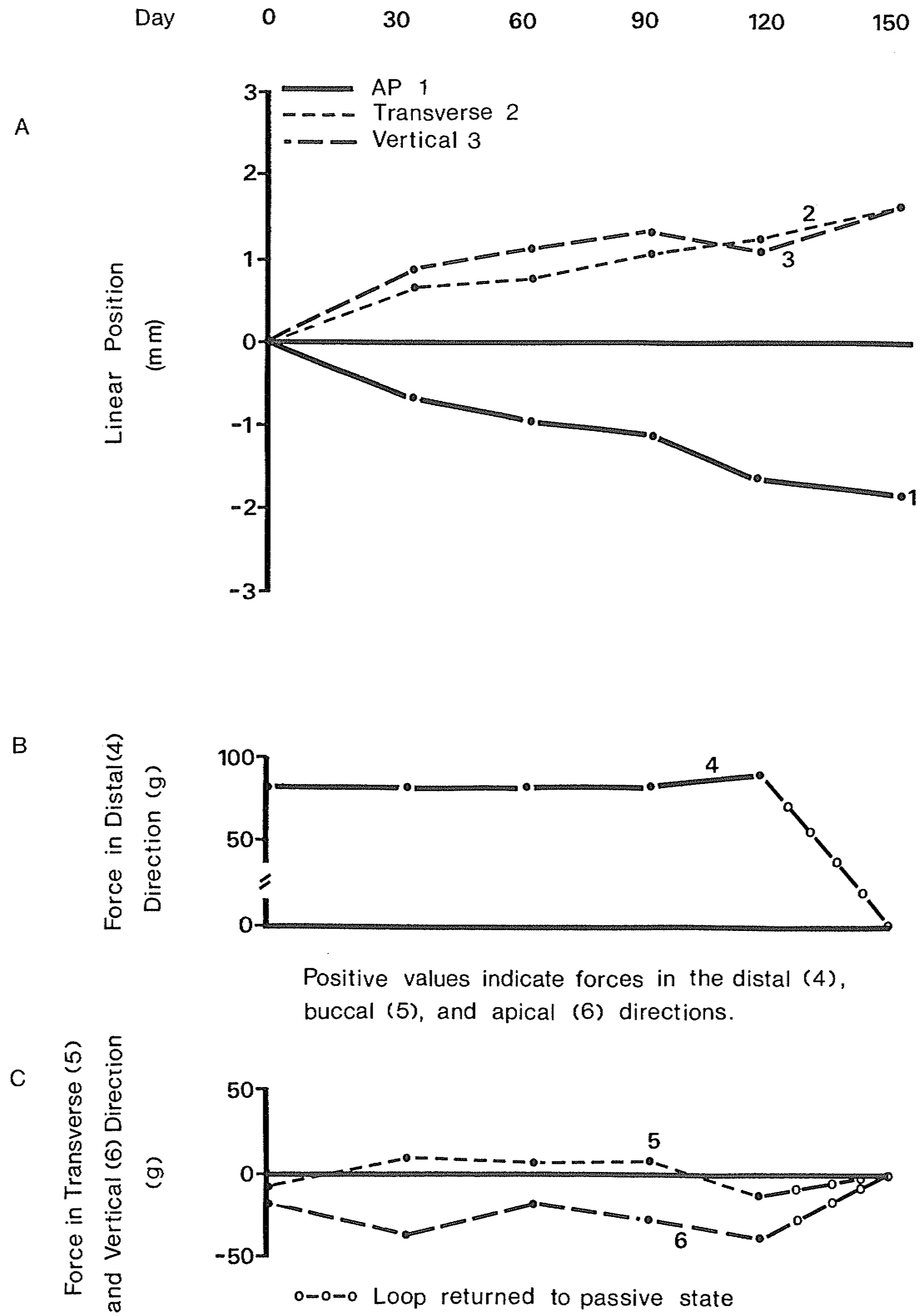


FIG. 4.5 Patient TW (right cuspid)

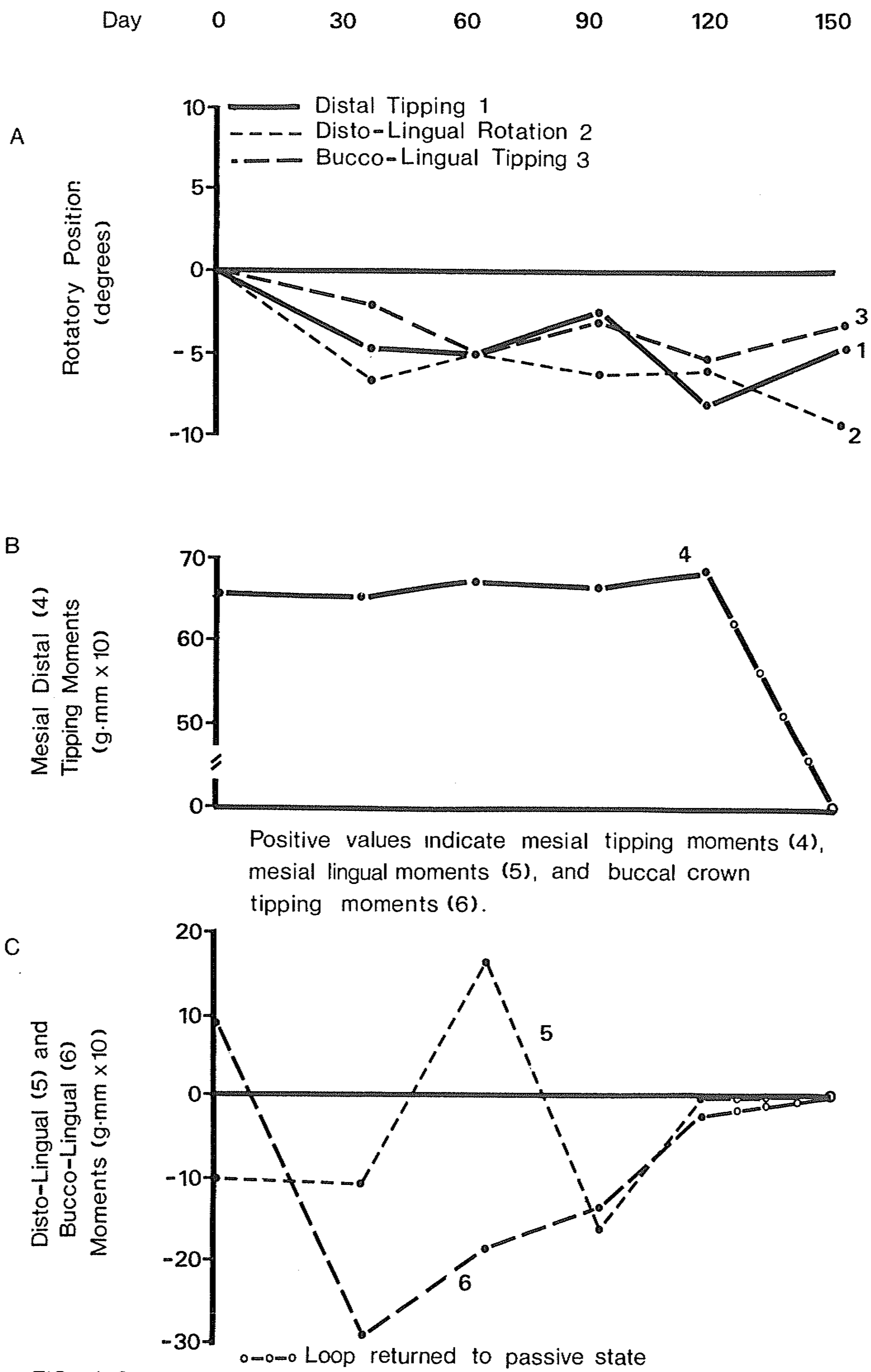


FIG. 4.6

Patient TW (right cuspid)

4.2.4 Patient T.W (Left cuspid).

Retraction of the left cuspid tooth was followed for a similar time and the "L" loop was activated similarly to the right cuspid.

From Figure 4.7, it can be seen that 2.3mm of retraction was achieved over the five month period, with an average rate of movement of 0.4mm per month. It appears that during the first two activations, the tooth had retracted distally only 0.4mm. Most retraction occurred during the third and fourth activations, with a tapering off in distal movement during the final two activations.

The corresponding force values for retraction are shown in Figure 4.7. From this plot it can be seen that the "L" loop produced a force level which ranged from 110g to 160g.

Buccal movement in this case was minimal, with a maximum buccal movement of 0.45mm occurring. The tooth did appear to extrude 1mm up to and including the third activation, however beyond that there was a reduced amount of extrusion. The final value indicates 0.6mm of extrusion.

Figure 4.7, shows that forces in the transverse plane were small (within 30g range) and consistent. The measured forces in the vertical dimension appear to be quite high, being consistently around 70g to 80g. The positive sign observed for this force is due to the fact that the loop is being used on a left cuspid, and the orientation of the loop in the machine can change the sign of the resulting force values. In this case a positive value still indicates an extrusive force.

