THE UNIVERSITY OF MANITOBA

THE INFLUENCE OF LIGATION ON ORTHODONTIC FORCE AND MOMENT DELIVERY

THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF PREVENTIVE DENTAL SCIENCE
WINNIPEG, MANITOBA

BY

KEITH J. LEVIN

FEBRUARY, 1985

THE INFLUENCE OF LIGATION ON ORTHODONTIC FORCE AND MOMENT DELIVERY

BY

KEITH J. LEVIN

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

TABLE OF CONTENTS

ABSTRACT

A number of factors can lead to variability in the performance of an orthodontic appliance. The present study investigated the ligation process which couples the archwire to the bracket slot and its influence on force and moment delivery.

Equipment developed at the University of Manitoba for the examination of the three dimensional force and moment characteristics of orthodontic appliances was modified to achieve the present investigation into ligation.

Results were obtained by applying a variety of ligation techniques to a low-modulus orthodontic archwire .406 mm. (.016 inch) TMA. Steps were taken to minimize the presence of variables other than ligation. The archwire was applied to different situations of initial malalignment and alignment involving model teeth. A majority of the measurements were recorded from the center tooth of a three-tooth segment. Additional data was obtained from two-tooth segments. The data accumulated indicated the tendency for tooth movement in response to the ligated archwire. The results obtained suggest the following:

(1) Variation in ligation tension influenced the initial alignment force by a factor of between 2:1 and 3:1 depending upon the geometry of the initial malalignment.

(2) Variation in ligation tension significantly altered the load deflection rate of the low modulus archwire studied.

(3) The alignment force provided by the low modulus archwire often fell to zero or a subthreshold level before the teeth

were aligned. Ligation technique and initial malalignment geometry influenced this tendency.

(4) Secondary, or spurious forces frequently encountered during tooth alignment would result in a loss of three dimensional control over tooth position. These secondary forces are largely influenced by ligation tension.

(5) Ligature technique and to a lesser extent initial malalignment geometry influence the presence of friction.

(6) Frictional forces typically encountered when ligating low modulus archwires are capable of influencing the effective tooth alignment force.

(7) Elastomeric ligation provides the best overall performance with the low modulus archwire tested.

(8) Under controlled conditions consistent ligation is possible. Intraorally, however, the variability associated with ligation may be greater and would be contributed to by differences in interbracket dimension and initial tooth malalignment.

This thesis is dedicated to the memory of
my father, the late Dr. Samuel R. Levin.

ACKNOWLEDGEMENTS

I would like to thank a number of people involved in the completion of this thesis.

I am indepted to my advisor, Dr. K.R. McLachlan, without whom this thesis would not have been possible. His understanding and inspiration were of of tremendous benefit and were deeply appreciated.

Many thanks to Mr. H.J. Clark, of the Civil Engineering Workshop, for the help and craftmanship he provided in developing this project.

My sincere appreciation is extended to my committee members, Dr. A.T. Storey and Dr. D.M. Smith, for their valuable comments and suggestions.

The typing skills of Mrs. Joanne Gilbert and the artistic ability of Mr. John Gustavson were essential for the presentation of this thesis and were greatly appreciated.

The friendship and comradery of my classmates, Dr. John Campbell and Dr. Rafael Martinez will be treasured forever.

Finally, I would like to thank my family and Heather for their support and understanding throughout this program.

LIST OF FIGURES

Figure Page

Figure Page

LIST OF TABLES

Table Page

CHAPTER I

INTRODUCTION

INTRODUCTION

To achieve optimal patient care, the orthodontic profession should strive to use treatment modalities that it thoroughly understands and effectively control to ensure that treatment is as biologically compatible and mechanically precise as possible. The fixed multibanded appliance is widely used. Although it is mechanically complex the orthodontist should attempt to understand its capabilities and limitations and what factors can influence these parameters. When using this appliance the pracitioner should try to control the factors which could lead to variability in its performance if treatment is to be carried out in a consistent mannner.

Orthodontic research has examined the influence of various physical characteristics of the fixed appliance on the delivery of forces and moments to the teeth. However by no means have all the sources of variability been elucidated. In particular, the nature of the ligation process which couples the archwire to the bracket slot provides a source of variability. The degree to which the operator can control the ligation process is also uncertain. The purpose of this investigation was to examine these particular variabilities. In order to do this an attempt was made to control as many of the variables influencing force and moment delivery as possible and concentrate on the influence of the ligation process.

Equipment at the University of Manitoba previously used to investigate the simultaneous three dimensional force and moment characteristics of orthodontic appliances was modified to achieve the present investigation into ligation, and its influence on force and moment delivery.

CHAPTER 2

REVIEW OF THE LITERATURE

REVIEW OF THE LITERATURE

It is desirable to eliminate or diminish uncontrolled variability in tooth movement when providing orthodontic treatment. To this end several authors have commented on the need for greater control during mechanotherapy. Isaacson and Burstone (1976) stated that if tooth movement is to be predictable the clinician must be able to deliver predictable force systems. They suggested that it would be useful to determine whether there is such a thing as optimum stress on the periodontal membrane to move teeth as rapidly as possible with minimal tissue damage and discomfort. Pryputniewicz and Burstone (1979) reiterated the knowledge that the relationship between an applied force system and the resulting tooth displacement plays an important role in predicting tooth movement. They also claimed that to understand the response of a tooth to various loads it is necessary to determine the displacement characteristics of the loaded tooth along all three axes simultaneously. An interest in quantification of the result of applied force systems has been present in the orthodontic literature for some time. In 1917 Hanau suggested making mathematical predictions of the amount of tooth movement in response to a specific force in a specific time, followed by a comparison with the actual tooth movement. He suggested differences could be due to different tissue resistance than had been predicted. Presumably any differences detected could be used when planning future treatment procedures. Strang (1964) stated that a precise force application technique was desirable so that one could be assured of positive results when the technique is applied correctly, eliminating trial and error procedures and decreasing the necessity for clinical experience. An awareness of force distribution is important for a number of reasons in establishing a precision technique (Waters _et_ _al_, 1975b).

In this review of the literature mechanical elements of fixed orthodontic appliances and their associated variability will be discussed. Various aspects of biological criteria essential to proper mechanotherapy including the concept of optimal force will be considered. Finally literature directly relevant to ligation and its subsequent influence on orthodontic force systems will be reviewed.

Mechanical Factors Influencing Force Delivery

As early as 1933 investigators were aware that orthodontic archwires behaved as beams constrained or supported at the brackets or tubes placed on the teeth (Peyton and Moore, 1933 a and b; Richmond, 1933 a and b; Brumfield, 1937; Sved, 1937). Mechanical elements of beam deflection theory are factors which influence the delivery of orthodontic force and are well represented in the engineering literature (Warnock and Benham, 1970).

The load deflection rate (LDR) is, by definition, the amount of load necessary to produce a unit deflection of a beam or an archwire. It has also been referred to as spring constant or spring gradient and is constant within the proportional limit of any material and geometry. For orthodontic purposes it may be simplest to regard it as the stiffness of the archwire and to examine the influence of various factors (Burstone et al, 1961; Jarabak and Fizzell, 1972; Waters, 1976; Thurow, 1982). Consideration of the relationship between these factors and archwire stiffness yields an equation of the form:

$$\frac{W}{df} = \frac{kEI}{\ell^3}$$ in which

W = load
df = deflection
$\frac{W}{df}$ = stiffness
E = modulus of elasticity
I = second moment of area
ℓ = beam length
k = a constant depending on beam constraint

This equation precisely outlines the interrelationship of the elements of beam deflection theory.

The modulus of elasticity (E) represents the slope of the stress/strain curve. It is an inherent mechanical property of a particular alloy and varies between different types of archwire material. For example its value is lower for beta-titanium alloys then for stainless steel alloys and is lower yet for nickel-titanium alloys (Burstone, 1981). Stiffness of the beam varies directly with changes in the modulus of elasticity. It has been suggested that variation in test span length may influence the value derived for E in mechanical testing (Brantley et al, 1978).

The second moment of area (I) of an archwire will depend upon its shape and dimension. For round wires $I = \frac{\pi d^4}{64}$ and thus beam stiffness will be proportional to d^4 where d is the diameter of a round archwire. For rectangular wires $I = \frac{bh^3}{12}$ where b represents the dimension perpendicular to the direction of loading and h represents the dimension in the plane of loading. Beam stiffness for rectangular wires will vary with both dimensions but is more sensitive to changes in the direction of load application (Burstone, 1981; Hocevar, 1981).

Beam length (ℓ) is typically thought to represent interbracket distance in orthodontic application of beam theory and has been widely reported as such in the orthodontic literature (Sved, 1937; Stoner, 1960; Burstone, 1962a; Creekmore, 1976). However, in practice it may not be entirely accurate to equate interbracket distance with effective beam length. It more correctly should be considered the distance between points of constraint along the archwire. Some orthodontic investigators have more accurately considered beam length in terms of the manner of constraint and the distance between constraints (Jarabak and Fizzell, 1972; Waters, 1976; Waters et al, 1975b, 1981; Sullivan, 1982, Thurow, 1982). Beam stiffness is inversely proportional to ℓ^3 and thus small changes in beam length can dramatically alter the force level achieved with a given deflection of a particular wire.

The constant, k, present in the stiffness equation given above represents the type of beam constraint configuration being examined. In a cantilever beam situations (eg. an accessory arm extending from an archwire) the value for k=3. If the beam is supported at each end and a load at the midpoint of the span is considered, k=48. If the beam is fixed or constrained at each end and a load at the midpoint of the span is considered, k=192. These three situations represent only a small sample of the wide variety of possible beam configurations and resultant constants. For a more complete listing the reader is referred to Oberg and Jones (1944). Thus a change in k from 192 to 3 can result in constraint altering beam stiffness by a factor of 64:1. Apparently similar beam or archwire situations can have different constraint factors due to the ligation process and in actuality beam stiffness may be increased 400%. The influence of beam constraint on its stiffness has been reported in the orthodontic literature (Sved, 1937; Newman, 1963; Jarabak and Fizzell, 1972; Waters, 1976; Waters _et al_, 1975b, 1981; Sullivan, 1982; Thurow, 1982).

Factors influencing beam stiffness and the force levels achieved by orthodontic appliances seem to be well known and widely reported in the literature. However unwanted variability in tooth movement exists and its source, though not clearly established, may be broadly considered as being either biological or mechanical in nature.

Biologic Response to Orthodontic Force

The exact nature of the biologic response to orthodontic force application is unknown at a cellular level (Rygh, 1984). Theories to explain the initiation of the biologic response have included oxygen tension, secondary chemical messengers and piezoelectric effect.

Isaacson and Burstone (1976) stated "Relatively little is known about the effects of force systems on patterns of tooth displacement. What we do know is derived from clinical observation, simple mathematical models and inadequate experimental approaches." They suggested that there is a need to establish correlations between stress pattern established and the biologic response to them. This has been attempted by several investigators in the past. Some of the more notable authors dealing with this subject include Schwarz, 1932; Oppenheim, 1944; Reitan, 1951; Utley, 1968; Rygh, 1972, 1973; all of whom investigated the periodontal reaction to applied forces in a variety of animal and human models. All of these authors, along with Storey (1973) concluded that there is a range of biological reactions depending on force level.

Burstone (1962b) described three levels of observation to describe tooth response to force. Firstly, clinical, which involves symptomatic description such as rate, pain, mobility, bone loss and root resorption. Secondly, cellular, including bone dynamics and connective tissue changes. Thirdly, stress-strain relationships, which Burstone feels is the most important and the least understood. Stress determined at different areas of the periodontal membrane (PDM) would provide the best opportunity to correlate force application with tooth response.

In a later article, Burstone (1981) described four categories of force magnitude and biological response achieved by various amounts of archwire displacement. Firstly, excessive force, which results in undermining resorption and tissue damage. Secondly, optimal force which yields direct resorption. Thirdly, suboptimal force which also achieves direct resorption but at a lower rate. Finally, subthreshold force which does not produce tooth movement. He also suggested tipping tooth movements would have a lower threshold than bodily tooth movement.

Biological Variability

A number of papers have suggested a biological basis for variability in orthodontic response.

As early as 1927, Irish found there were various patient reactions to the same force. This finding was reiterated by Orban (1936) and Oppenheim (1936 a and b). In 1944 Carey observed that a previous "bone disturbance" would result in a different rate of tooth movement.

Moyers and Bauer (1950) stated that speed of the clinical response would be determined by the PDM response. They concluded that blood supply was further restricted with bodily tooth movement as compared to tipping movement and this resulted in a latent response. Storey and Smith (1952) felt it was difficult to determine the distribution of applied force over the contact area between tooth and bone. They suggested that the pressure, not the force, exerted at the interfaces between tooth, PDM and bone was significant. In a later article Storey (1973) concluded that a bodily applied force, compared to a tipping one, would result in slower tooth movement.

Halderson (1961, Halderson _et al_, 1953) stated that tooth movement was determined by the speed with which circulation was reestablished in pressure areas. Individually variable natural forces including muscle contraction, blood pressure and air pressure could influence tooth response.

Reitan (1957, 1960) found variation in tissue response within subjects of similar age groups and between non-adult and adult groups. He encountered hyalinized areas less frequently in bodily tooth movement versus tipping movement. Such areas were unavoidable in some cases, such as those with short roots.

Stoner (1960) suggested it was not likely that all teeth required an identical minimal force to move them. Determining factors would include: direction of tooth movement; density of the bone; and size of the root. Burstone et al (1961) proposed the following influences: root length, diameter and contour; nature of PDM; and site of force application. Neuger (1967) stated that identical torquing auxiliaries would achieve varying results due to individual dental characteristics such as axial inclination and intercanine width. Schwartz (1967) felt there were many variables that could influence the orthodontic result in spite of a properly designed appliance. These include patient cooperation, tissue response, and morphogenetic limits. He also proposed that biomechanics should not neglect internal forces such as tissue resistance and muscle pressures.