As far as tipping and rotatory movements are concerned, Figure 4.8, shows an interesting response in tooth movement. The tooth tipped distally a total of 11 degrees, however this was not a progressive tip, with about 5 degrees of mesial crown tip occurring between the third and fourth activations. Note also that the tooth maintained its orientation between the second and third activations and also between the fifth and sixth activations.

The rotation around the long axis of the tooth produced some interesting results. It can be seen that the tooth actually rotated disto-buccally for the first two activations. This amounted to approximately 6 degrees from the tooth's original position. From the third activation onwards, there was a steady disto-lingual rotation with a total change of 11 degrees. This meant that the tooth was ultimately disto-lingually rotated 5 degrees from the original position.

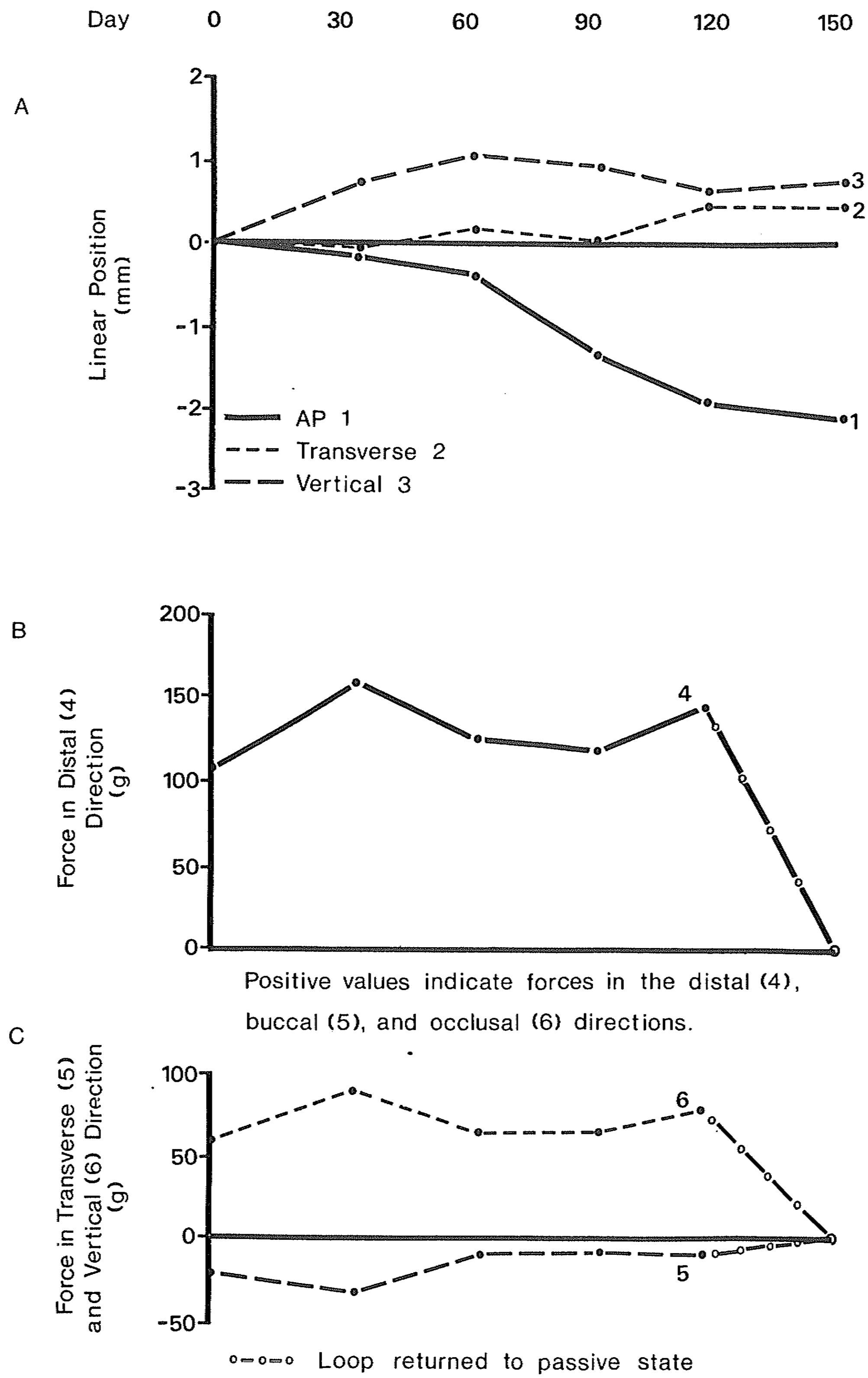


FIG. 4.7 Patient TW (left cuspid)

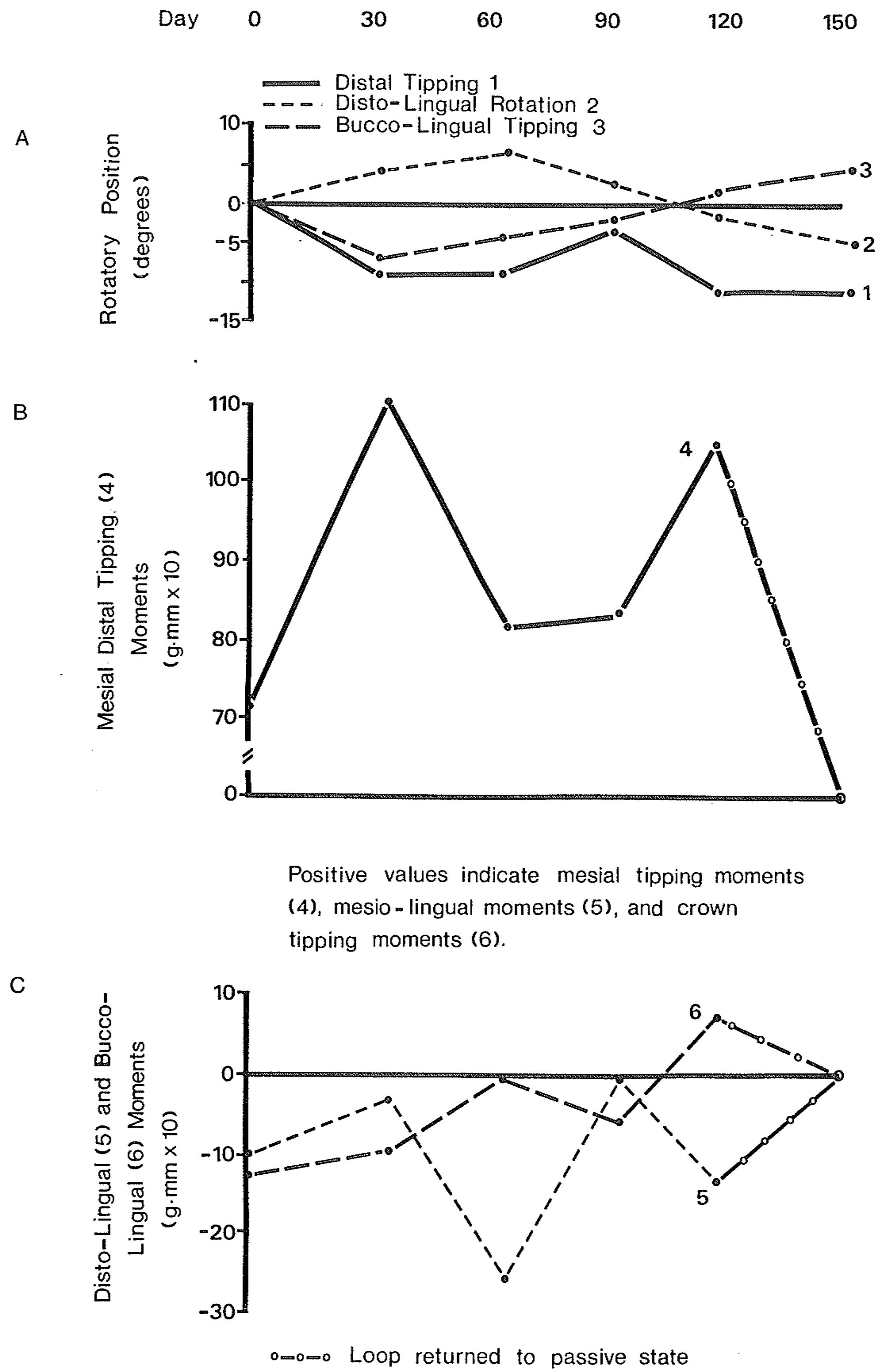


FIG. 4.8 Patient TW (left cuspid)

Figure 4.8, also indicates that the tooth tipped buccally after the first activation, however, past that point there was a steady lingual crown tip which ended in the tooth being lingually tipped approximately 4.5 degrees.

The mesial-distal moments felt at the bracket were generally within a 300 g-mm range (from 820 g-mm to 1100 g-mm). The first activation was the only exception, being 720 g-mm. See Figure 4.8. The values for these moments would normally be recorded with a negative sign. Once again, this is due to the orientation of the loop in the measuring machine. The sign has been changed in this case for ease of reference, and would still indicate mesial tipping moments.

Figure 4.8, shows the moments developed around the other two axes, and although not being consistent, were within a 300 g-mm range.