A series of investigators have concluded that biological variability plays a role in tooth response based on data they collected. Andreason and Johnson (1967), comparing human tooth movement in response to forces of various levels, found large intra-group variability. Utley (1968), in an elaborate study performed on cats, found that cuspids of the same arch moved in similar fashion regardless of different magnitudes of force and that each animal had an independent rate of tooth movement. Hixon et al (1969, 1970) found a large variation in response between patients. The 1970 study involved bodily cuspid movement into an extraction space and metallic intra-bony implants as references from which to assess the response. In both studies, attempts were made to control the forces and moments being delivered. The authors recognized sources of mechanical variability in their 1969 study and attempted to eliminate them in their 1970 work. However, even the more stringent method used in their later experiments could not completely assure the uniformity of the forces and moments acting on the measured teeth. They observed wide variation in responses between individuals. The 1970 study concluded "These data indicate that the major source of variation is probably not the magnitude of force but variation in metabolic response" and that "The variation in the physiologic or biochemical response of the tooth supporting apparatus is large." Both studies found great variation when an attempt was made to define root areas for selected mandibular teeth. Sleichter (1971), studying cuspid retraction in humans, hypothesized that production of cell free zones may not deter tooth movement for a significant length of time. He suggested these zones could contribute to the inter-individual response variation to similar force levels and the intra-individual response similarity to dissimilar force levels that he found. Huffman and Way (1983), also studying cuspid retraction in humans, concluded that, as a result of biological variation, the rate of tooth movement may vary between individuals.

Considerable evidence for biological variability has been presented. One should keep in mind, however, the potential influence of mechanical variability and the difficulty in ascertaining the actual forces and moments delivered intra-orally.

Optimal Force

In spite of a number of investigators suggesting wide biological variation the orthodontic community has long sought to establish a value for the optimal force to move teeth. Although various authors differ strongly on its exact characteristics it can be generally interpreted as representing a force or stress capable of moving teeth as rapidly as possible with minimal tissue damage and discomfort (Isaacson and Burstone, 1976). In characterizing an optimal force it should be realized, based on previous discussions, that it is actually pressure, or force/area that must be optimal and the area in question represents the contact patch between root surface/PDM, PDM/alveolar bone, or less favourably root surface/alveolar bone. This area, as already mentioned, may vary depending on the physical characteristics of the tooth and on the type of tooth movement being attempted (eg. bodily versus tipping movement). Thus, for statements of optimum force to be meaningful they should actually be descriptions of optimal pressure or at least describe optimal forces for particular teeth and/ or particular types of tooth movement. In characterizing an optimal force system there is an obligation to consider the nature of the applied force over time (eg. continuous versus intermittent), or its duration. Unfortunately few articles address all of these considerations and many widely held clinical beliefs and assumptions would seem to be based on information that may be incomplete.

Hanau (1917) was one of the first to suggest the importance of gentle continuous forces. Schwarz (1932), in a landmark paper on optimal force, suggested orthodontic treatment without necrotic regions in the PDM could be achieved only if the force (pressure) applied to the PDM was less than the pressure in blood capillaries, namely 25 gm/cm^2. A large part of Schwarz's conclusions appear to stem from histologic findings based on moving teeth in a dog by use of a recurved finger spring. The force delivered was stated to be 3 gm. at one end of the spring, 67 gm. at the other and 15-20 gm. in the middle. No explanation of how the spring was calibrated or measured was provided. The teeth moved by the middle part of the spring displayed ideal histologic criteria and thus was born the optimal force (pressure) value of 20-25 $gm./cm^2$ coinciding with the value of blood capillary pressure.

Richmond (1933 a and b) commented on earlier investigations suggesting a maximum force of 85 gm. He recommended a physiologic maximum to be 280 gm. Oppenheim (1936 a and b) stated that it was impossible to move teeth in a way that imitated natural movement of teeth, even if light intermittent forces were applied, and unavoidable damage would increase with continuous force. He advocated rest periods between application of force. Orban (1936) concluded that continuous force is biologically preferable because it will not reduce the activity of the resorbing connective tissue. Interestingly, in a 1944 article Oppenheim seemed to partially reverse his previous conclusion and stated that light continuous forces would reduce osteoid formation, maintain PDM width and increase the number of osteoclasts and thus were more desirable than light intermittent forces. However he also stated that clinically it is difficult to achieve forces light enough to approach physiologic tooth movement. Thus periods of rest between force application were considered advisable.

Stuteville (1938) and Paulich (1939) both reviewed the literature pertaining to optimal force. Stuteville concluded that teeth could be moved biologically if the applied force did not produce ischemic areas and suggested a light force was approximately 5 gm., while heavy forces were in the range of 150-200 gm. He considered the important points to be the amount of force, the distance through which the force was active, and the presence of interfering forces of occlusion. Paulich stated that the general feeling was that optimal force was continuous and less than 25 gm./cm ^{2} , and heavy forces were tolerated only if they were intermittent.

Sved (1948) preferred intermittent forces as these would avoid rearranging bone trabeculation parallel to the applied force. He suggested light pressure and felt increased force wouldn't result in increased tooth movement.

Several authors reiterated Schwarz's ideas on optimal force or pressure appeared on several occasions long after they were originally proposed. Moyers and Bauer (1950) concluded a force of 15 to 25 gm.

acting over a distance of .2 mm. would be ideal. They did not comment on the change from a unit of pressure to a unit of force. They suggested that edgewise appliances do not usually deliver such forces. Halderson et al (1953) essentially reiterated these findings. In later papers Halderson (1957, 1961) suggested forces less than capillary pressure were ideal, minute forces would be 25 gm./cm ^{2} and light force was 30 to 115 gm. He did not account for the shift between units of force and units of pressure.

Storey and Smith (1952) found that no specific values for heavy force had been settled upon. Their experimental findings concluded that 150 to 200 gm. of retractive force was optimal for distal cuspid movement and 300 to 500 gm. resulted in maximum mesial molar movement. Forces below 150 gm. resulted in practically no tooth movement and those below 300 gm. achieved no appreciable molar movement. They concluded that it is not force, but rather pressure at the interfaces between the tooth, PDM, and the bone that is significant. Begg (1956) quoted, and largely agreed with, Storey and Smith's figures and with their ideas on differential force as a treatment technique.

Reitan (1957) found periodontal tissue generally reacted more favourably to interrupted continuous or intermittent force than to continuous force. He suggested 150-250 gm. for bodily retraction of the maxillary cuspids, 100-200 gm. for mandibular cuspids and 500 gm. as being too strong for any bodily tooth movement. He found 25 gm. satisfactory for extruding individual anterior teeth and felt direct resorption would occur if torquing procedures were carried out with 130 gm. force at the apex. In a later paper (1960) Reitan suggested

130 gm. to be a light force for bodily movement and 25 gm. a light force for tipping. He found hyalinized areas with 25 gm. or 125 gm. of tipping force, but less extensive areas with the lighter force.

Stoner (1960) concluded that a force that is optimum for one type of movement may be ineffective or traumatic for another, suggesting the importance of considering area in deriving optimal force.

Burstone and Groves (1960) found optimal maxillary anterior retraction occurred with 50-75 gm./quadrant, with no increase in rate of movement accompanying forces above this value. They also concluded that 25 gm./quadrant was above the threshold value, if one existed.

Burstone _et_ _al_ (1961) questioned the desirability of continuous forces if high load deflection rates are used but pointed out that constant force was desirable. Burstone (1962 a and b) went on to state that an ideal retractive force was constant and optimal force would result in direct bone resorption needing no time for repair. He also concluded that threshold forces may differ for different types of tooth movement.

A force of less than 2 gm. exerted by buccal musculature was capable of moving premolar teeth in a study reported by Haack (1963) and Weinstein (1967). Total tooth movement in 50 days amounted to less than .1 mm.

Newman (1963) suggested light continuous forces of 28 gm. to 113 gm. achieved direct alveolar bone resorption while heavy intermittent forces greater than 225 gm. resulted in undermining resorption, osteoid formation and retarded tooth movement.

A number of investigators have questioned the concept of optimal force as proposed by Storey and Smith and the differential force theory of Begg. Andreason and Johnson (1967), using eccentric headgear, found 400 gm. moved maxillary molars distally more rapidly than 200 gm. In an investigation of cuspid retraction in cats, Utley (1968) compared three force levels; light (40-60 gm.), medium (135-165 gm.) and heavy (400-500 gm.) and found the tooth moved equally in rate and amount regardless of force level. Hixon et al (1969, 1970) studied cuspid retraction in humans and concluded in 1969 there was "...little evidence to support the theory of optimal forces" since forces 3-4 times greater than advocated were capable of moving teeth. In 1970 they also concluded there was "...no evidence to support the idea of differential force." Cuspid retraction with light force (150-200 gm.) versus heavy force (1200-1500 gm.) was studied by Sleichter (1971). He found no difference in rate and suggested that any force between 150 and 1500 gm. would result in space closure of about .5 mm. per week. Boester and Johnston (1974) investigated cuspid retraction with four different force levels and concluded that 57 gm. gave significantly less movement than 142 gm., 227 gm. and 312 gm., with no significant differences between the latter three levels. Andreason and Zwanziger (1980) also studied cuspid retraction and molar movement with light (100-150 gm.) and heavy (400-500 gm.) forces. They found that, generally, both molar and cuspid moved, with increased force resulting in increased movement, and questioned the uniformity of response suggested by Storey and Smith (1952). Huffman and Way (1983) used 200 gm. to retract cuspids and observed a rate of movement very similar to that achieved by other investigators using

50-75 gm. or 600 gm.

A number of authors have considered the importance of factors other than rate of tooth movement in deriving an optimal force concept. Gianelly and Goldman (1971) recommended assessment of root area, number of teeth to be moved and the intended type of movement. They also commented on biological variables previously discussed such as bone density, ligament elasticity and root conformation as factors capable of influencing the relationship between applied force and resultant tooth movement. Jarabak and Fizzell (1972) proposed an optimal pressure of 2-2.5 gm./mm^2, with the value varying between teeth and between patients. Root size and type of tooth movement (bodily versus tipping) are variables to consider in establishing optimal pressure in their opinion, since, "...root pressure is the important factor in determining tooth movement, not force applied to the crown." Andrews (1975) suggested 600 gm. as an optimal force to retract cuspids. He felt a higher than typically suggested force (200-300 gm.) was necessary because with bodily movement versus tipping being attempted, force was more evenly distributed over the root surface. Ricketts _et al_ (1979) offered a table of optimal forces depending on the proposed tooth movement and root size based on an optimal pressure of 100 gm./cm^2 of root surface exposed to movement.

The literature does not permit one to arrive at definite conclusions as to what single force or pressure is best to move teeth. The biological variabiltiy previously discussed, as well as the frequent lack of consideration of root area no doubt contribute to the wide array of values presented as appropriate goals to strive for in establishing a mechanical treatment plan. Lack of accuracy in establishing the force (or pressure) values actually applied may have contributed to the lack of agreement over optimal force. For example, what one considered to be 150 gm. and another called 300 gm. may in fact have been the same force. While there is obvious variability in the definiton of "light-force" there is also variability between orthodontists regarding the mechanical techniques considered capable of delivering such force.

Clinical Beliefs

The orthodontic community has long considered "light" archwires as being capable of delivering light forces and that such forces were biologically harmonious or physiologic. Halderson et al (1953) considered beginning treatment with light round wires sound therapy since it took full advantage of tipping movements and involved lighter forces than heavier wires. Ackerman et al (1969) felt multilooped archwires were no longer necessary with the availability of highly resilient archwires and suggested .012 inch (.3 mm.) diameter (stainless steel) engaging all teeth, as an initial archwire. Drake et al (1982) concluded beta titanium archwires eliminate the need for looped archwires. The assumption underlying these statements is that multilooped archwires could be abandoned because of the light forces available with other methods.

Numerous authors have questioned the ability of orthodontic appliances to deliver forces light enough to comply with previously held beliefs of optimal force. Others have doubted the correlation between the force system intended and the one actually present clinically. One of the most widely quoted researchers on optimal force felt that claims suggesting ideal orthodontic force can result in tooth movement with only frontal absorption should be treated with reservation (Storey, 1973).

As early as 1933, Richmond (1933 a and b) suspected that few orthodontists could guess within 75% the amount of pressure exerted at a given attachment. He cited the example of a lingually displaced premolar reversing the applied force at the neighbouring molar from the expansion effect originally intended in the archwire.

In 1937 Sved demonstrated that force levels of nearly 1100 gm. would occur with .25 mm. displacement of a heavy archwire over typical interbracket distances.

Oppenheim (1944) found undermining resorption when light forces were used and concluded the "suspicion may be justified that supposedly light forces are still too great."

Greater discomfort of some patients in light force areas than in heavy force areas led Sleichter (1971) to conclude that in many light force appliances there are several heavy, less obvious forces present. For example, Steyn (1977) concluded that when torque was applied to maxillary incisors the laterals were subjected to appreciably more force (moment) than the centrals. This condition would be further aggravated by the typically smaller root surface of the lateral as compared to the central incisor.

Burstone et al (1973) demonstrated commonly accepted clinical assumptions regarding force systems and orthodontic wire configuration to be false. Koenig and Burstone (1974b) mathematicaly evaluated the force from a 6 mm. closing loop fabricated from .016 inch (.15 mm.) round stainless steel activated 1.3 mm. to be slightly over 500 gm.

Waters et al (1975b and 1981) concluded that in spite of the widely held belief that light forces should be used, archwires conventionally used for initial tooth alignment generate high forces even when deflected only small amounts. Waters et al went on to state that an appraisal of the appropriate levels of orthodontic force may be due. The authors suggested a number of protective mechanisms that act to diminish the delivery of heavy forces:

(1) some plastic deformation of the wire occurs even with small deflection,
(2) especially with heavy loads, some tooth movement occurs almost immediately, thus decreasing the load,
(3) force is dissipated throught interdental contacts,
(4) binding occurs between archwire and bracket,
(5) bending of the alveolar process may occur.

The clinician does not have direct control over many of these factors or may not be aware of the extent to which they occur, and thus not attempt to influence them.

In 1982, Sullivan conclusively demonstrated that archwires considered to be "light wire" appliances actually delivered forces and moments that would be considered to be excessive from a study of the orthodontic literature. He felt these biologically high forces should either be accepted as satisfactory by the orthodontic community or else alternative techniques to achieve lower forces should be sought.

Mechanical Difficulties in Delivering Optimal Force

There are mechanical difficulties in delivering optimal forces. To overcome these difficulties, the orthodontist must be aware of them, and understand them.

In 1950 Moyers and Bauer concluded that appliances capable of delivering bodily movement were the most difficult to adjust to achieve lighter ranges of forces.

It was observed by Storey and Smith (1952) that rate of tooth movement changed as force delivered changed during reactivation of their cuspid retraction appliance.

Halderson _et al_ (1953) concluded nearly all forces associated with edgewise mechanics are high and treatment is successful due only to the short distance through which the appliance is activated and to sufficient time between activations to allow tissue recovery.

Burstone _et al_ (1961) advised considering a number of factors in designing an orthodontic appliance to achieve a particular force delivery. These included:

1) the relationship between force and activation
2) the load that results in permanent deformation
3) the range of activation within the elastic limit.

The authors noted with a lower load deflection rate (LDR) there would be more constant force during loading. The LDR may change with large deflections due to a change in archwire configuration. It is important to keep the final load of the wire less than its maximum to minimize the risk of permanent distortion.

A year later Burstone (1962a) commented that small interbracket distances typically present in multibanded appliances result in high LDR, and increasing this distance reduces the LDR and results in less force change as tooth movement occurs. He considered the limiting factor in decreasing the cross section of an archwire to reduce LDR to be avoiding a concommitant decrease in maximum elastic load to a point where permanent distortion can occur with accidental loading during activation of the appliance. Burstone stated that any design factor which reduces archwire stiffness adjacent to the malpositioned tooth results in increased reciprocal forces on adjacent teeth. If a perfectly rigid wire is used the reactive force is distributed around the arch and side effects aren't localized at adjacent teeth.

Mahler and Goodwin (1967) discussed the use of small archwires for maximum tooth movement with a minimum of adjustment. The mechanical property they considered important in achieving large movement with minimal force change was the elastic deformation/force ratio. This should be as high as possible. The archwire's ability to withstand forces induced by food excursion and accidental manipulation should also be considered.

Waters (1975a) pointed out that any light archwire has the disadvantage of not resisting unwanted extrinsic forces.

Burstone and Goldberg (1980) and Drake et al (1982) compared the mechanical properties of various orthodontic alloys and discussed the importance of large springback or large deflection without permanent deformation. This property is proportional to yield strength/modulus of elasticity.

With high elastic recovery, large forces can be applied to the teeth unless the stiffness of the component is very low, in the opinion of Waters et al (1981). They suggested that protection against heavy forces may be provided by permanent distortion. Upon engaging an archwire into the brackets of even slightly irregular teeth, the radius of curvature of the wire may be reduced below the minimum it can sustain without permanent distortion.

Sullivan (1982) demonstrated that light wires used for alignment resulted in spurious effects on adjacent teeth (as suggested by Burstone 1962a) and on the malposed tooth itself. In addition he found permanent deformation occurred with activations less than those which commonly occur clinically.

The above articles have illustrated some of the difficulties in attempting to deliver optimal force, especially when initially aligning malposed teeth. There are other factors that make it difficult to control or even be aware of the forces and moments being delivered by a multibanded orthodontic appliance.

Changes In Force and Moments With Tooth Movement

One factor that should be kept in mind when attempting to design and monitor an orthodontic force system is that changes occur as teeth move. Practitioners have been aware of these phenomena for some time (Irish, 1927; Sved, 1948; Storey and Smith, 1952; Johns, 1953).

Halderson et al (1953) felt the decrease in force as tooth movement occurred was important to allow tissue recovery.

In the opinion of Reitan (1957), force diminished rapidly after the hyalinized area was removed and the tooth moved.

A variety of investigators in the field of biomechanics have concluded that force systems change as teeth move (Burstone and Koenig, 1974; Waters et al 1975b; Waters, 1976; Pryputniewicz, et al 1978b), however it has been suggested that constant force would be a desirable characteristic in delivery of optimal force (Burstone et al, 1961; Burstone, 1962a; Mahler and Goodwin, 1967; Burstone and Goldberg, 1980).

In 1981 Burstone suggested a technique which he felt could deliver a more constant force as a malaligned tooth was brought into the arch. An archwire of low LDR formed beyond the final desired position of the tooth (i.e. a buccal stepout for a lingually malposed tooth) would produce force in the optimal and suboptimal ranges. Movement would stop with the tooth in its desired final position as the archwire began to deliver force of subthreshold intensity.

Such a technique would necessitate a rectangular archwire of very low LDR and, as has been previously discussed, reduction of this characteristic can be limited by other factors.

Earlier, Burstone (1962a) pointed out that reducing archwire rigidity increased the expression of reciprocal forces on adjacent teeth. This effect, in which a malposed tooth can set up a series of alternating forces in subsequent neighbouring teeth has been termed the "ripple effect" and noted eariler by Steiner (1932) and Sved (1937). Waters _et al_ (1975b) suggested that the manner by which the archwire was held in the bracket (supported versus constrained) could influence it. In 1982 Sullivan graphically demonstrated the ripple effect in all three dimensions and felt it could easily lead to a loss of control over the final position of the teeth.

In view of the changeable nature of force and moment as teeth move, an extra-oral investigation into factors influencing these elements must involve a dynamic method, where variable displacement of the tooth can be achieved. Furthermore, to most closely simulate the clinical situation, the tooth should be initially malaligned and respond to applied force and moments by correcting its position with respect to the adjacent teeth.

Statically Indeterminate Nature of the Continuous Arch

A number of authors have commented on the complicated pattern of forces and moments present in continuous arch treatment. Owing to the large number of points along the archwire subjected to varying actions and reactions the force system is considered to be statically indeterminate (Sved, 1937; Burstone, 1962a; Burstone et al, 1973; Koenig and Burstone, 1974a; Isaacson and Burstone, 1976).

In 1952, Sved suggested solving the problem of the elastic arch as a beam with multiple supports, but also felt that the laws of static equilibrium were not applicable because of the large number of simultaneous equations to be solved.

Burstone and Koenig (1974) concluded that many unpredictable and undesirable tooth movements during treatment result from relatively unknown force systems delivered by commonly used orthodontic appliances. They questioned the dogma of the ideal arch "if a wire is bent into a shape in which one would like to find the brackets at the end of treatment, the teeth will move to that position." While there may be some validity to the concept if rigid wires are used, with more flexibility a complicated force system is introduced, resulting in undesirable side effects. Even though the force and moments delivered change as a flexible wire deactivates, Burstone and Koenig felt the initial force system was significant since it was the one most likely to be active when the archwire was in place.

Waters (1976) reiterated the conclusion that a complete analysis of force distribution from a non-aligned flexible archwire is complicated and only gives an instantaneous picture, changing as the teeth move in response to the force.

An interesting historical perspective is provided by a quote from Fish (1917). "Until orthodontists outgrow the use of indeterminate appliances, and borrow from engineering the practise of laying out on paper what you propose to do before you try to do it, orthodontia will continue to be purely experimental."

Techniques Used to Measure Orthodontic Force Systems

A variety of methods and techniques have been used to study orthodontic appliances in an attempt to understand their characteristics and improve operator control. Since it is impossible at present to place stress gauges in the PDM, knowledge of stress-strain phenomenon must be derived from other approaches, such as mathematical models. Such models are no better than the assumptions on which they are based (Burstone, 1975).

Experimental and analytical studies of force systems delivered by orthodontic appliances have been hampered by the lack of an adequate model for analysis, and simple beam theory coupled with basic experiments have not accelerated understanding of the problem in the opinion of Koenig and Burstone (1974b). They felt a need for an analytic model based on engineering principles to predict force systems by the statically indeterminate appliances in three planes of space.

An extensive examination and discussion of the variety of techniques used to measure force and moment delivery is beyond the scope of this literature review. It is valuable to consider techniques discussed in the literature that are pertinent to the present investigation.

Mathematical three dimensional analyses, both linear and nonlinear, of orthodontic appliances were carried out by Defranco _et al_

(1976) and Greif et al (1978).

Pryputniewicz, Burstone and others (Pryputniewicz et al, 1978 a and b; Pryputniewicz and Burstone, 1979) in describing their holographic measurement technique, stressed the importance of simultaneous three dimensional consideration of forces and moments along the axes of the Cartesian Coordinate system. They also discussed the importance of measuring these quantities as changes in deflection occur.

A number of investigators have employed measurement techniques involving brackets and occasionally ligation, but none involved three dimensional analysis and very few considered changes in force systems as displacement occurred.

Brackets were used intraorally in studies carried out by Hixon et al (1970), Andreason and Zwanziger (1980), and Huffman and Way (1983). These investigators were concerned with the relationship between applied force and resultant tooth movement and measured tooth displacement by various means.

A far greater number of investigators have employed brackets in extraoral studies.

Strain gauges have been used to record the forces and moments acting on brackets mounted to model teeth (Neuger, 1967, Andreason and Quevedo, 1970, Schrody, 1974, Steyn, 1977; White et al, 1979). However none of the investigations to date have considered the orthodontic force system along all three axes of the Cartesian Coordinate system.

Other mechanical techniques for force evaluation were used in studies carried out by Kamiyama and Sasaki (1973), Riley et al, (1979), Frank and Nikolai (1980) and Waters _et al_ (1981).

A series of investigations into the relationship between archwire and bracket slot when the archwire is twisted was carried out using a torquemeter (Hixson _et al_, 1982; Olsen, 1983; Sebanc _et al_, 1984.

Although there have been several studies involving brackets and ligation, none utilized a simultaneous three dimensional analysis of forces and moments. Very few investigations closely simulated the mechanical connections between archwire and tooth as they occur clinically. Both of these shortcomings should be dealt with to add validity to a measurement technique. Refinements in measurement technique would likely improve our understanding of the mechanical characteristics of orthodontic appliances.

Established Sources of Mechanical Variability

In addition to the mechanical factors which can influence force and moment delivery and the biological variability that may contribute to inconsistent responses to orthodontic appliances, other sources of mechanical variability have been discussed in the literature. Some of these mechanical inaccuracies may be partly responsible for the range in patient response attributed to variation in tissue response and may also contribute to the range of optimal force values.

Archwire size has been shown to be more variable than many orthodontists may suspect. It should be recalled that a small change in wire dimension results in considerable alteration of beam stiffness

(LDR is proportional to d^4 or bh^3). Burstone et al (1961) found significant variation in different batches of supposedly identical diameter archwires from the same manufacturer and concluded that higher predictability in establishing LDR would be possible if wire dimensions and quality demonstrated greater standardization.

Dellinger (1978) considered variability in archwire dimension to contribute to a loss of control in force delivery. This opinion was reiterated by other authors (Lang et al, 1982; Sebanc et al, 1984).

Creekmore (1979) was among the first to recognize the influence of variability in bracket slot size on play or slop between archwire and bracket slot. The amount of play possible, measured angularly, later came to be known as deviation angle. Slot size variability has been discussed by Thurow (1982), Hixson et al (1982) and Sebanc et al (1984).

Variability in molar tube size will also contribute to a loss of control over force delivery. It has been investigated by Raphael et al (1981) and Lang et al (1982). They compared the theoretical degree of rotation of various archwire-tube combinations to the measured amount and found the latter to be higher. The amount of deviation present depended on the manner in which the molar tube had been formed. Raphael et al (1981) concluded that "...depending on the brand and type of appliance used the input of torque may result in a totally unpredictable output of tooth movement."

The presence of edge bevel on orthodontic wires that are assumed to be rectangular results from the manufacturing process. This bevel results in greater deviation angle than would be predicted by considering only the variability associated with archwire and bracket slot dimension (Hixson et al, 1982). The amount of bevel present varies between manufacturers and the average percentage contribution of edge bevel to deviation was calculated to range from 3% to 63% (.2° to 12.9°) by Sebanc et al (1984).

The importance of play, or deviation angle has been discussed by other authors. Drenker (1956) acknowledged its presence in calculating force and moments resulting from second order bends and Schrody (1974) accounted for it in his evaluation of the effects of edgewise torque.

Sullivan (1982) discussed factors influencing play and suggested ligature tension as a variable that could have a large effect on it. Although ligation was not used in his method, different amounts of play, achieved by using tubes of different bore to hold the archwire, resulted in large differences in force and moment delivery.

Olsen (1983) also reviewed elements contributing to deviation angle and found tight stainless steel ligation capable of eliminating it. He also discussed the importance of controlling deviation between archwire and slot and suggested that in certain situations it may be desirable for such play to exist.

Other mechanical factors subject to variability may contribute to inconsistencies in force and moment delivery. A number of authors have commented on variability in bracket placement resulting in change in the force systems produced (Hixon et al, 1970 and White et al, 1979).

Dellinger (1978) and Sebanc et al (1984) concluded that bracket placement variability associated with the range in tooth profile and size could result in a considerable loss of control and a great range of clinical results. Both research groups suggested a lack of accuracy and clinical effectiveness with straight wire appliances due to variation in dental anatomy.

Another variable that may contribute to a range of clinical results is operator inconsistency in archwire formation. This has been discussed by Mahler and Goodwin (1967), Steyn (1977) and White *et al* (1979).

The inaccuracy provided by variability in archwire and bracket slot dimensions may contribute to a lack of predictability in orthodontic force systems. This tendency would be aggravated by inconsistent bracket placement and/or archwire formation.

Friction

Friction is a mechanical element of almost all orthodontic appliances that can exert a large influence on force and moment delivery. As early as 1960, Stoner recognized appliance friction as a source of inaccuracy.

Hixon *et al* (1969, 1970) did not consider friction between the archwire and bracket slot to significantly reduce applied force because of tooth jiggling due to mastication and other oral forces. They contrasted dynamic friction (intraoral) with static friction (extraoral) and stated the former was consistently 5% of the applied force, whereas the latter varied between 10% and 20% depending on the magnitude of the applied force.

A number of other investigators considered frictional losses to significantly influence tooth movement. Paulson et al (1970) cited friction due to ligation tightness as an important variable in cuspid retraction. Similarly, Andrews (1975) accounted for frictional losses in establishing an optimal force for cuspid retraction. Riley et al (1979) felt frictional forces between archwire and slot may reduce force available for tooth movement.

Frank and Nikolai (1980) suggested that tooth movement continues until the resistance of deformed PDM structures and kinetic frictional forces exceed delivered force. When periodontal resistance decreases and occlusal forces, wire resiliency and masticatory action reduce the "friction lock", tooth movement occurs again. Jarabak and Fizzell (1972) suggested a similar mechanism.