5. DISCUSSION

5.1 Introduction.

This study was undertaken primarily to develop a technique which could be used to investigate the relationship between tooth movement and known force systems.

The movement of four cuspid teeth was studied to enable us to develop a degree of confidence in the reproducibility of the technique. Comparisons of the various tooth movements have been made merely to describe the trends seen in the four measured cases, and to determine whether these changes reflect, in any way, the clinical expectations of the measured force systems.

5.2 Stability of Reference Teeth.

It is well accepted that there are many difficulties in identifying and/or producing stable reference points in the oral environment. It does seem that the degree of stability of various landmarks is an unanswered question. With this in mind, it was decided that for the purposes of this study, maximum anchorage units would be established in an effort to reduce any resultant movement from the retraction procedures.

It is therefore assumed that these anchorage units are stable, and so could be used as reference points upon which to monitor cuspid movement. The following discussion indicates the methods used in substantiating the evidence for stability of the anchor teeth, and ultimately the confidence placed in these teeth as reference points.

For the three patients used in this study, it was found that the orientation splint fitted all relevant casts with acceptable accuracy. In the context of this statement, acceptable meant that there was negligible rocking and movement of the splint on each of the casts. This implied that the anchorage units from both sides of the mouth stayed accurately related to each other during the time of treatment in each case.

To verify the stability of the anchor segments, selected points were taken from the anchorage teeth of one side. Also, using selected points from the contralateral anchorage teeth, a three dimensional axis system was established. By comparing the change in position of the points on the ipsilateral teeth to the axis system developed on the contralateral side, the change in relative position between these two sides could be determined using the initial and final casts.

For patient C.K it was found that a difference of approximately 0.25mm existed between sides in both the

antero-posterior and the transverse planes. Negligible movement was detected in the occluso-gingival plane.
For patient T.W it was found that a difference of approximately 0.3mm existed in the antero-posterior plane and 0.4mm in the transverse plane. Negligible movement was detected in the occluso-gingival plane.

For both patients, C.K and T.W, the use of 1:1 photographs, hand manipulation of dental casts and visual inspection of actual maxillary-mandibular posterior tooth relationships further corroborated the evidence for anchorage unit stability.

For patient J.H, a slightly different story unfolded. Using the technique previously described, it was found that the anchorage units varied by 0.7mm at the end of treatment. Considering the orientation splint still fitted accurately, this difference was difficult to explain. When the 1:1 photographs were superimposed, and visual inspection of true intraoral tooth relationships were made, it was felt that the right side anchorage unit had moved mesially approximately 2.5mm. This meant that the anchor teeth on the right side were unacceptable as reference points. An explanation of this phenomenon was not found. However, as described in the results section, it was seen that relatively high force levels (over 200 g) were used to retract this cuspid. Also it should be remembered that unlike the other two cases, the second permanent molars were not incorporated into the anchorage units. Possibly as a result of these two factors it was felt that the right side anchorage units slipped mesially while the left side rotated slightly. The left side anchor teeth appeared to be the centre of rotation. The implication here was that a very minor rotation of the left side anchorage teeth would be detected as a significant mesial movement of the right side anchorage teeth. These observations raise questions about the value of the Nance holding appliance in this type of anchorage control. Interestingly, however, both the photographs and visual inspection indicated there was little change in position of the left side anchorage teeth. As a result of the foregoing, it was felt that the reference axis system in this case should be derived only from the left side anchor teeth.

Based upon the aforementioned evidence, it was decided that a high degree of confidence be placed in the described anchor units as reference teeth.

5.3 Assessment of Force System Measurement.

As previously mentioned, the machine used for measuring the force systems developed by the loops has an error range of 3% of full value for both force and moments. The full scale range of the machine is 1000g and 20,000 g-mm.

Due to the fact, that in this study, the force values measured were within 25% of maximum limit and, the moments were less than 10% maximum limit, then it could be argued that at these low levels the measured data could be significantly affected by the machine error. This limitation of the present machine was recognised and accepted. For this reason, not only are the actual values for forces and moments considered, but also the general consistency of those values for each loop.

5.4 Assessment of Tooth Position Changes and Related Force Systems.

Accepting a high degree of confidence in the stability of the reference teeth, the next stage was to assess a degree of confidence in the calculated tooth positions and relate those changes to the actual force systems applied at each activation.

It was felt that discussion of the data would be made more relevant if the six individual tooth movements were described separately. Thus under each of the appropriate headings, data from the three patients concerning similar tooth movements will be discussed. Once again, this is not meant to be a comparison of various tooth movements, but rather to (i) reflect the ability of the technique to accurately describe changes in tooth position, and (ii) to assess the reproducibility of the technique.

5.4.1. Antero-Posterior Movement.

For all patients, the three linear movements described actually reflected the clinically expected movements during cuspid retraction. For patient J.H, the cuspid moved distally at an average rate of 0.8mm per month. The interesting observation concerning this movement was that between the fourth and fifth activation, the ligature tying the loop back was lost three weeks prior to the fifth activation. Although the tie back ligature was reported lost at this time, it could have come loose much earlier. From Fig. 4.1, it should be noted that the cuspid actually moved mesially about 0.2mm during this interval, relative to its position at the end of the third activation. The distally applied force averaged 220g for this patient. Although it was initially intended to use force levels of approximately 150g or less for this study, anatomic considerations in this patient meant that the loop had to be made smaller than originally planned. Thus the higher force levels.

Patient C.K, showed distal movement of the cuspid tooth at an average rate of 0.6mm per month. It is interesting to note that for the first three activations, tooth movement averaged only 0.25mm per month. It was not until the fourth activation that a greater rate of tooth movement occurred (Fig. 4.3). There may be a number of possible explanations for this observation. Firstly it can be seen that the average force value for retraction was 112g. This is near half the average force value reported for patient J.H. It may be that this lower force level was not adequate to initiate immediate tooth movement. Secondly, and also in contrast to patient J.H, patient C.K was an adult. Patient J.H, was 12 years of age. It may be that age plays a role in initiation and rate of tooth movement. The third possible explanation is that when looking at Fig.4.4, it can be seen that the tooth underwent a significant amount of disto-lingual rotation, especially during the first two intervals. This in itself was not considered an untoward result, because upon examining the patients casts, it was noted that the cuspid tooth was initially rotated slightly disto-buccally in relation to the anchor teeth. It appears that the first two to three activations of the loop resulted more in a disto-lingual rotating movement than to actual linear movement. Considering that all loops were completely deactivated at each visit and coupled with the probability that these rotations would not account for a 1 mm deactivation, a definitive explanation is not possible at this time.

When looking at the results obtained for patient T.W, it can also be seen that a very slow rate of retraction was achieved for both cuspids. This may have been due to the long interval between the third and fourth activation. However, as for patient C.K, this patient was also an adult . In addition, quite low force levels were used during the retraction procedure. For the right cuspid, an average distal force of 82g was used and for the left, an average of 132g. Note that in both cases, the first two intervals showed less than 1mm of distal movement. This trend was also similar to that observed in patient C.K. From the second interval on, the rate of tooth movement appeared to be more rapid for the left cuspid compared to the right. Interestingly, the left cuspid had the higher average force level.

5.4.2. Transverse Movement.

When looking at the transverse movement recorded in patient J.H, it can be seen that, except for the first interval, there was a steady trend toward buccal movement. This is interpreted as expansion of cuspid position during retraction. In contrast to this observation, Fig. 4.1 indicates that the force in the transverse plane was 25g to 50g and lingually directed. An explanation of this is that the cuspid follows the arch form, which is generally wider as the tooth moves posteriorly. This would give an expansive type of movement. The resultant force being recorded at each activation may be a combination of two components. The first consideration is that as the tooth moves buccally during retraction, the loop is also displaced in a buccal direction. This would then be recorded as a lingually directed force as the loop attempts to return to its original position. The second consideration is that a lingually directed force results from loop activation. The latter is possibly the more realistic cause of this force because, as can be seen from Fig. 4.1, the lingually directed force is about 50g even at the first activation.

As far as buccal movement was concerned, patient C.K showed a very similar trend to that observed in patient J.H. The tooth moved buccally 2.6mm. Once again it was felt that this expansion was due to distal movement of the tooth into a wider section of the arch, and not directly due to a buccally directed force. In fact the transverse force averaged only 7.5g in a lingual direction. It should be remembered that, for the purposes of cuspid retraction, transverse or buccally directed movement is considered desirable. Note from Fig.4.3, that the rate of transverse movement seems to be directly related to the rate of distal movement.

For both cuspids in patient T.W, there was also a trend toward buccal movement. The reasoning for this has been explained earlier, but it is interesting to note that the left cuspid seemed to move buccally only 0.5mm compared with the right cuspid which moved 1.6mm. This difference may be due to the observation that in Fig 4.7, there appears to be a slight lingually-directed force on the left cuspid. This compares with the right cuspid which appears to have a slight buccally-directed force.

5.4.3. Vertical Movement.

The vertical movement seen in the cuspid for patient J.H, varied from intrusion to extrusion. Although there appeared to be some initial intrusion, the general trend was toward extrusion. This was reflected in the values for force in this dimension, which indicated a relatively constant but small extrusive force. The extrusive forces appeared to become slightly larger and more consistent after the third activation. Note that during the interval in which the tie back was lost, there was also a lesser amount of expansion and a small amount of intrusion recorded. These observations reflect the ability of this technique to detect changes in tooth position as a direct result of changes in the applied force system.

Results from patient C.K, showed negligible movement in the vertical plane. Although the related vertical forces averaged about 50g in an extrusive direction, it was obvious that the vertical loop was able to control this extrusive tendency.

Both cuspids in patient T.W, underwent similar amounts of extrusion during retraction and, interestingly, the trends in movement between activations were very similar as well. The measured forces in this plane reflected the observed tooth movements i.e., both were extrusive and varied in magnitude from an average of 30g to 70g.

5.4.4. Mesial Distal Tipping Movements.

In regard to mesio-distal tipping for patient J.H, the recorded values fall within a +/- 5 degree range. This small range is particularly significant when one considers that the standard deviation for this movement was calculated at 1.5 degrees. This information implies that the magnitude of values for mesio-distal tipping are not as significant as the variations recorded between individual values. It seems that during retraction, the tooth was tipping slightly mesially and slightly distally in an alternating fashion. This is in agreement with some earlier studies (Chapter 2), which describe clinical translation as being a series of "jiggling movements".

The moments developed by the appliance require some explanation. As mentioned earlier in Chapter 4, the moments developed by these appliances were measured at the bracket. This meant that we were actually measuring the moments produced entirely by activation of the loop and not due to the effect of distance. Positive moment values indicate that the loop had a tendency to rotate the tooth mesially. For patient J.H, and in the antero-posterior plane, when average values for distal force and mesio-distal tipping moments were used, this loop produced a moment to force ratio (M/F) of + 4.5 mm, when measured at the bracket. Of course, in reality, the line of action of the loop is pulling away from the centre of resistance of the tooth. This would have a tendency to tip the tooth distally. The actual moments and ultimately the type of tipping observed are a combination of the above mentioned values. The resultant moment values for a given tooth are not given in this study due to our inability to accurately define the centre of resistance of a tooth.

However, if we were to assume a value for this position, then a general idea of force systems acting on the whole tooth could be made. As an example of this, let us assume that in patient J.H, the centre of resistance is 12mm apical to the bracket. This means that an average 220g distally applied force would produce 2640 g-mm of distal tipping moments. Now from Fig. 4.2 , it can be seen that the average value for moments resulting from loop activation was 1000 g-mm, with a mesial tipping action. Combining these two values gives a resultant moment value of 1640 g-mm with a distal tipping tendency. This would give an ultimate M/F ratio of -7.5 mm. The significant point here is that, even allowing for the tipping moments produced as a result of distance, the loop in this case, even without compensating moment bends, has been able to counteract partially the overall distal tipping tendency. This is reflected in the tooth position data which indicates no clinically significant tipping during retraction. The implication here is that, if no preactivation bends are placed in a loop and if the appliance is allowed to completely deactivate, then no visible tipping should be evident.

When looking at the measured rotatory movements in patient C.K, Fig. 4.4 shows the trends in mesio-distal tipping movements to be very similar to those observed in patient J.H. The magnitude of tipping varies slightly, however the tooth appears to initially tip mesially and then alternate between distal and mesial tipping until its ultimate position shows it to be tipped slightly distally. Once again it is not so much the actual values of tipping which are significant, but rather the trends in movement. The tooth does appear to be jiggling mesio-distally as it is retracted.

If as was done for patient J.H, an assumed position for centre of resistance is given as 12mm, then using the same steps described earlier, it can be calculated that a M/F ratio of -6:1 would be produced in this case. This M/F ratio once again has a tendency to tip the tooth distally. As for patient J.H, this loop was able to control the M/F ratio and ultimately allow only slight distal tipping to occur during retraction.

The tipping movement seen in the right cuspid of patient T.W, was once again a trend of alternate mesio-distal tipping around a maximum degree of tipping of 8 degrees. The final reading indicated the tooth was tipped to the distal about 5 degrees. Considering that a standard deviation for rotational and tipping changes was in the vicinity of 1.5 degrees, these values for tipping could be regarded as negligible. For this particular loop, the average value for moments recorded at the bracket is 670 g-mm. This gives a moment to force ratio of +8.2 mm, with a mesial tipping tendency. This higher M/F ratio would tend to imply that this loop had more control over distal tipping than the vertical loops used in patients J.H and C.K. Generally the results tend to reflect this idea; however within the small angular changes noted in all cases, the vertical loops did show similar control to that seen in the "L" loops. This may be due to such factors as loop stiffness and/or variations in the actual heights of centres of resistance.

The mesio-distal tipping seen in the left cuspid indicates a significant amount of distal tip (approximately 11 degrees). It should be noted however that most of this tip occurred during the first activation, i.e. 8 degrees. From that point on, there appears to be that typical alternating pattern between distal and mesial tipping seen in the previously mentioned subjects. The related moments showed that the loop produced 900 g-mm with a mesial tipping tendency. This gave a moment to force ratio of + 7 mm, which was similar to that produced by the loop on the right side.

5.4.5. Disto-lingual, Mesio-lingual Rotating Movements.

For patient J.H, the tooth appears to rotate minimally, both in a mesio-lingual and disto-lingual direction. The movement is of an alternating pattern with the ultimate value being about 4 degrees disto-lingual rotation.

If we analyse the force system related to this movement in a way similar to that described for mesio-distal tipping, further understanding between applied moments and resultant tooth movement can be gained. Assuming the bracket is placed 5 mm buccal to the centre of resistance of the tooth, and an average force of 220g is applied, then a resultant moment of 1100g is produced. This would have a tendency to rotate the tooth disto-lingually. However as can be seen from Fig.4.2 , the moment measured at the bracket in this plane averages 230 g-mm. For this example, the resultant moments tending to tip this tooth disto-lingually are 1330g-mm. Due to the fact that minimal rotation appeared to occur in this dimension, it is obvious that the vertical loop was able to partially counteract these moments and ultimately control tooth position during retraction. It is this stiffness of the vertical loop in the transverse plane, compared with an "L" or "T" loop which gives it this control of tooth position. It is interesting to compare this situation with the results from patient T.W, in which "L" loops were used.

It should be emphasised that these examples are not a definitive statement on the relationship between force systems and tooth movement, as they are based upon assumed and averaged values. They are merely meant to aid in understanding the application of the force system to observed tooth movement.

The observed disto-lingual rotation in patient C.K, has already been mentioned in regard to the large initial rotation. From the second activation on, it can be seen that an alternating trend from mesio-lingual to disto-lingual movements were recorded. In contrast to patient J.H, the recorded moments for this dimension, although small, were all positive in value. This indicates the loop had a slight tendency to rotate the tooth disto-buccally. Of course these were the moments measured at the bracket. Once again the actual tooth changes measured in this plane were a reflection of the ability of the vertical loop to control rotations.

The disto-lingual rotation seen in the right cuspid of patient T.W (Fig. 4.6), shows once again a trend toward a jiggling type of movement with an ultimate value of nearly 9.5 degrees of disto-lingual rotation being observed. Once again, the ability of the loop to resist this disto-lingual rotating tendency is a measure of its stiffness and ultimately its control during retraction. Even allowing for the observation that 9.5 degrees of disto-lingual rotation occurred, this still may be clinically insignificant in regard to ultimate tooth position.

The disto-lingual, mesio-lingual rotation seen on this tooth is initially opposite to that expected (Fig. 4.8). It was felt this was due to the tooth being initially placed in a disto-lingual orientation in relation to the anchor teeth. Upon activation of the loop, the tooth moved disto-buccally for the first two activations, until it was in closer approximation to the alignment of the anchor teeth. This movement was supported by analyzing the study casts taken during treatment. Once the tooth reached a certain position, which was after the second activation, it started a progressive trend towards a disto-lingual rotation. The tooth was ultimately rotated 11 degrees from its original position. This was a similar amount to that recorded for the right side cuspid. It does seem that this tooth did not alternate significantly between activations but rather steadily increased its disto-lingual rotation.

The "L" loops, although allowing more disto-lingual rotation to occur, appeared to offer clinically acceptable control in this plane during retraction.

5.4.6. Buccal Lingual Crown Tipping Movements.

When looking at the changes in bucco-lingual crown tip in all the patients studied, an important aspect concerning tooth position must be considered. The points on the cuspid teeth used to determine buccal crown tip were the most incisal and most gingival. The axis from which this movement was related was the transverse axis. To measure changes in angulation, the distance between the above mentioned points on the cuspid and the transverse axis were recorded. It was felt that these points could be subject to relative change when the cuspid underwent disto-lingual or mesio-lingual rotations. This could possibly lead to inaccuracies in assessment of crown tip due to changes in another plane. For this reason, calculations were made to determine the effect of mesio-lingual and disto-lingual rotations on the relative distance between the measured points on the cuspid teeth. Even for the patient with the most severe disto-lingual rotation, (patient C.K with 18 degrees), it was found that a change of 0.1 degrees would occur. Considering our measuring limitation, this value was considered insignificant for all the patients used in this study.