Waters et al (1981) hypothesized that with binding of the archwire in the bracket the deflected span would not return to its original configuration and no force would be applied to the teeth. Friction between archwire and bracket, along with bends in the archwire, could contribute to such binding.

Sullivan (1982) found strong evidence for frictional forces influencing force and moment delivery when three dimensions were considered. The presence of large mesiodistal forces as a consequence of buccolingual tooth movement were related, directly or indirectly, to frictional effects. These forces displayed high variability and considerable hysteresis.

If the clinician is to attempt control over frictional effects it is necessary to consider factors which influence them.

Archwire size appears to have a direct influence on friction according to some investigators. Ackerman et al (1969) recommended using small diameter archwires to reduce friction and binding. Andreason and Quevedo (1970), studying .022 X .028 inch (.559 X .711 mm.) brackets found increasing archwire size from .014 to .018 inch (.036 to .046 mm.) resulted in friction increasing arithmetically, and further progression in wire size caused a geometric rise. Paulson et al (1970) also suggested that larger archwires result in greater friction. In comparing intraoral results of cuspid retraction along different archwire sizes Huffman and Way (1983) concluded archwire size did not significantly influence friction.

The influence of bracket width on friction has also been investigated. Andreason and Quevedo (1970) concluded bracket width did not effect a change in friction. Kamiyama and Sasaki (1972) and Thurow (1982) found frictional force to be inversely proportional to bracket width. Thurow suggested that the shorter distance between bracket ends resulted in a greater force perpendicular to the archwire. Andreason and Zwanziger (1980) and Frank and Nikolai (1980) concluded there was a direct relationship between frictional force and bracket width. Frank and Nikolai went on to point out that a decrease in bracket width was accompanied by an increase in unrestricted tipping. They also concluded that of all the variables studied, tipping angulation of the wire with respect to the bracket was most influential. This interrelationship of decreased bracket width and greater tooth tipping may be responsible for the lack of agreement regarding the influence of bracket width on frictional force.

Investigators have concluded that an increase in play between archwire and bracket slot, leading to tipping and a reduced contact area, results in increased sliding friction (Andreason and Quevedo, 1970, Jarabak and Fizzell, 1972, Sullivan, 1982, Sebanc et al, 1984). In situations where teeth do not need to slide along an archwire it may be advantageous to increase play between archwire and slot to achieve a loose fit and allow the archwire to slide through the bracket as a nonaligned tooth is brought into alignment (Waters et al, 1981). It is important to consider the influence of archwire size relative to bracket slot size in this regard.

When binding angulation occurs as teeth move along an archwire it is tempting to consider increasing the applied force (eg. retraction) to overcome the friction which is "stalling" tooth movement. However, Jarabak and Fizzell (1972) and Thurow (1982) suggested that in such a situation any increase in active force will only increase frictional force proportionately.

Surface irregularities of both bracket slot and archwire have also been suggested as factors that influence the amount of friction present (Frank and Nikolai, 1980; Thurow, 1982; Sullivan, 1982).

Lubrication, in the form of saliva, may not reduce friction to any extent. Andreason and Quevedo (1970) found no difference when a variety of friction producing situations were compared under wet and dry conditions. Jarabak and Fizzell (1972) commented on a possible reason for this behaviour. They suggested that archwire and bracket usually contact at one (or more) very small area(s) and lubricant would easily be squeezed out of the contact patch with no reduction in friction.

There is considerable lack of agreement on the factors which influence friction. However most investigators have suggested that frictional forces can influence the forces and moments available for tooth movement.

Ligation

Ligation has been widely reported to exert a strong influence over the amount of friction present in orthodontic appliances.

Newman (1963) suggested ligating teeth loosely to reduce binding and sliding friction. Similarly, Paulson <u>et al</u> (1970) concluded the friction introduced by ligature tightness was one of two important variables in cuspid retraction. Andreason and Quevedo (1970) acknowledged the importance of ligation in their study of frictional forces and used coil spring to standardize ligation tension at 150 gm. Jarabak and Fizzell (1972) emphasize the influence of ligation over sliding friction. Storey (1973) considered free movement of a ligated tooth along an archwire an impossibility and that determination of the force applied to such a tooth would be in error by an unknown amount.

When Kamiyama and Sasaki (1973) studied factors influencing friction they ligated the archwires to brackets loosely, presumably to minimize binding, but did not mention any method of standardizing ligation tension. Riley et al (1979) concluded stainless steel ligation generated higher frictional forces than elastic ligation, however they failed to mention how tightly the metal ligatures were applied.

In evaluating frictional forces present in simulated cuspid retraction Frank and Nikolai (1980) considered both ligation force and type. If stainless steel was employed, the ligation force was quantified on a subassembly using calibrated springs at levels of 150 gm., 225 gm., and 300 gm. They found ligature tie force to be highly influential over frictional resistance when the bracket slot-archwire angulation was low. The difference in friction produced by elastic ligation and steel ligation of 225 gm. was insignificant.

Waters et al (1981) recommended loose ligation to avoid binding, while Thurow (1982) suggested elastic ligation for cases requiring sliding of a bracket along an archwire because of its smoothness and limited strength. When Huffman and Way (1983) evaluated cuspid retraction intraorally they acknowledged ligation tension as a variable in evaluating friction and used loose steel ligation to the distal wing of the bracket.

Ligation can influence other mechanical variables that are important in controlling tooth movement in addition to frictional resistance.

Deviation angle, or play, results when the archwire does not completely fill the bracket slot. Burstone (1981) suggested ligation as a means to eliminate play in the first order direction in edgewise brackets by fully seating the archwire in the bracket slot. He also pointed out that ligation is capable of reducing second order play, if present. Hixson et al (1982) commented on ligation as one of several variables that influence archwire-bracket slot engagement. In 1983, Olsen demonstrated that tight stainless steel ligation totally eliminated all deviation angles in all conventional brackets studied. The magnitude of apically applied force required to introduce play was dependent upon the archwire size and edge bevel. Elastic ligation was ineffective in eliminating deviation angle at significant torque moments for all the archwire/bracket combinations Olsen studied. Loose stainless steel ligatures, either as a result of intended technique or due to repeated trials, also resulted in play between the archwire and bracket.

The manner in which the archwire is held in the bracket will influence the wire's behaviour as either a supported or constrained beam. As discussed earlier this may have a great influence over force and moment delivery. Additionally, ligation may influence the elastic or plastic deformation of the archwire along with other factors influencing tooth movement.

As early as 1937 Sved was aware that archwire behaviour was governed by the kind of attachment used and its degree of fixation. He gave examples of increasing force levels by more than two and one half times only by changing from a free support to a fixed one (supported beam to constrained beam). In 1948, Sved discussed the role of ligation in force delivery in light and heavy archwires. The intensity of force delivery in heavy wires was limited only by ligature strength. The amount of force achieved with light wire was limited by the elastic property of the archwire and ligation did not produce greater force with further tightening beyond a certain point. Sved considered this latter property desirable since it gave a factor of safety.

Waters et al (1981) suggested loose ligation as a method of minimizing both plastic deformation of the archwire and full bracket engagement resulting in severe wire curvature. They also suggested that when plastic deformation occurred LDR was altered and archwire recovery was not complete. Thurow (1982) concluded that elastic ligation provided an energy storage function in addition to, or in some cases instead of, the archwire. Elastic ligatures eased the individual teeth into full engagement over an extended period rather than with the instanteous heavy force application of wire ligation. Thurow considered steel ligatures more appropriate where appliance design called for a flexible archwire component such as a loop to act as the energy storage component.

Sullivan (1982) commented on several aspects of ligation and force delivery. He suggested the influence of archwire-bracket slot connection by ligation on the effectiveness of the stiffness of the wire. The difference in the beam type and subsequent force level due to a two point constraint versus a continuous bending constraint was discussed. The manner by which the archwire was restrained in the bracket, largely influenced by ligation, was also recognized as capable of altering the effective beam length. Earlier beam theory discussion illustrated the importance of beam length on LDR (inversely proportional to ℓ^3).

The variability of ligation has been recognized by several authors. The studies reported by Andreason and Quevedo (1970) and Frank and Nikolai (1980) used calibrated springs to achieve consistent ligation. Sullivan (1982), as a result of the inconsistent ligation tension encountered, used tubes instead of brackets and ligation in his investigation.

Ligation technique has been presented in orthodontic texts (Jarabak and Fizzell, 1972, Thurow, 1982) and most orthodontists use methods similar to those presented. Creekmore (1979) and Olsen (1983) commented on the importance of digitally seating the archwire into the bracket slot rather than relying on twisting the ligature with pliers to minimize play. Waters _et al_ (1981) recommended ligating aligned teeth first and then ligating the more irregular teeth working from the centerline and proceeding distally. Sullivan's (1982) suggestion of ligating irregular teeth more tightly than aligned teeth would be difficult to carry out if the technique proposed by Waters _et al_ (1981) is used.

Alternate ligation systems have been proposed by Fogel and Magill (1976) and Hanson (1980). Both involve self-locking components to eliminate ligature tying. The spring clip system, as discussed by Hanson (1980), was considered capable of contributing to the elastic torque of the archwire and controlling play, or deviation angle in various dimensions. Olsen (1983) tested the spring clip ligation method and concluded that it behaved much like elastic ligation and was relatively ineffective in eliminating archwire play.

Conclusion

The review of the literature has demonstrated the presence of biological and mechanical variables influencing tooth movement. To move teeth with greater control the orthodontist must attempt to understand and control as many of these variables as possible. The mechanical variables discussed may have influenced force delivery to such an extent that investigations into biological variability were hampered by inconsistent or incorrect technique. An ideal investigation into the relationship between orthodontic force systems and tooth response would be performed intraorally at the level of the PDM but would require techniques not presently available. In view of this impossibility a simultaneous three dimensional study of forces and moments on a dynamic model simulating the intraoral situation is the optimal method currently available.

The literature review also suggests that bracket and ligation phenomena can influence several aspects of force and moment delivery such as friction, deviation angle, archwire restraint, beam length, and archwire deformation.

For these reasons a simultaneous three dimensional investigation of the influence of ligation on force and moment delivery was initiated.

CHAPTER 3

MATERIALS AND METHODS

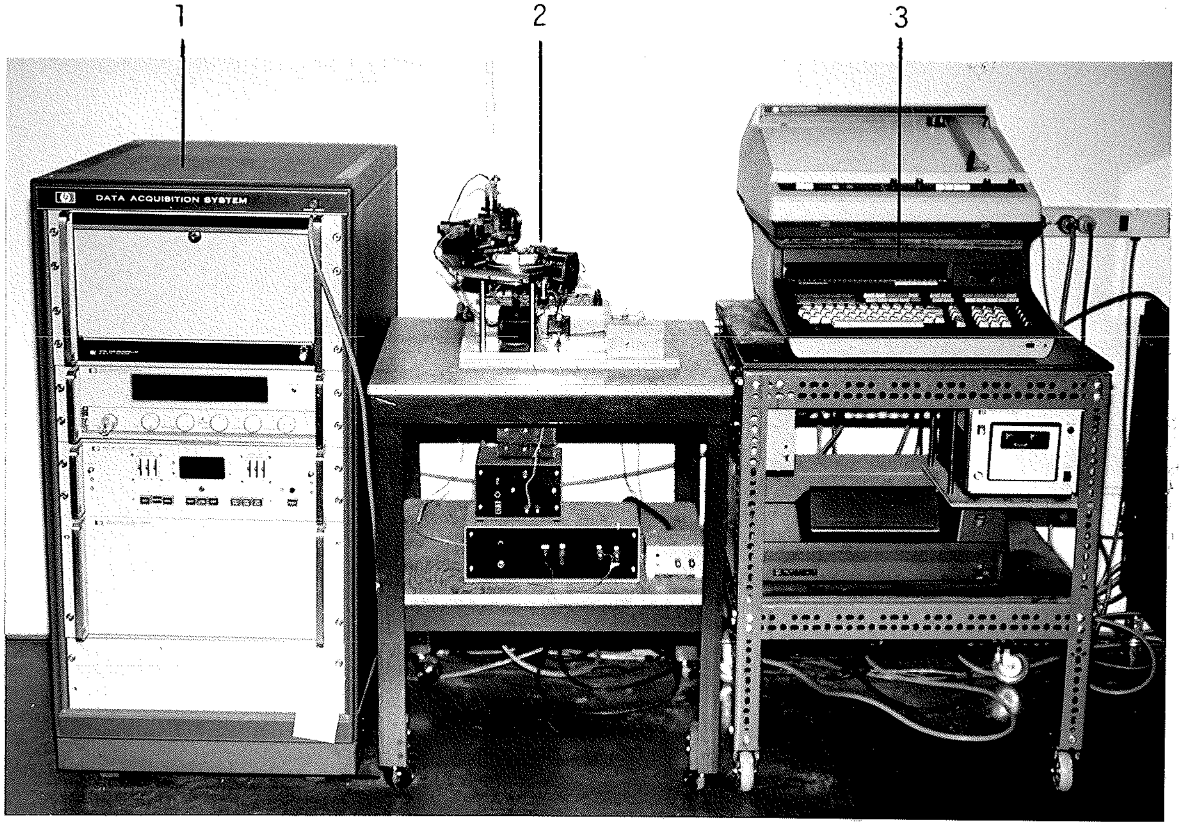
MATERIALS AND METHODS

Introduction

The method used in this investigation is based on instrumentation, previously used by Sullivan (1982), which allows simultaneous measurement of forces and moments along the three axes of the Cartesian Coordinate system.

The technique used in the present investigation differed significantly from previous studies using the same measuring apparatus. To study the influence of ligation modifications were necessary to allow the use of edgewise brackets. An important difference is that the "teeth" and archwire began in a malaligned state and motion of the activation system represented the tooth moving into alignment due to forces from the archwire. This modification made it imperative for one to be able accurately to measure the initial forces and moments caused by the ligation of the wire to the malaligned "teeth". These requirements, necessitated considerable change in the method as compared to previous investigations carried out in this laboratory. Details of these modifications are given later in this chapter. The three principle components (Fig. 1) of the previously described apparatus are:

(1) a measuring system,
(2) a data acquisition system,
(3) and a minicomputer and data storage system.



1. Data acquisition system (D.A.S.)
2. Measuring system
3. Minicomputer and data storage system

Figure 1: General view of the instrumentation.