For patient J.H, there appeared to be an initial buccal crown tip of 5 degrees, which was maintained within one or two degrees until the sixth activation. Between the sixth and seventh activations there was another increase in buccal crown tip of 3 degrees. The tooth ended up being tipped buccally 7 degrees from its original orientation. The relevant moments for this tooth movement showed a buccal tipping moment averaging 280 g-mm. Interestingly it can be seen from Fig. 4.1 that, generally speaking, there was an intrusive force acting until the last two activations. Buccal crown tip would be an expected movement from such a force. The last activation was of an extrusive nature which, arguably is seen as a slight lingual crown tip during that interval (Fig. 4.2).

From Fig.4.4, it can be seen that for patient C.K, the cuspid tooth tended to tip buccally during retraction. It appears the buccal-lingual crown tip is directly related to mesial and disto-lingual rotation. In general as the tooth rotates disto-lingually, it also appears to undergo a buccal crown tip. In a similar fashion, as the tooth rotates mesio-lingually, it appears to undergo lingual crown tip. The relationship between these two movements was also evidenced in patient J.H. The average moments for bucco-lingual crown tip were 150 g-mm with a buccal tipping tendency. However, the vertical force in this case averaged 50g and was of an extrusive nature. This would tend to produce a resultant lingual crown tip. Thus it may be that the buccally directed force resulting from significant rotation of the tooth may have been responsible for the overall buccal tipping moments.

For patient T.W, an alternating pattern of buccal and lingual crown tipping was evidenced on the right cuspid. The related moment values for this movement were fairly erratic and within +/- 150 g-mm. The erratic nature of the moment values was probably due more to the random error of the machine which has been discussed earlier.

Fig.4.8, also indicates the type of crown tip undergone by the left cuspid tooth. The overall lingual crown tipping observed, although only minimal, may have been due more to the extrusive force produced by this loop than to the buccal lingual moments seen in Fig. 4.8, which appear negligible.

Figures 5.1 and 5.2, show the general trends in tooth movement recorded for each of the patients. Due to the very small sample size, no specific implications can be drawn concerning the efficiency of one technique over another. However, some interesting trends can be seen.

In the case of linear movement, note that the primary objective of distal movement has been achieved. Also the clinically desired movement of transverse expansion has in general been recorded. It is also interesting to observe that, the vertical loops appeared to produce less extrusion. Implications concerning the inter-patient variation between these movements on the basis of age and time between appointments would be speculation. The important point here is that, considering the large changes in tooth position and the relatively small measurement error of 0.24 mm (95% confidence limit) it was felt these measured changes accurately reflected actual changes in tooth position.

As far as the rotational movements are concerned, note from Fig.5.2, that trends in movement in all three planes show reasonable similarity between patients. This is even more significant when one considers the small variation from original position in relation to the recorded measurement error for this aspect of the study i.e 3 degrees with a 95% confidence limit.

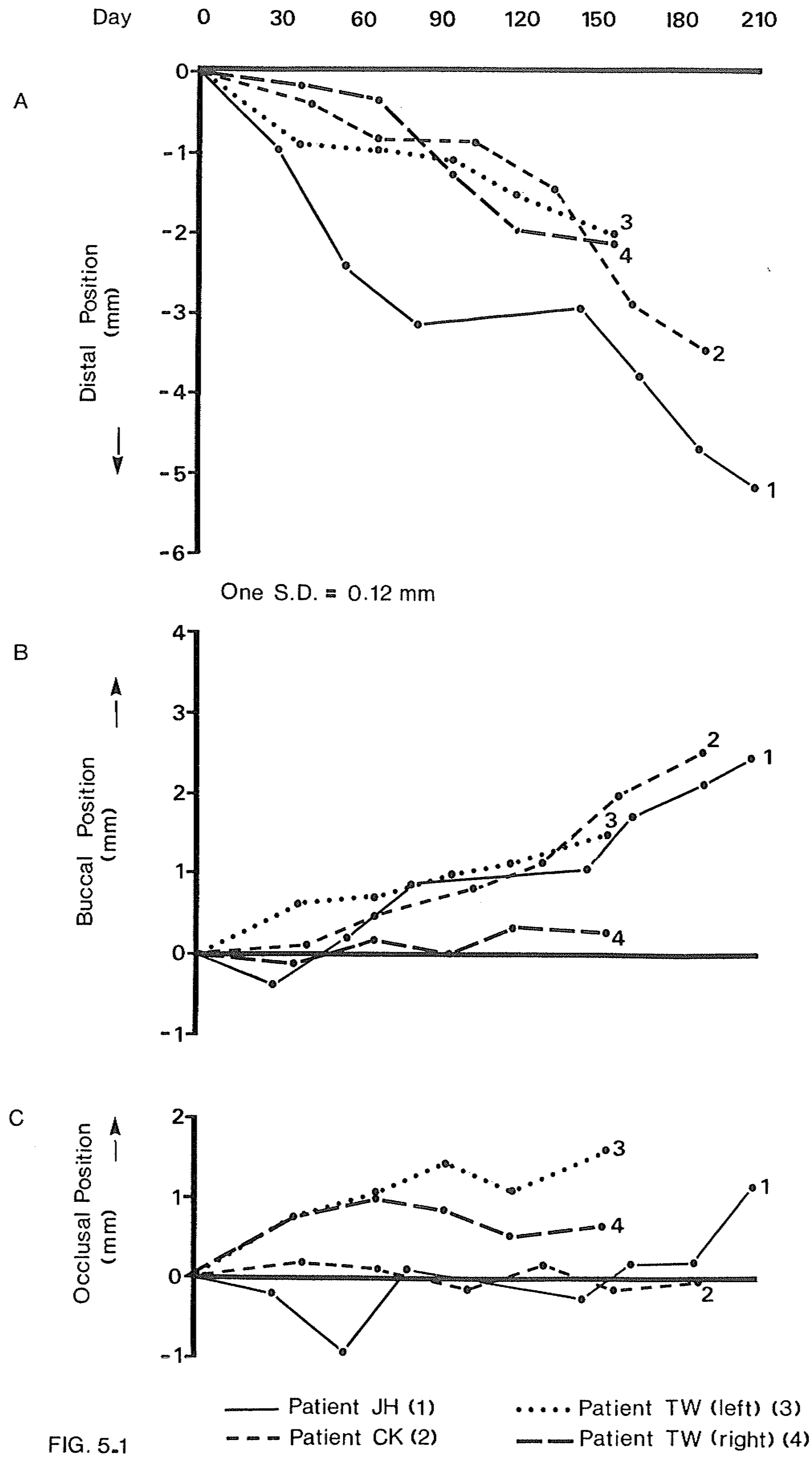
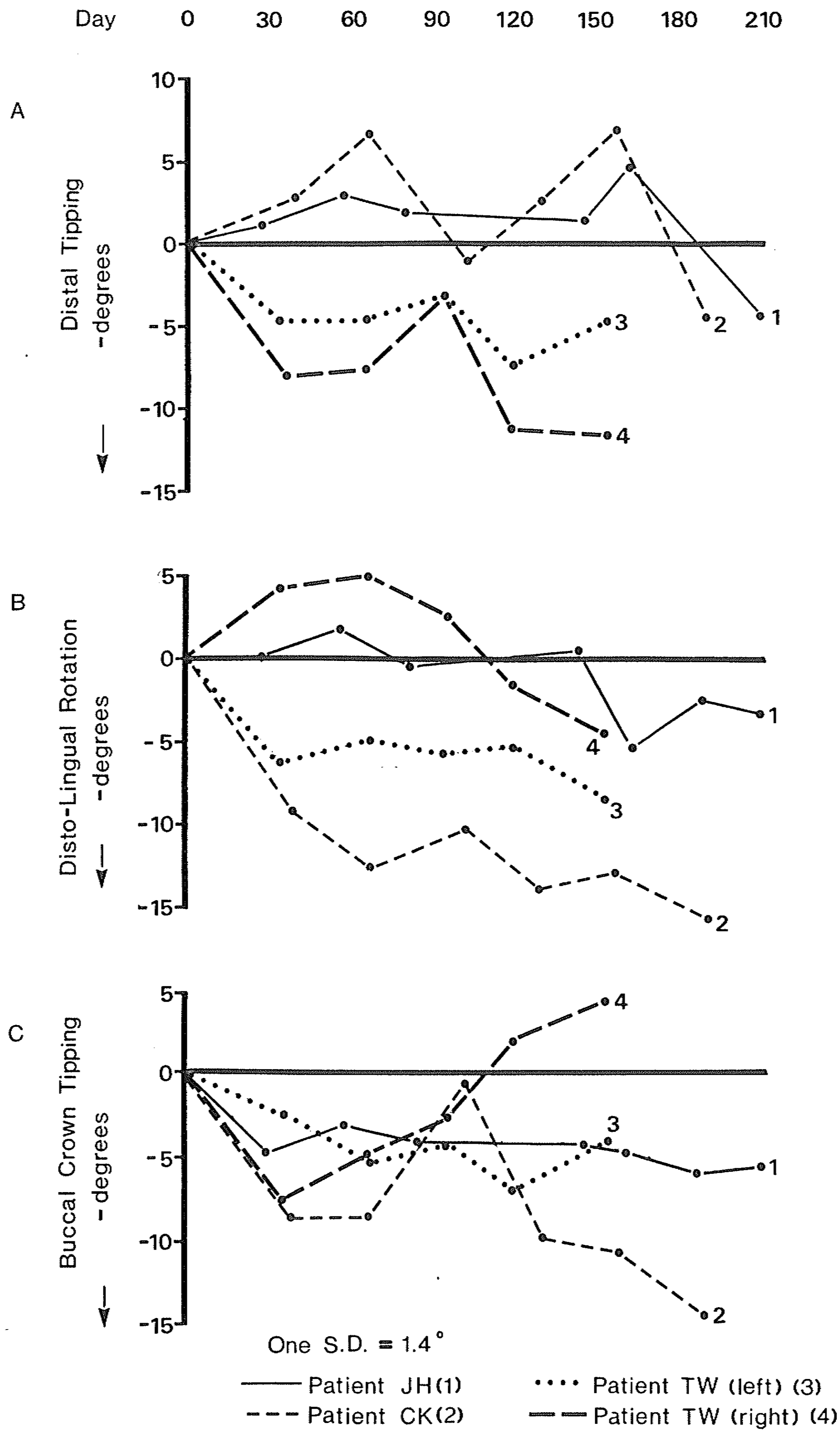