Measuring System

The measuring system employs six transducers to simultaneously assess three forces and three moments. The maximum capacity of the transducers is 1300 gm. of force and 23,000 gm.mm. of moment.

The forces and moments measured were as follows:

(1) force in the x direction (Fx): force in the buccal-lingual direction.

(2) force in the y direction (Fy): force in the occlusal-gingival direction.

(3) force in the z direction (Fz): force in the mesial-distal direction.

(4) moment around the x axis (Mx): rotation around the buccal-lingual axis.

(5) moment around the y axis (My): rotation around the occlusal-gingival axis.

(6) moment around the z axis (Mz): rotation around the mesial-distal axis.

(See Fig. 2 for graphic representation)

The measuring system was calibrated after prototype trials were completed and immediately before final data accumulation.

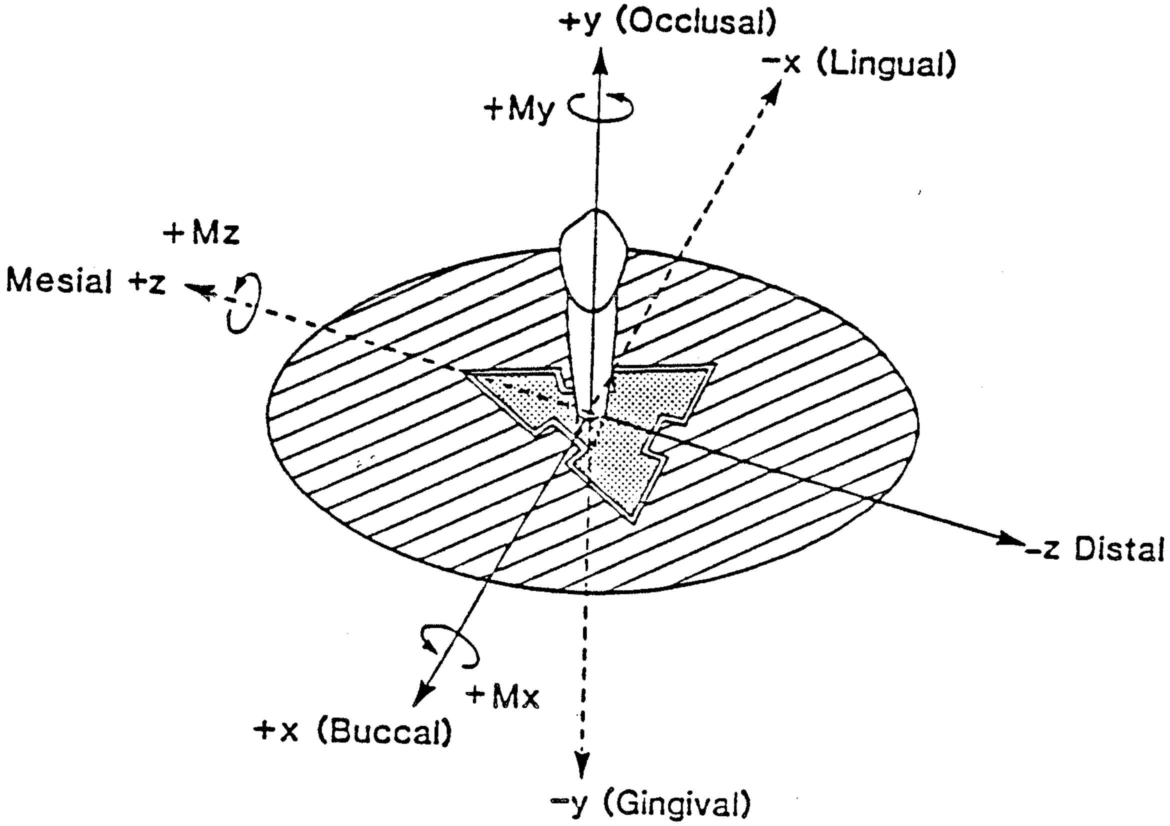


Figure 2: Relationship of forces and moments to the measured system.

The calibration process confirmed the accuracy of the system to be within 3%.

Data Acquisition System

The acquisition system (D.A.S.) was a 300 channel Hewlet Packard cross bar scanner. This system received input from the transducers in the measuring system and fed into the minicomputer. Input to the data acquisition system could be controlled either remotely by the minicomputer or directly by the operator. The former procedure was used in data accumulation, the latter in system calibration.

Minicomputer and Data Storage

Output from the data acquisition system was fed into a Hewlet Packard minicomputer model 9830A. Magnetic tape cassettes were used for program and data storage. An x-y plotter and a line printer were employed for data presentation.

Computer Programs

Three different computer programs were used in this investigation. All were written in BASIC and two were modifications of programs used previously by Sullivan (1982) and others.

The data acquisition program used was similar to that of Sullivan (1982) and again provided procedural order, keyboard control over experimental variables and graphic display on the x-y plotter. When an experimental trial was completed the acquisition program provided data storage onto a separate magnetic cassette tape.

The data analysis program used was also similar to that of Sullivan (1982) and converted data from the magnetic tape to a more usable form. A variety of relationships between force, moment and activation could be presented on either the x-y plotter or the line printer. Graphic presentation could be chosen in which the horizontal axis was proportional to force or activation and the vertical axis to force or moment.

Subprograms were also established for data presentation in which the values of forces and moments that typically were of relatively low magnitude (such as for Py, Pz, Mx, My) would be expanded in relation to the vertical axis. This alternative programming permitted easier analysis of the relationships amongst these values and between them and other variables such as activation, Px or Mz.

Activation System Design

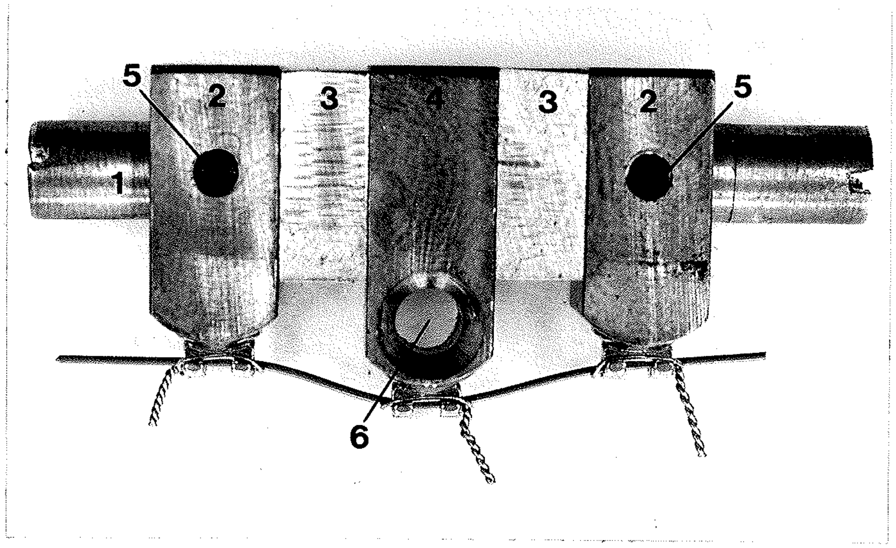
The goals in designing the activation system were to establish a method of employing wires ligated into edgewise siamese brackets while minimizing the influence of variables other than ligation on forces and moments. The clinical situation of aligning a buccally or lingually malaligned tooth was simulated in the activation system. Brackets used were Ormco* cuspid/bicuspid with no tip or torque in the slot relative to the base.

A series of brass "tooth" replicas were fabricated with a curved labial surface (Fig. 3). These brass replicas will be referred to as teeth for the remainder of the thesis and typical dental terminology will be used when describing their size, orientation and movement. The buccal surface of the model teeth had a radius of curvature which matched that of the bonding bases of the Ormco brackets. The dimensions of the brass teeth were uniform and constant in the mesial-distal and occlusal-gingival dimensions. The teeth were level and aligned in the occlusal-gingival direction. To simulate a buccal or lingual malalignment the outside or end teeth of a three-tooth segment were fabricated 2 mm. shorter or longer than the center tooth, which represented the malaligned tooth. The buccal-lingual dimension of the center tooth, which was attached to the measuring system was constant for all clinical situations tested. The buccal-lingual dimension of the end teeth, which were attached to the activation system, was constant within the buccal malalignment group or the lingual malalignment group (Fig. 3).

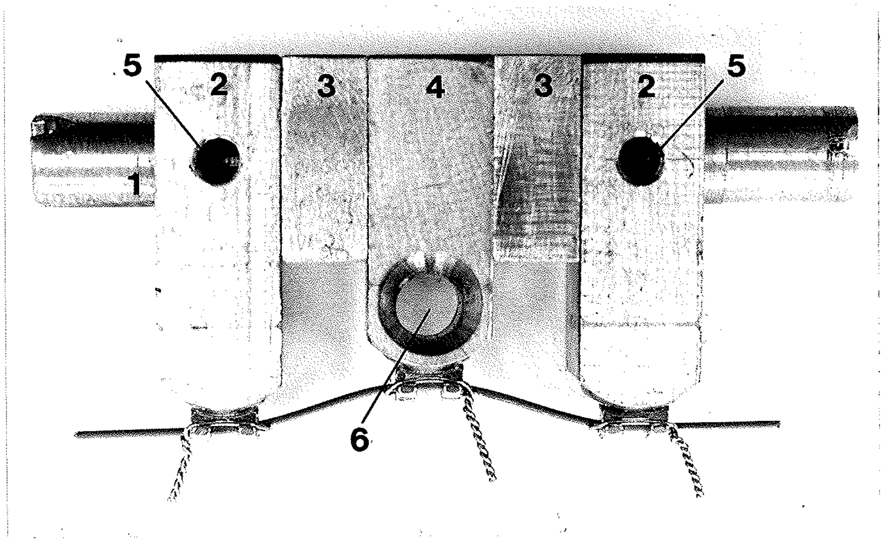
Stainless steel spacer blocks were used to estaslish the mesial-distal relationships between the three teeth (Fig. 3). The inter-bracket distance was constant at 6.7 mm., corresponding to a distance of 10 mm. between centers of the brass teeth and a bracket slot width of 3.3 mm. between the extreme of each bracket wing (Fig. 4).

---

* Ormco, Glendora, California.



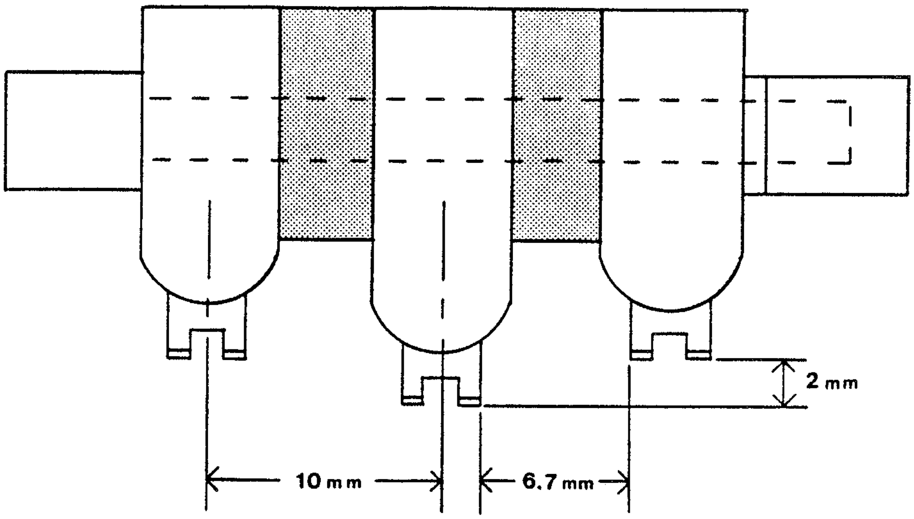
Buccal Malalignment



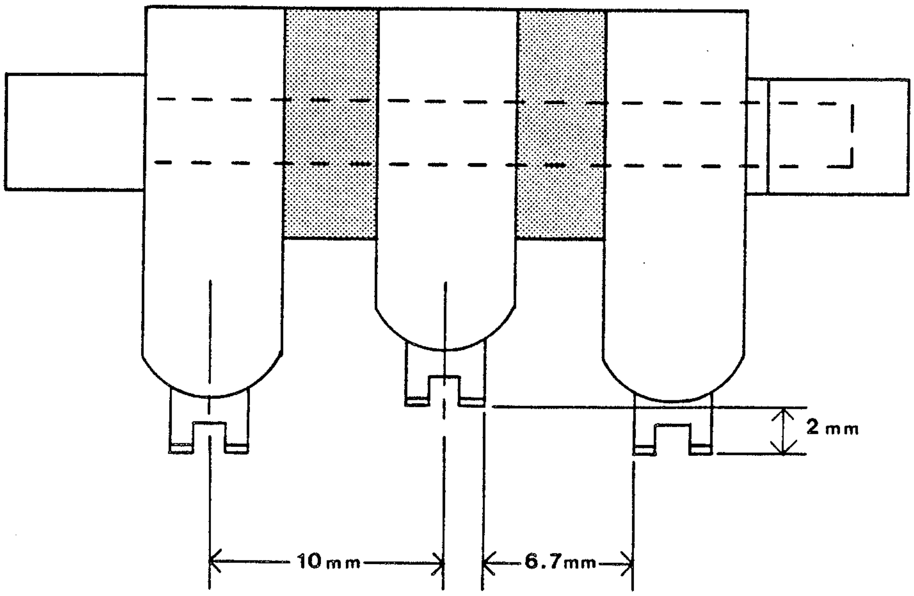
Lingual Malalignment

1. threaded bolt
2. brass end tooth
3. steel spacer block
4. brass center tooth
5. tapped screw hole
6. countersunk hole

Figure 3: Three-tooth assembly.



Buccal Malalignment



Lingual Malalignment

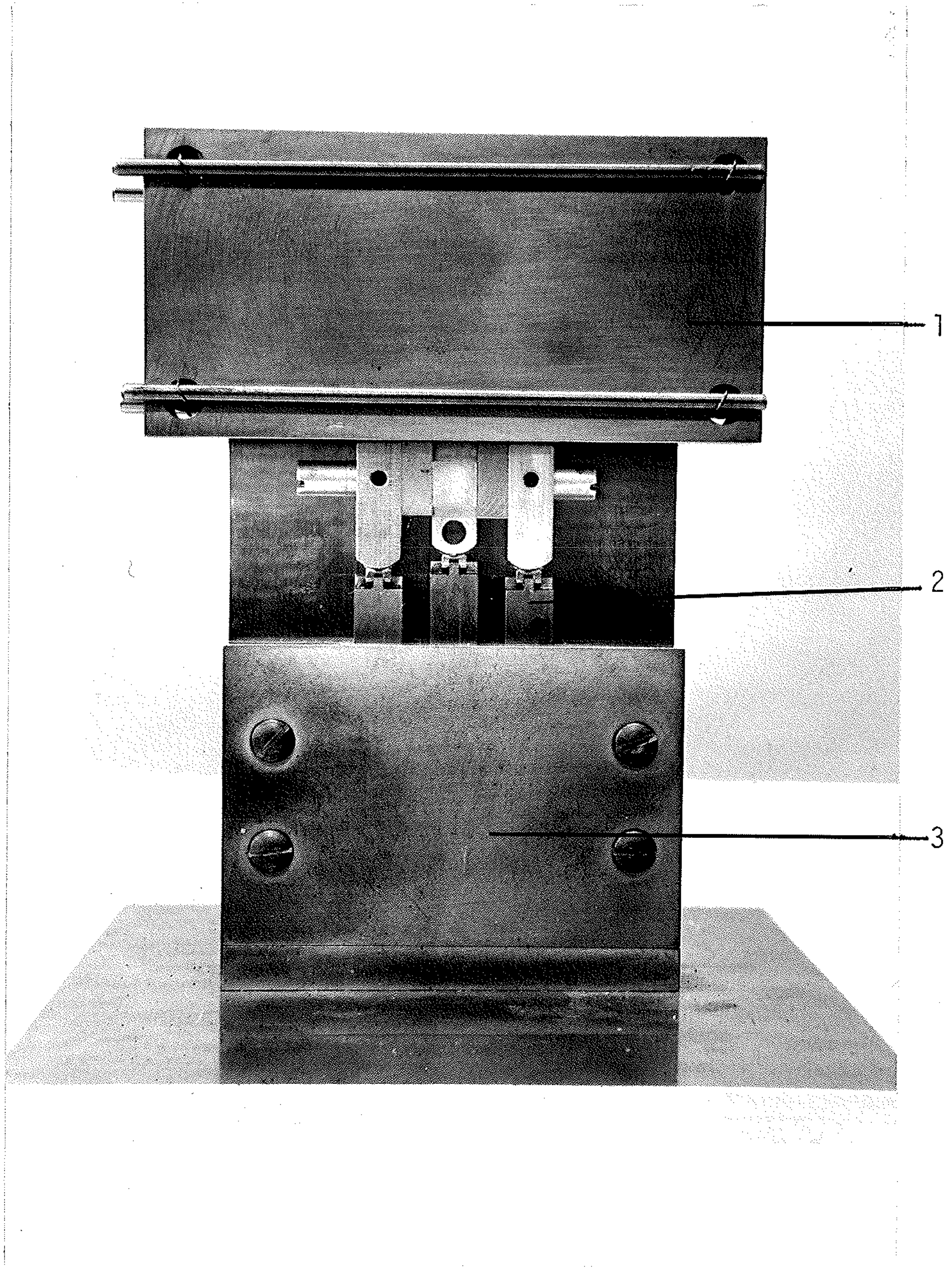
Figure 4: Three-tooth assembly - interbracket dimensions.

An earlier investigation by Sullivan (1982) used an inter-attachment distance that varied between 2 mm. and 4 mm. He found the elastic limit for a number of low modulus archwires to be roughly 1.5 mm. at the intertube distances he had chosen. In this work it was felt that a large interbracket distance would be useful in avoiding permanent deformation of the archwires being studied. Although an interbracket distance of 6.7 mm. is greater than that usually found intra-orally it could represent the clinical situation of not initially bonding and/or bonding all of the teeth in an arch. The larger interbracket distance also ensured easy access to the brackets to achieve a controlled ligation technique. It was hoped that the longer distance between brackets would reduce both the load deflection rates and the force levels achieved by the low modulus archwires as compared to Sullivan's study.

A threaded bolt was passed through the assembly of teeth and spacers and tightened with a washer and nut (Fig. 3). An aluminum, alloy jig was fabricated with a rectangular channel to hold and accurately align the teeth and spacer blocks while the alignment bolt and nut were tightened. In this way the brass teeth were kept in uniform relationship to each other in all dimensions with their occlusal, gingival and lingual surfaces flush.

An idea as to how the teeth were fitted to the entire system can be gained by referring to Figure 3. While still held rigidly together, the end teeth were fixed to the activation system through the tapped screwholes. The center tooth was secured to the measuring system by a screw through the countersunk hole in that tooth. Thus, after removal of all temporary constraints, such as the threaded bolt and spacer blocks, the forces and moments generated by the archwire were equilibriated through the measuring system rather than through the constraints. Relative motion between the center (measured) tooth and the end teeth was achieved by moving the latter teeth. Thus the inherent immobility of the measuring system was easily overcome.

A system was developed to consistently mount brackets to the brass teeth while they were held in constant position relative to each other. The bracket mounting system placed the brackets at the same position on the labial surface of the brass teeth (Fig. 5). The lingual surfaces of the teeth, which were planar and flush to each other were held against a brass block that travelled along a vertical stainless steel plate. The sliding brass block was held to the plate by spring loaded steel rolling pins. The occlusal surfaces of the three teeth, planar and parallel, also travelled along the steel plate held against it by digital pressure. The labial surfaces of the teeth engaged the bonding bases of the brackets. The brackets were held by T-shaped steel templates that closely engaged the bracket slot and interwing space of the labial surface of each bracket. The bracket holding templates were mounted to correspond to the interbracket spacing established by the steel spacer blocks between the brass teeth. The center or middle bracket holder was spring loaded to accomodate the buccal and lingual malalignment situations. The bracket holders were rigidly held to the vertical stainless steel plate via a fixed brass block (Fig. 5).



1. Sliding brass block
2. Bracket holding templates
3. Fixed brass block

Figure 5: Bracket mounting system.

The Ormco brackets were kindly supplied by the manufacturer and were selected to eliminate those with small geometric irregularities. Brackets were attached to the brass teeth with rapid setting two part epoxy resin. The bonding strength of this system was established to be in excess of 1600 gm. for any type of shearing or tensile load applied.

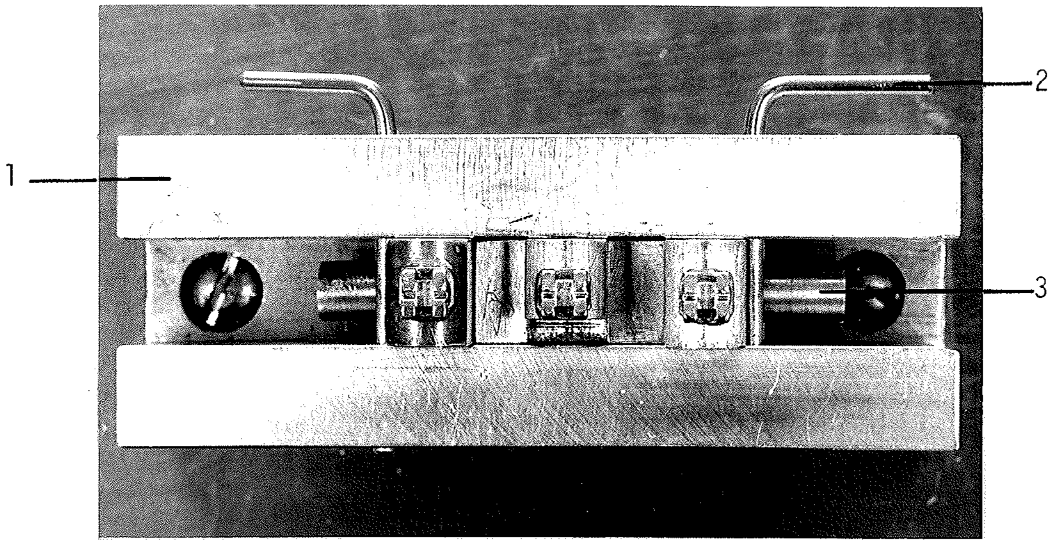
The aluminum alloy alignment and holding jig was attached to a heavy steel plate. The three-tooth assembly, held rigidly in the jig by retaining pins, was stabilized by the steel plate enabling an archwire segment to be ligated into the exposed brackets with relative ease (Fig. 6). Subsequent to ligation the teeth and spacer blocks, still held rigidly by the nut and bolt could be released from the aluminum jig by removing the retaining pins.

Once released from the aluminum jig, the teeth and spacer blocks were attached to a brass holding jig that was rigidly held by screws to the lingual surfaces of the three teeth (Fig. 7, top). The assembly could then be transferred to the measuring and activation systems.

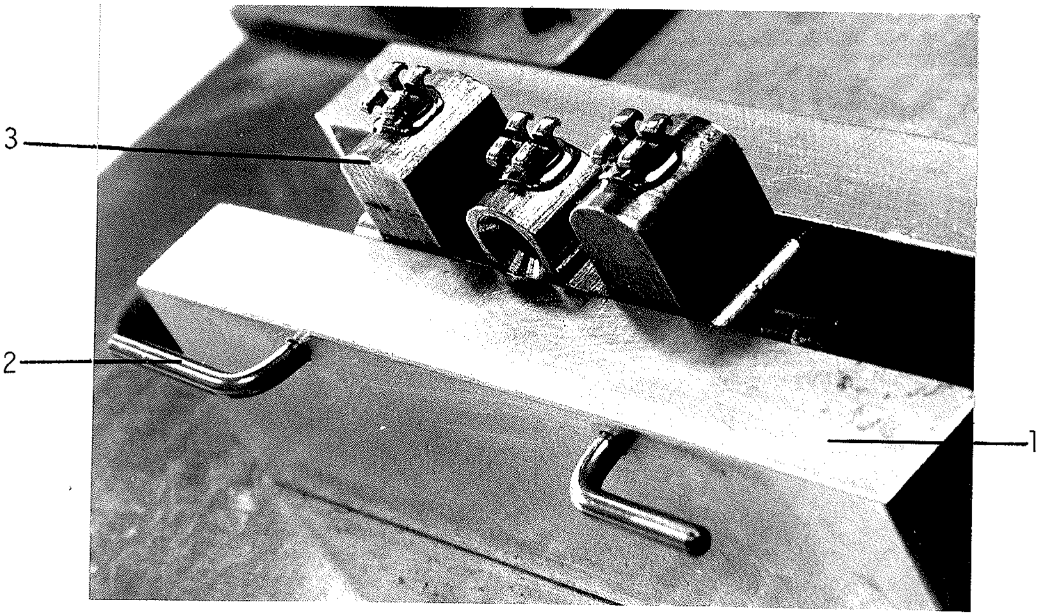
One of the most difficult aspects of this investigation was establishing a technique to mount the ligated archwire/three tooth assembly to the measuring system without artificially creating a variety of forces and moments that would significantly mask the force system being investigated. The system that was successful in achieving this goal was based on dental composite resin (Kerr* Resin Bonded Bridge Cement).

---

* Kerr Canada, Mississauga, Ontario.



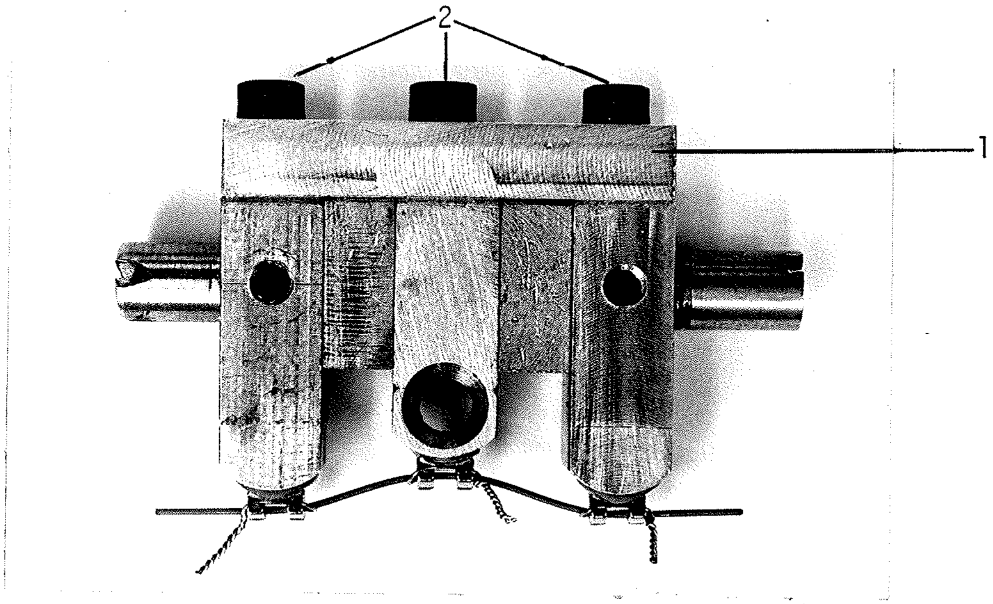
Top View



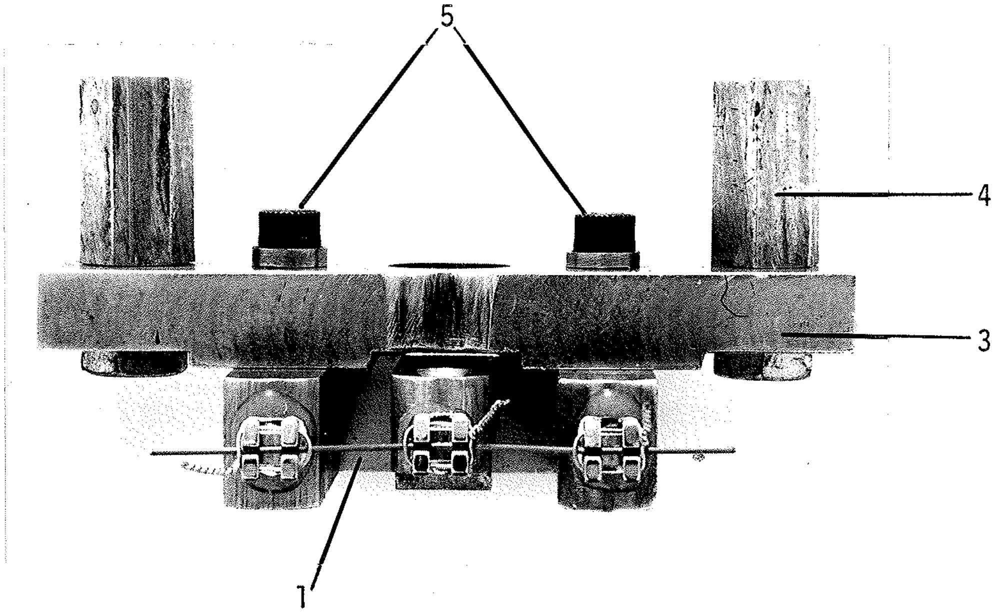
Oblique View

1. aluminum alloy jig
2. retaining pins
3. three-tooth assembly including spacer blocks and threaded bolt

Figure 6: Aluminum alloy alignment and holding jig.