Day
0
30
60
90
120
150
180
210
A
Distal Position (mm)
0
-1
-2
-3
-4
-5
-6
One S.D. = 0.12 mm
B
Buccal Position (mm)
4
3
2
1
0
-1
C
Occlusal Position (mm)
2
1
0
-1
Patient JH (1)
Patient CK (2)
Patient TW (left) (3)
Patient TW (right) (4)

FIG. 5.1



Day 0 30 60 90 120 150 180 210
A
Distal Tipping -degrees
10
5
0
-5
-10
-15
1
2
3
4
B
Disto-Lingual Rotation -degrees
5
0
-5
-10
-15
1
2
3
4
C
Buccal Crown Tipping -degrees
5
0
-5
-10
-15
1
2
3
4
One S.D. = 1.4°
Patient JH(1)
Patient CK(2)
Patient TW (left) (3)
Patient TW (right) (4)

FIG. 5.2

5.5 Summary of Discussion.

The development of a technique to relate tooth movement to known force systems has been undertaken. The results of this study were considered an indication of the ability of this technique to achieve its desired objective. For any technique to be assessed it has to be used for its desired purpose. In the case of this study, the technique was used to describe cuspid retraction in a small sample of patients. The derived results reflect clinical expectations, especially in regard to measured tooth movement.

Stable reference points were developed in the mouth, from which other individual tooth movements were monitored. In this case, the three-dimensional linear and rotational movements of four cuspid teeth during retraction were measured. Results tended to indicate that the teeth were retracted with minimal untoward secondary movements.

The in vitro phase of the study showed that forces and moments could be measured in three dimensions at the initial and subsequent activation appointments. The error range of the present measuring machine was identified and accepted for the purposes of this study. With this in mind, the force and moment levels actually recorded tended to be reasonably constant for each activation.

This study was not intended to compare the advantages of one retraction technique with another. As a result, implications concerning the inter-patient variation in tooth movement and applied force systems cannot be made.

Factors such as sample size, age, inter-appointment timing and the possibility of biological variation have not been addressed in this study. The variations in measured tooth movement to the applied force systems are the only interesting observations generated from what is considered at this time, a reliable and valid technique.

6. CONCLUSIONS and RECOMMENDATIONS

6.1 Conclusions

The purpose of this study was to develop and assess a technique which could be considered useful in furthering the understanding between known applied force systems and resultant tooth movement. To this end, both an in vivo and an in vitro component was required. Analysis of the results led to the following conclusions:

1. The technique is a reliable and valid method for assessing changes in tooth position as a result of applied forces.
2. Careful preparation of anchorage resulted in minimal movement of posterior segments during retraction. Thus, a high degree of confidence can be placed in the stability of reference points.
3. Changes in linear tooth movement can be measured to within +/- 0.12 mm with a 95 % confidence limit.
4. Changes in rotational tooth movement can be measured to within +/- 3 degrees with a 95% confidence limit.

5. Loops can be duplicated to produce force systems which are within a +/- 20% range. This value was well within the error range for the machine in all the loops tested.
6. Measured tooth movements in general, tended to reflect clinical expectations. The primary objective of cuspid retraction was achieved in all cases. A significant increase in the transverse position of the cuspids was also recorded.
7. The movement of the studied teeth in most planes appears to be a jiggling process.
8. The studied teeth did not undergo any clinically unacceptable movements during retraction, even though no counteracting moment bends were placed in any of the loops.
9. Although it should be emphasised that no definitive statements can be made concerning variations in tooth movement in this study,some interesting observations did become evident;
   (i) Higher force magnitudes seemed to produce more distal movement and an increased rate of movement without producing an increase in untoward side effects.

(ii) The M/F ratio at the bracket varied from 4.5mm to 8.4mm. These variations appeared to produce no clinically significant effect on ultimate tooth positions. This indicated that the loops used had a constant M/F ratio and that they had completely deactivated at each visit.

10. Some aspects of this study were tedious and time consuming. However, these problems can be readily overcome with the acquisition of more expensive measuring apparatus.

In general, the techniques presented and assessed in this study are considered reliable foundations upon which more detailed studies concerning tooth movement and force systems could be based. It has reduced or controlled many of the variables which have been evident in past studies.

Refinements to the technique and application to various aspects of tooth movement studies could lead to a far greater understanding of the relationship between force systems and resultant tooth movement.

6.2 Recommendations for Future Research.

Based on the results of the present study, recommendations for future research include:

(A) The decrease of the maximum range of the measuring machine so that the impact of the full range error of the machine will be decreased.

(B) The study of tooth movement over shorter time periods for more accurate assessment of tooth response to known forces. Ideally, a day-to-day recording of tooth position would yield results concerning the magnitude of various primary and secondary movements during a particular procedure.

(C) The study of tooth movement using pre-calibrated loops, delivering identical force systems so inter-patient variation in tooth movement could be identified.

(D) Utilization of the Reflex Metrograph to facilitate the accurate measurement of tooth position and make studies using large samples of patients a more inviting prospect.

(E) The study of tooth movement in response to known force systems using a larger number of subjects and forces of varying magnitudes to pursue similar orthodontic procedures may permit a relationship between force magnitude and resultant tooth movement to be determined.

BIBLIOGRAPHY

Andrews, L.F. 1975. The Straight Wire Appliance. Syllabus of philosophy and techniques. Edition 2.

Bench, R.W.,C.F. Gugino, and J.J. Hilgers, 1978. Bioprogressive Therapy. J. Clin. Orthod. 12:123-139.

Berkowitz, S., and S. Pruzansky. 1968. Stereophotogrammetry of serial casts of cleft palate. Angle Orthod. 38:136-149.

Boester, C.H., and L.E. Johnston. 1974. Concepts of differential and optimal force in canine retraction. Angle Orthod. 44(2):113-119.

Broussard, G.J., C.J. Broussard, H.R. Buck, and G.J. Shia. 1964. Clinical application of the Broussard auxiliary edgewise bracket. Amer. J. Orthod. 50:881-899.

Buchner, H.J. 1953. Closing spaces in orthodontic cases. Angle Orthod. 23:158-165.

Burstone, C.J. 1962. The biomechanics of tooth movement in Vistas in Orthodontics. Kraus, R.S. and R.A. Riedel, R.A. (ed.) Lea and Febiger, Philadelphia.

Burstone, C.J. 1962. Rationale of the segmented arch. Amer. J. Orthod. 48:805-822.

Burstone, C.J. 1982. The segmented arch approach to space closure. Amer. J. Orthod. 82(5):361-378.

Burstone, C.J. 1985. Application of bioengineering to orthodontics IN: Graber, T.M. and Swain, B.F. (eds) Orthodontics: Current Principles and Techniques; C.V. Mosby Co, St. Louis.

Burstone, C.J., J.J. Baldwin, and D.T. Lawless, 1961. The application of continuous forces to orthodontics. Angle Orthod. 31(1):1-15.

Burstone, C.J., and K.J. Hanley, 1985. Modern Edgewise Mechanics, Segmented Arch Technique. A Technique Manual. Univ. of Connecticut Health Centre.

Burstone, C.J. and H.A. Koenig, 1976. Optimizing anterior and canine retraction. Amer. J. Orthod. 70:1-19.

Burstone, C.J., H.A. Koenig, and D.J.S. Solonche, 1973. Force system from two teeth bracket system. J. Dent. Res. Internat. Assoc. Dent. Res. 52:77 (ABS).

Burstone, C.J. and R.J. Preputniewicz, 1980. Holographic determination of centres of rotation produced by orthodontic forces. Amer. J. orthod. 77:396-409.

Chaconas, S.J., A.A. Caputo and R.K. Hayashi, R.K. 1974. Effects of wire size, loop configuration and gabling on canine retraction springs. Amer. J. Orthod. 65:58-66.

Christiansen, R.L. and C.J. Burstone. 1969. Centres of rotation within the periodontal space. Amer. J. Orthod. 55:353-369.