Top



Bottom

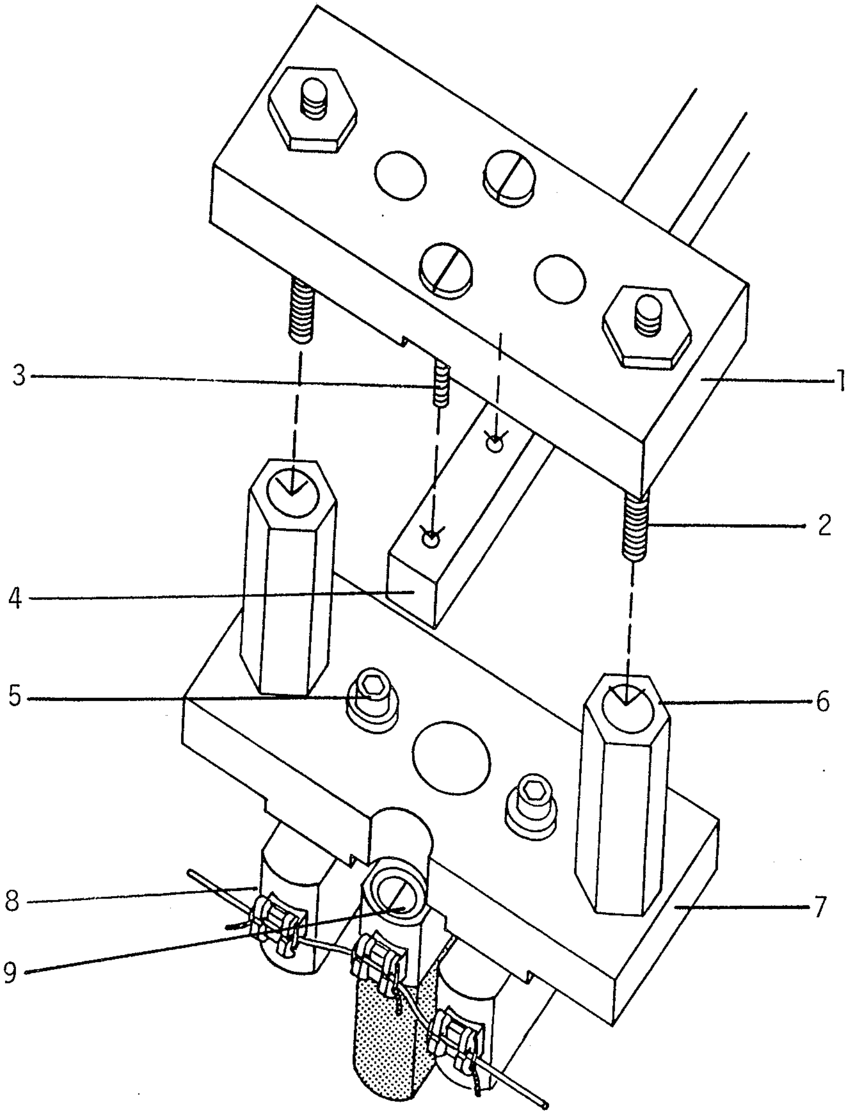
1. brass jig
2. screws attaching brass jig to three-tooth assembly
3. lower brass plate
4. brass sleeves
5. screws attaching end teeth to lower brass plate

Figure 7: Brass jig: Top: Three-tooth assembly and brass jig (threaded bolt and spacer blocks in place).
Bottom: Three-tooth segment and brass jig (without bolt and spacer blocks) mounted to lower brass plate.

The rigidly held three-tooth assembly including the ligated archwire was attached to the inferior surface of a brass plate by threaded screws that engaged the end teeth only. This brass plate holding the teeth also supported a brass sleeve at each end of its superior surface. Once attached to the brass plate, the threaded bolt and spacer blocks were removed from the three-tooth assembly. The three teeth remained attached to the brass holding jig along their lingual surfaces (Fig. 7, bottom).

The three teeth and brass jig, together with the plate and sleeves, were attached to the measuring system with a screw via the center tooth only. A second brass plate was attached to the activation system of the instrument. This second plate had threaded pins projecting from its inferior surface which fit inside the brass sleeves of the first plate. The threaded pins did not contact the sleeves at any point. Resin was placed into the brass sleeves and the pins were lowered into the sleeves before the resin set (Fig. 8).

Upon completion of the setting of the resin, the lower plate and all three teeth were firmly attached to the upper plate and the activation arm of the instrument. (The strength of the threaded pin/resin system used was established to be in excess of 2000 gm. for any type of loading that would be encountered in this experiment. Perpendicular loading of the pins, held by resin in the sleeves, produced no measurable pin displacement with loads in excess of 2000 gm.). The forces and moments generated by this coupling process were monitored and the trial could be discarded if excessive levels were



1. Upper brass plate
2. threaded pin (inserts into resin)
3. screws attaching upper brass plate to horizontal arm
4. horizontal arm of activation system
5. screws attaching end teeth to lower brass plate
6. brass sleeves (containing resin)
7. lower brass plate
8. three-tooth segment
9. screw holding center tooth to measuring system

Figure 8: Procedure for attaching upper and lower brass plates including three-tooth segment.

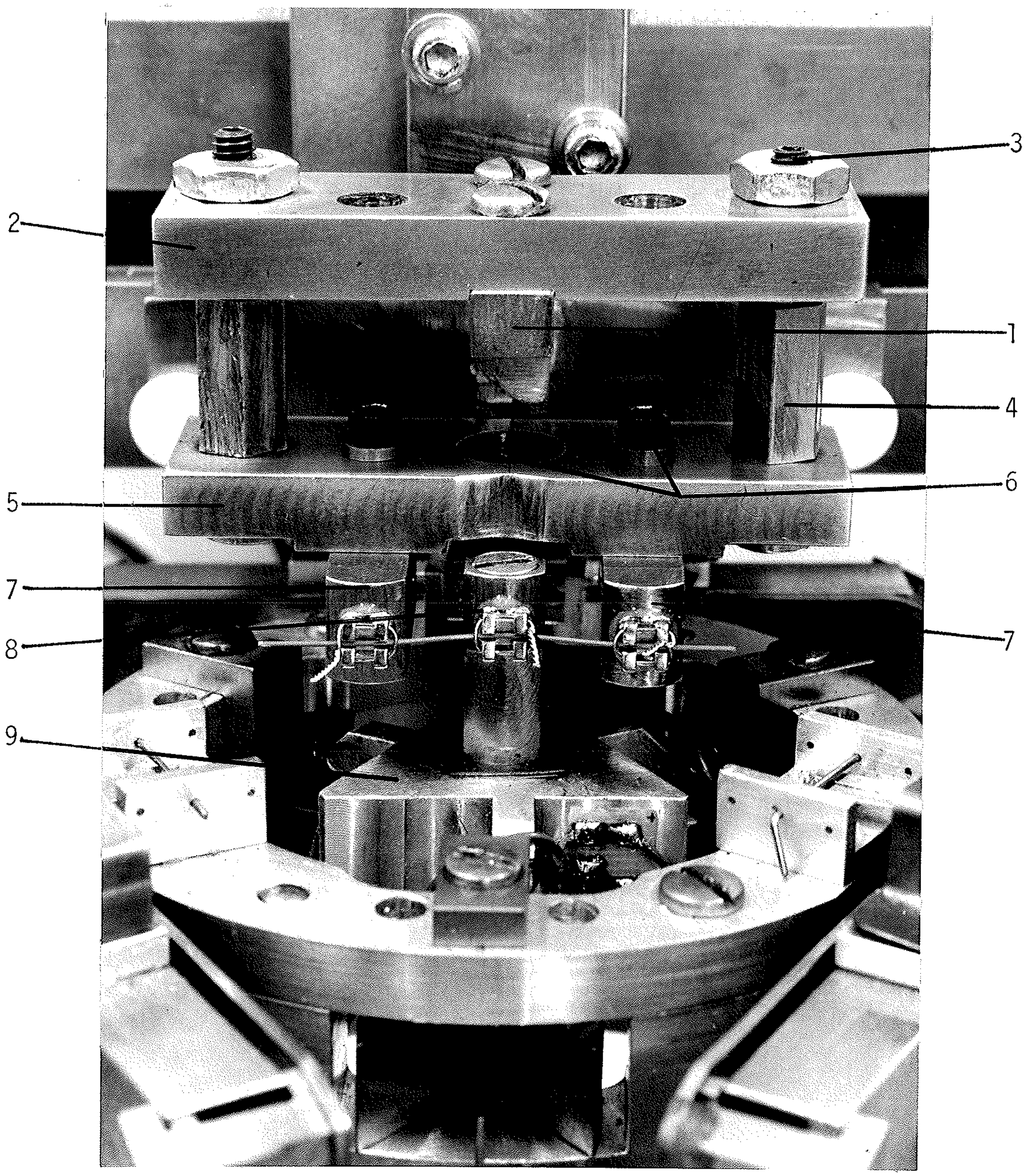
introduced.

By removing the brass jig holding the teeth rigidly together the center tooth was no longer attached to the activation system of the instrument. Only the end teeth, via the brass plates, sleeves, resin and threaded pins travelled with the activation arm. The center tooth remained stationary, attached to the measuring system (Fig. 9). Forces and moments generated by the ligated archwire acted on the center tooth and measuring system.

The measuring instrument allows linear movement of the activation system in all three directions. This investigation, however chiefly utilized its capacity in the buccal-lingual (X) dimension. For a general view of the instrument with the three-tooth segment in place see Figure 10.

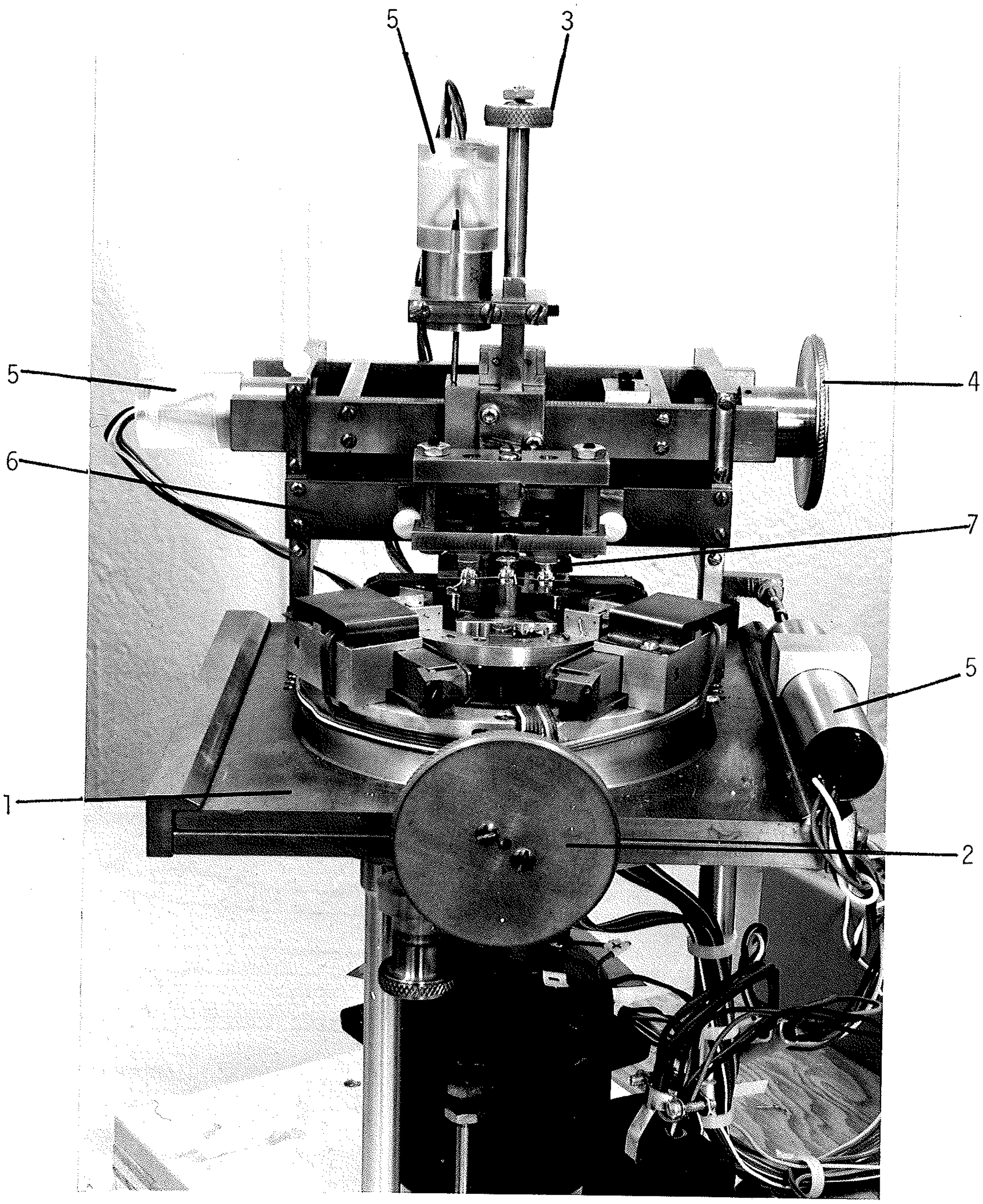
An activation range of 2 mm. in either the buccal or lingual direction was used. This brought the malaligned tooth (either lingual or buccal) into a position of alignment with its neighboring teeth. Ten activation points were selected along the 2 mm. path (.2 mm. intervals). Activation distances, selected by the operator, were monitored by linear voltage displacement transducers (L.V.D.T.) and controlled by the minicomputer.