Croome, C. 1963. The principles and application of translatory cuspid retraction. Angle Orthod. 33:258-266.

Davis, H.D. 1983. Retraction of canines using bonded tube-brackets. Brit. J. Orthod. 10:187-197.

Farrant, S.D. 1976. An evaluation of different methods of canine retraction. Brit. J. Orthod. 4:5-15.

Fortin, J.M. 1971. Translation of premolars in the dog by controlling the moment to force ratio on the crown. Amer. J. Orthod. 59:541-551.

Gjessing, P. 1985. Biomechanical design and clinical evaluation of a new canine retraction spring. Amer. J. Orthod. 87:353-362.

Gottlieb, B. 1946. Some orthodontic problems in histologic illumination. Amer. J. Orthod. and Oral Surg. 32:113-133.

Halderson, H., E.E. Johns, and R. Moyers. 1953. The selection of forces for tooth movement. Amer. J. Orthod. 39:25-35.

Hanau, R.L. 1917. Orthodontic mechanics: dental engineering. Int. J. Orthod. 3:410-416.

Hirvonen, M.K. 1983. The effectiveness of loops in continuous arch therapy. University of Manitoba, M.Sc. Thesis.

Hixon, E., and P. Klein. 1972. Simplified mechanics: a means of treatment based on available scientific information. Amer. J. Orthod. 62:113-141.

Hixon, E.H., T.O. Aasen, J. Arango, R.A. Clark, R. Klostermean, S.S. Miller, and W.M. Odum. 1970. On force and tooth movement. Amer. J. Orthod. 57:476-489.

Hixon, E.H., H. Atikian, G.E. Callow, H.W. McDonald, and R.J. Tacy. 1969. Optimal force, differential force, and anchorage. Amer. J. Orthod. 55:437-457.

Huffman, D.J., and D.C. Way. 1983. A clinical evaluation of tooth movement along arch wires of two different sizes. Amer. J. Orthod. 83:453-459.

Jones, M.L., S. Ang and W.J.B. Houston. 1980. Frames of reference for the measurement of occlusal changes and the integration of data from orthodontic models and cephalometric radiographs. Brit. J. Orthod. :195-203.

Kusy, R.P. and C.J.F. Tulloch. 1986. Analysis of moment to force ratios in the mechanics of tooth movement. Amer. J. Orthod and Dentofac. Orthop. 90:127-131.

Lack, M.L. 1980. An investigation into the three-dimensional force and moment characteristics of selected cuspid retraction mechanisms. MSc. Thesis, University of Manitoba.

Lee, B.W. 1965. Relationship between tooth-movement rate and estimated pressure applied. J. Dent. Res. 44:1053. (ABS).

Levin, K.J. 1985. The influence of ligation methods on orthodontic forces and moments. University of Manitoba, M.Sc. thesis.

Levine, G. 1985. An investigation of intramaxillary anchorage with low modulus archwires. University of Manitoba, M.Sc. thesis.

McLachlan, K.R. 1987. Personal Communications.

Mitchell, D.L. 1973. Correlation of tooth movement with variable forces in the cat. Angle Orhtod. 43:154-161.

Nikolai, R.J. 1975. An optimum orthodontic force theory applied to canine retraction. Amer. J. Orthod. 68:290-302.

Oppenheim, A. 1944. A possibility for physiologic tooth movement. Amer. J. Orthod. 30:345-368.

Orton, H.S. and F. McDonald. 1985. A simple sectional canine retraction technique using the properties of nickel titanium rectangular wire. Europ. J. Orthod. 7:120-126.

Paquien, J.P. 1978. The measurement of forces and moments delivered by dental appliances. MSc. Thesis, University of Manitoba.

Paulson, R.C., T.M. Speidel and R.J. Isaacson. 1970. A laminagraphic study of cuspid retraction versus molar anchorage loss. Angle Orthod. 40:20-27.

Pryputniewicz, R.J., and C.J. Burstone. 1979. The effect of time and force magnitude on orthodontic tooth movement. J. Dent. Res. 58:1754-1764.

Quinn, R.S. and D.K. Yoshikawa. 1985. A reassessment of force magnitude in orthodontics. Amer. J. Orthod. 88:252-260.

Reitan, K. 1957. Some factors determining the evaluation of forces in orthodontics. Amer. J. Orthod. 43:32-45.

Reitan, K. 1960. Tissue behaviour during orthodontic tooth movement. Amer. J. Orthod. 46:881-900.

Richmond, S. 1987. Recording the dental cast in three dimensions. Amer. J. Orthod. 92(3):199-206.

Ricketts, R.M., R.W. Bench, C.F. Gugino, J.J. Hilgers, and R.J. Schulhog. 1979. Bioprogressive Therapy. Rocky Mountain Orthodontics.

Schwartz, A.M. 1932. Tissue changes incidental to orthodontic tooth movement. Internat. J. Orthod. 18:331-352.

Senior, W.B. 1985. A simple orthodontic appliance for dealing with a common canine problem. Brit. J. Orthod. 12:102-105.

Simon, P.W. 1924. On gnathostatic diagnosis in orthodontics. Int. J. Orthodontia, Oral Surg. and Radiography. 10:755-785.

Sleichter, C.G. 1971. A clinical assessment of light and heavy forces in the closure of extraction spaces. Angle Orthod. 41: 66-75.

Smith, R.J. and C.J. Burstone. 1984. Mechanics of tooth movement. Amer.J. Orthod. 85:294-307.

Smith, R., and E. Storey. 1952. The importance of force in orthodontics. The design of cuspid retraction springs. Austr. Dent. J. 56:291-304.

Sonya, D. 1987. Orthodontic tooth movement in response to known force systems: molar uprighting. University of Manitoba, M.Sc. thesis.

Storey, E. 1973. The nature of tooth movement. Amer. J. Orthod. 63:292-314.

Storey, E., and B. Smith. 1952. Forces in orthodontics and its relation to tooth movement. Austral. J. Dent. 56:11-18.

Strang, R.H. 1964. The value of a precision technique. Amer. J. Orthod. 50:113-114.

Takada, K., A.A. Lowe, and R. DeCou. 1983. Operational performance of the Reflex Metrograph and its applicability to the three-dimensional analysis of dental casts. Am. J. Orthod. 83:195-199.

Thurow, R.C. 1962. Edgewise Orthodontics, ed. 2, pp. 85-128, 142. The C.V. Mosby Company,St.Louis,

Utley, B.K. 1968. The activity of alveolar bone incident to orthodontic tooth movement as studied by oxytetracycline-incurred fluorescence. Amer. J. Orthod. 54:167-201.

Van Der Linden, F.P.G.M., H. Boersma, T. Zelders, K.A. Peters and J.H. Raaben. 1972. Three-dimensional analysis of dental casts by means of the Optocom. J.Dent. Res. 51:1100. ABS.

Waters, N.E., C.D. Stephans and W.J.B. Houston. 1975. Physical characteristics of orthodontic wires and archwires. Part 2. Brit. J. Orthod. 2:73-83.

Weinstein, S. 1967. Minimal forces in tooth movement. Amer. J. Orthod. 58:881-903.

Yang, T.Y. and J.J. Baldwin. 1974. Analysis of space closing springs in orthodontics. J. Biomech. 7:21-28.

Yoshikawa, K. 1981. Biomechanical principles of tooth movement. Dent. Clin. Nth. Am. 25:19-26.

APPENDIX A

Using the apparatus described in Appendix B, the three dimensional force and moment characteristics were quantified for both the vertical and "L" loop. The height of the loop in relation to the height of the centre of resistance, and the interbracket position of the loops were varied independently.

The procedures followed involved taking a reading from the measuring machine prior to ligating the loop in position. Once the loop was ligated in place a second reading was taken. This second reading was called zero, so as to negate the effects of ligation. The loops were then activated through 2 mm, with a reading being taken from the machine at 0.5 mm intervals. A final reading at zero activation was also taken, to determine whether any permanent deformation of the wire was evident. This procedure was repeated for each loop and for four interbracket positions. The data collected was transferred to an IBM computer and using a modified program, the location of the centre of resistance of the machine tooth could be varied in relation to the height of the loop. They were ;

(a) Centre of resistance at the bracket.

(b) Centre of resistance 5 mm occlusal to the height of the loop.

(c) Centre of resistance located at height of loop.

(d) Centre of resistance located 2.5 mm apical to the height of the loop.

(e) Centre of resistance located 5 mm apical to the height of the loop.

The interbracket distance for this study was set at 20mm. Four interbracket positions were investigated. Namely;

1. Centre (10mm).
2. Off centre 2.5mm towards cuspid bracket.
3. Off centred 5mm towards cuspid bracket.
4. Off centre 7.5mm towards cuspid bracket.

Table A.1 gives the derived moment to force ratios for both loops whilst varying the two design parameters. Negative values for M/F ratios indicate a distal tipping tendency. The table describes the distal tipping tendency resulting from a distally applied force.

Results from this study indicated that a more favorable M/F ratio could be achieved if the loops were;

(i) Placed more closely to the cuspid bracket, and,

(ii) Made higher than the height of centre of resistance of the tooth.

Interbracket Position

Ratio	Loop centred 1*	Loop 2.5mm off centre 2*	Loop 5mm off centre 3*	Loop 7.5mm off centre 4*
0	+1.1 +7.4	+2.2 +8.9	+3.7 +9.4	+4.6 +8.9
2.0	-3.9 +2.4	-2.8 +3.9	-1.3 +4.4	-0.4 +3.9
1.0	-8.9 -2.6	-7.8 -1.1	-6.3 -0.6	-5.4 -1.1
0.8	-11.4 -5.1	-10.3 -3.6	-8.8 -3.1	-7.9 -3.6
0.6	-13.9 -7.6	-12.8 -6.1	-11.3 -5.6	-10.4 -6.1

The far left vertical column describes the ratio between loop length and the height of the tooth's centre of resistance. The ratios (from top to bottom), correspond with the lettering a-e given in the text.

The top horizontal row describes the interbracket position of the loop(* numbering corresponds with the description given in the text).

The upper figure in each square represents the M/F ratio derived for the vertical loop.

The lower figure in each square represents the M/F ratio derived for the "L" loop.

Negative values indicate a distal tipping tendency.

Table A.1. Derived M/F ratios of loops with varying loop heights and interbracket positioning.

APPENDIX B

The measuring apparatus used in this study is basically a modification of that used in past studies by Lack (1980), Sullivan (1982), Hirvonen (1983), Levin (1985) and Levine (1986). The essential components of the machine are;

(a) A measuring system.

(b) A data acquisition system.

(c) A minicomputer.

For this study, the above mentioned instrumentation was also linked to an IBM computer with multiple display functions. Fig. B.1, shows the above instrumentation.

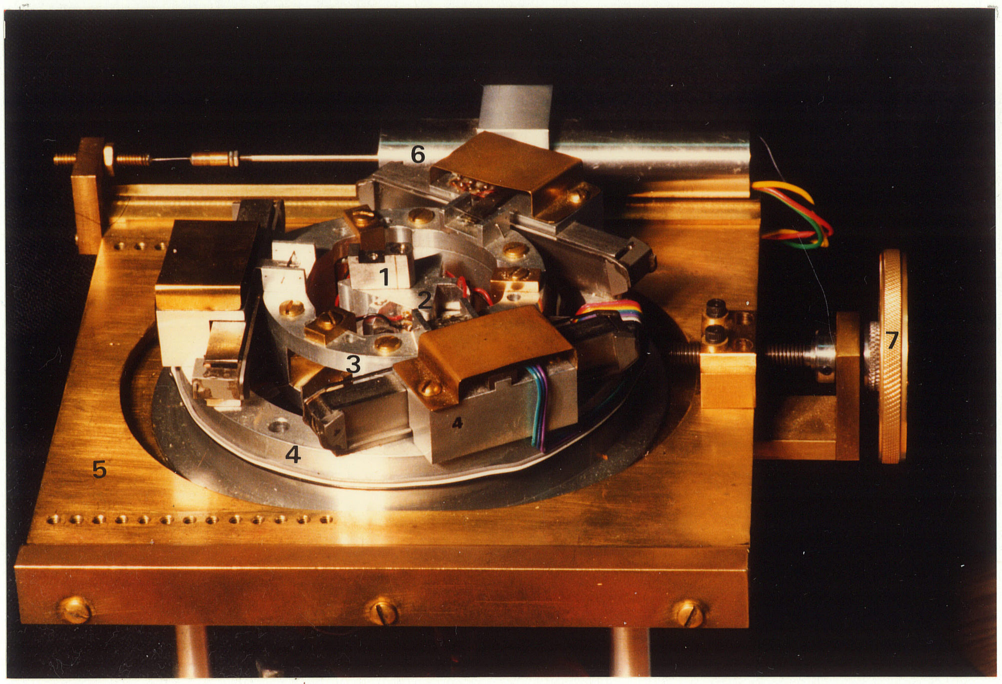
B.1 The Measuring System:

The measuring system makes use of six transducers arranged in a geometrical configuration which permits the computation of three forces and moments by a "linear combination of the six transducer responses" (Paquien, 1978).

There are four major parts to the instrument: the frame, an internal suspended ring, a triangular block and an electromagnetic vibrator. See Fig. B.2. Two types of transducers are used on the measuring machine. Type A transducers measure horizontal forces and the pivoting

1. Measuring machine.
2. Hewlett-Packard minicomputer.
3. Data Acquisition System.
4. IBM minicomputer.

Figure B.1. General view of measuring instrumentation.



1. Centre of measuring machine.
2. Triangular block.
3. Internal ring with Type A transducers.
4. External ring with Type B transducers.
5. Frame.
6. Linear voltage displacement transducer.
7. Adjustment screw.

Figure B.2. Detailed view of measuring instrumentation.

moment. Type B transducers are attached to the frame and to the suspended ring, and measure vertical forces and tipping moments.

It should be noted that due to the geometric layout of the measuring system, loops used in this study were analyzed in a horizontal position. As a result, the relationship between the axes of the measuring system and those of the measured tooth have been adjusted from those used in earlier studies. The axis system is represented in Fig. B.3.

The centre of measurement of the measuring system, and the centre of resistance of the measured tooth are coincident.

The measuring instrument has a maximum force range of 1000 grams and a maximum moment range of 20,000 gram millimetres. The machine has a total error range of +/- 3% of maximum force and moment values.

The Data Acquisition System and Minicomputer are those described by Lack (1980).

B.2 Computer Programs:

Modified programs were written for this study by McLachlan. They consisted of a data acquisition program and a data analysis program. In addition a data transfer program was written, which allowed collected data to be directly transferred to the IBM personal computer for storage and analysis. With these programs it was possible to change the effective centre of resistance of a measured tooth for a specific loop. Changes in the nature of the force system could then be assessed.

Relationship between the axis system in the measuring instrument and the forces and moments applied to the tooth.

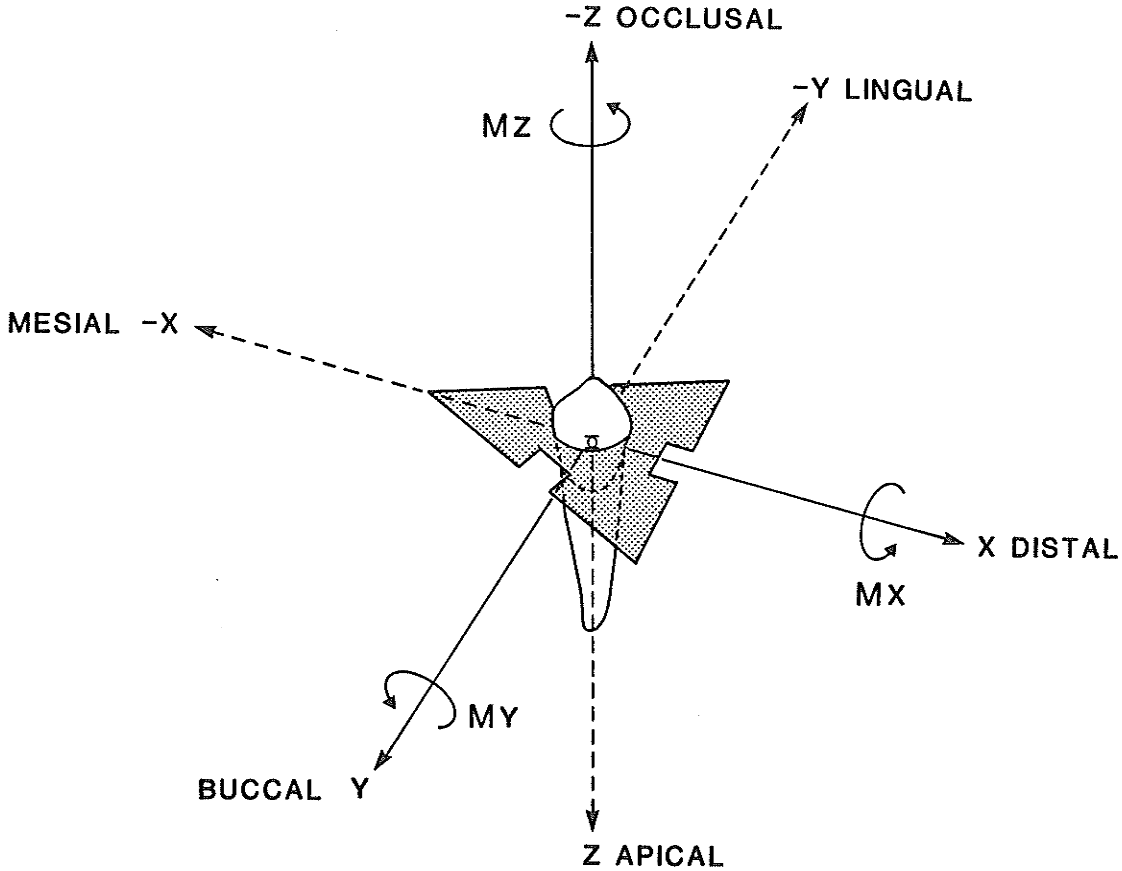


Figure B.3