The activation system has additional features which help to simulate the clinical situation. The measuring device allows a .2 mm. freedom of movements in its housing when fully loaded. This, approximately, duplicates the width of the PDM space (Stuteville, 1938; Isaacson and Burstone, 1976). The activation system requires mechanical vibration to be consistently applied in frequency, duration and



1. horizontal arm of activation system
2. upper brass plate
3. threaded pin
4. brass sleeves (containing resin)
5. lower brass plate
6. screws attaching end teeth to lower brass plate
7. end teeth
8. center tooth
9. measuring system

Figure 9: Detailed view of three-tooth segment attached to activation and measuring systems.



1. horizontal activation plate
2. adjustment screw (+ x)
3. adjustment screw (+ y)
4. adjustment screw (+ z)
5. L.V.D.T. (linear voltage displacement transducer)
6. Vertical extension of horizontal activation plate
7. three-tooth segment

Figure 10: General view of the instrument.

intensity. This vibration also approximately simulates the effects of mastication and occlusal interdigitation on the orthodontic appliance. Vibration is applied before initial readings are recorded and at every step of the activation process.

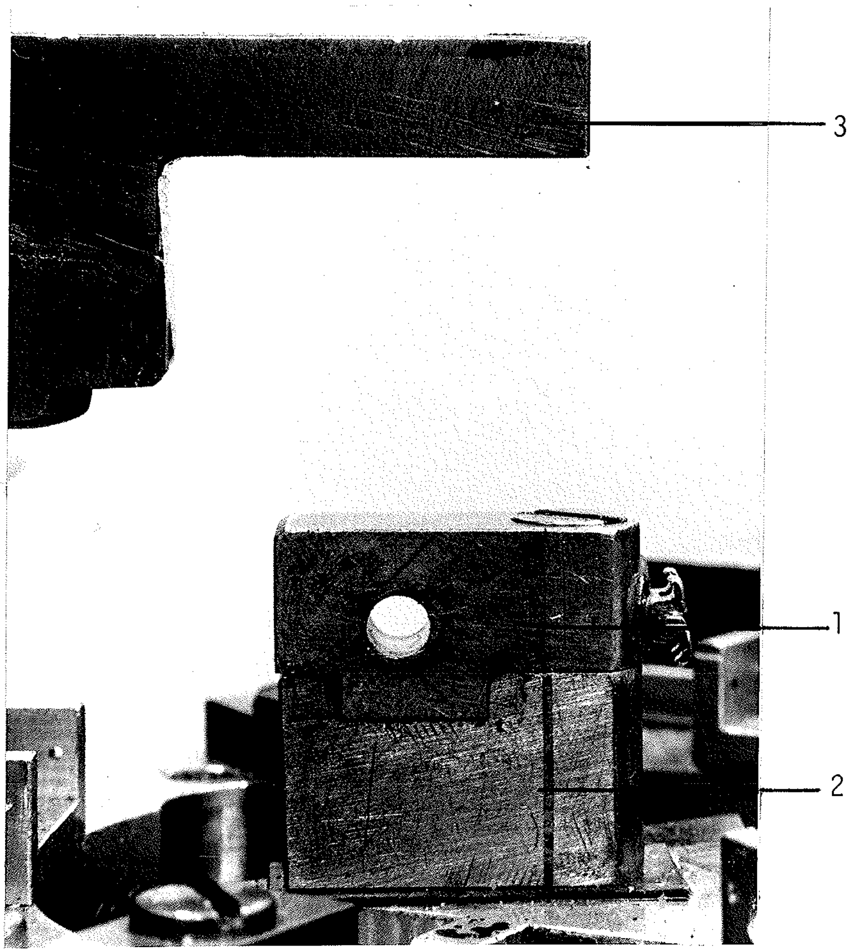
To allow assessment of intraoperator variability 10 sets of buccal and lingual malalignment tooth configurations were fabricated. Within each subgroup the sets were manufactured to uniform and constant dimensions and brackets were mounted uniformly. An operator could ligate a number of archwire segments sequentially without the delay of experimental procedure between subsequent ligations. The design of the activation system is complicated by allowing the teeth to be ligated other than directly on the instrument. However this feature allows various operators to perform ligation on the model teeth at a site of their choice.

Due to the time required in establishing the overall experimental method, an assessment of interoperator variability was not possible at this time. Instead, this study involved data accumulated by one operator, namely the author. The three teeth were mounted to the measuring and activation systems using the procedure described but without an archwire in place. Subsequent to the resin setting process an archwire was ligated to the teeth. By monitoring the measuring system it was ascertained that accidental overloading did not occur with the ligation process. Once resin setting had occurred a number of trials could be consecutively carried out, thus conserving time and material.

In addition to the above mentioned experiments involving three-tooth segments operated over a 2 mm. distance buccally or lingually other investigations were carried out. These included trials in which the three-tooth segments operated over a 4 mm. distance and experiments in which archwire segments were ligated to only two of the three teeth. These additional experiments provided further insight into the phenomena observed in the previously described trials.

Model Tooth

The central measured tooth used in this investigation involved two separable components (Fig. 11). The inferior component, made of steel, was attached to the measuring system and remained in that position at all times. The superior component of the model tooth was made of brass. The two components were held rigidly by a screw. With both parts in place the dimensions of the model tooth as shown in Figure 12 are closely representative of the clinical situation. The brass component was the center tooth of the three-tooth segment described above. An edgewise bracket was mounted to the labial surface of the brass component of the model tooth (Fig. 11). The dimensions of the center tooth were identical for both the lingual and buccal malalignment combinations with the offset achieved by changes in the dimension of the outside or end teeth.



1. brass superior component - center tooth of three-tooth segment
2. steel inferior component - attached to measuring system
3. horizontal arm of activation system

Figure 11: Model tooth.

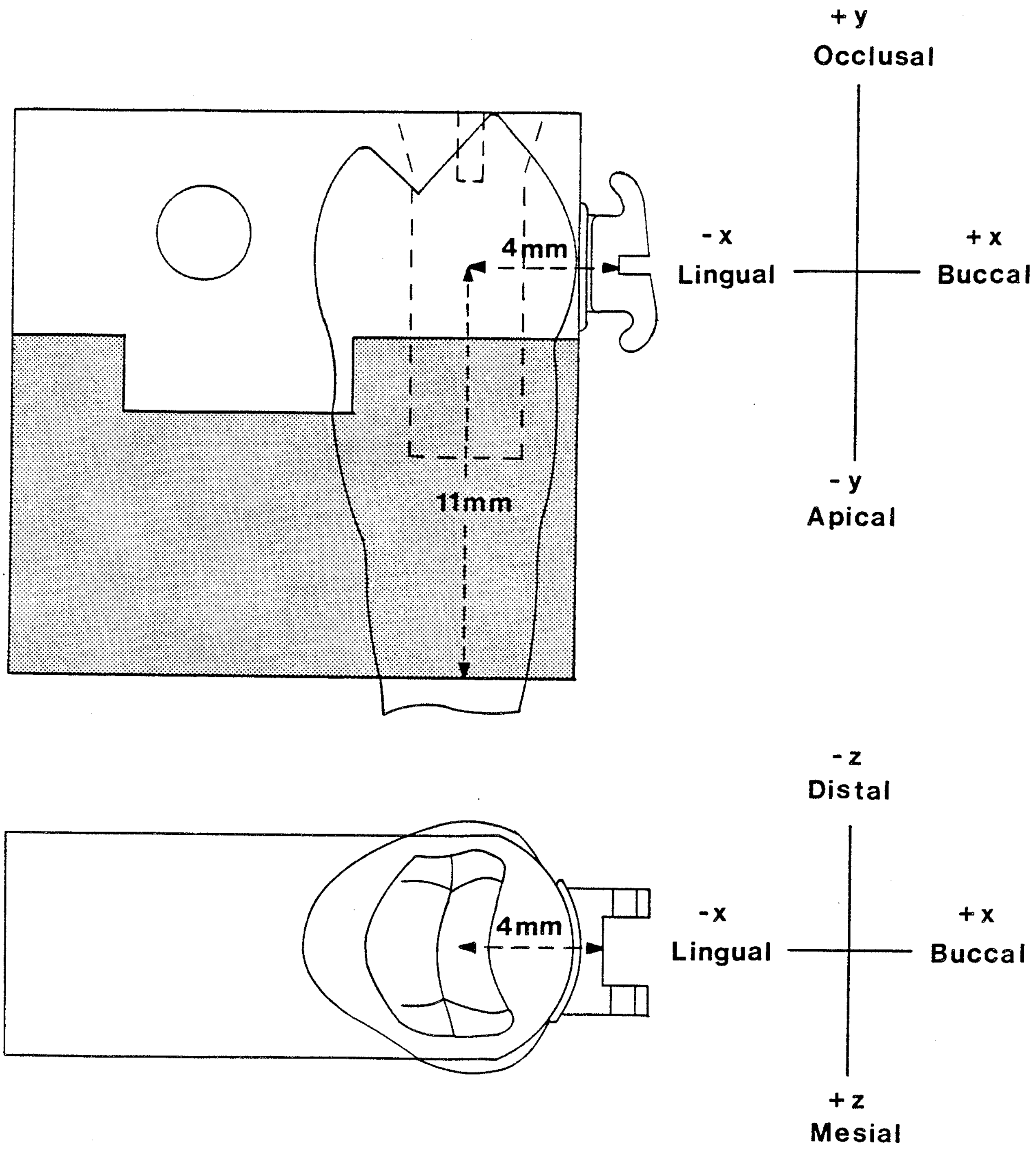


Figure 12: Relationship of bracketed model tooth to clinical situation.

Wires Tested

A variety of archwire segments were initially tested, each having a length of 35 mm.

Beta Titanium alloy (TMA*) was available as straight lengths in small round diameters. Its low modulus of elasticity lends it to clinical applications requiring tooth alignment. By investigating its performance in the buccal and lingual malalignments, as presented in this experiment, it was possible to assess the ability of TMA to resist permanent deformation on bracket engagement and deliver the force system necessary to achieve tooth alignment.

Other wires tested included multistranded wires (Triflex**), a nickel-titanium alloy archwire (Nitinol***) and stainless steel archwires (Tru-Chrome**) A variety of difficulties were encountered in applying these wires to the method developed for this experiment. Details of the difficulties encountered are discussed in Results.

Ligation Material

Ligaion material used was either elastomeric** or .254 mm. (.010 inch) dead soft stainless steel***. The elastomeric ligatures were stored briefly on stainless steel canes before being used

---

* Ormco, Glendora, California
** Rocky Mountain, Denver, Colorado
*** Unitek, Monrovia, California

experimentally. This was felt to represent the clinical situation and provided as much prestretching as would likely occur when used intraorally.

Experimental Procedure

The influence of ligation on force and moment delivery was investigated on buccal and lingual malaligned three-tooth segments. The archwire used was .406 mm. (.016 inch) TMA (Ormco) in a straight segment. Loose and tight steel ligation was used for both types of malalignments. Thus four subgroups were investigated:

(1) Buccal-loose
(2) Buccal-tight
(3) Lingual-loose
(4) Lingual-tight.

Within each subgroup ten trials were consecutively performed, attempting to keep the ligation tension identical for each set. The center tooth was ligated first, with the pigtail tie on the right hand side. The end tooth to the right of the center tooth was subsequently ligated, also with the pigtail tie oriented to the right. The end tooth to the left of the center tooth was ligated last, with the pigtail tie oriented to the left. The archwire was held in the bracket slot by finger pressure as the ligation process was initiated. The initial twists of the ligature strands were achieved manually, establishing the desired tension. The ligature strands were further coiled with a Mathieu* needle holder. The ligature wire passed both tie wings. The pigtail tie end was cut, but not tucked under the archwire.

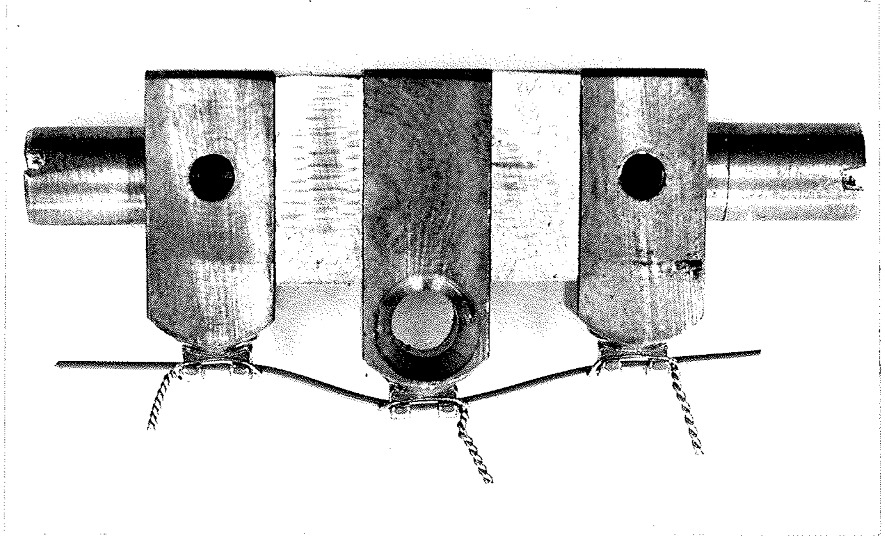
For tight ligation the archwire was firmly seated in the bracket slot and the ligature wire was held in close approximation to the tie wings as it was coiled. For all teeth ligated tightly the archwire was held within the outline of both tie wings of the brackets when viewing from the occlusal surface (Fig. 13).

The parameters of loose ligation were not as clear as they were for tight ligation. When ligating the center teeth loosely, sufficient tension was applied to cause the archwire to pass through the outline of both tie wings as it left the bracket. However the archwire did not necessarily have to remain lingual to the labial outline of the tie wing along its entire mesial-distal dimension. When ligating the end teeth loosely, the archwire had to pass within the outline of one of the tie wings, but not necessarily both. For lingual malalignments the archwire passed within the outline of the tie wings nearer to the center tooth. For buccal malalignments the archwire passed within the outline of the tie wings further from the center tooth (Fig. 14).

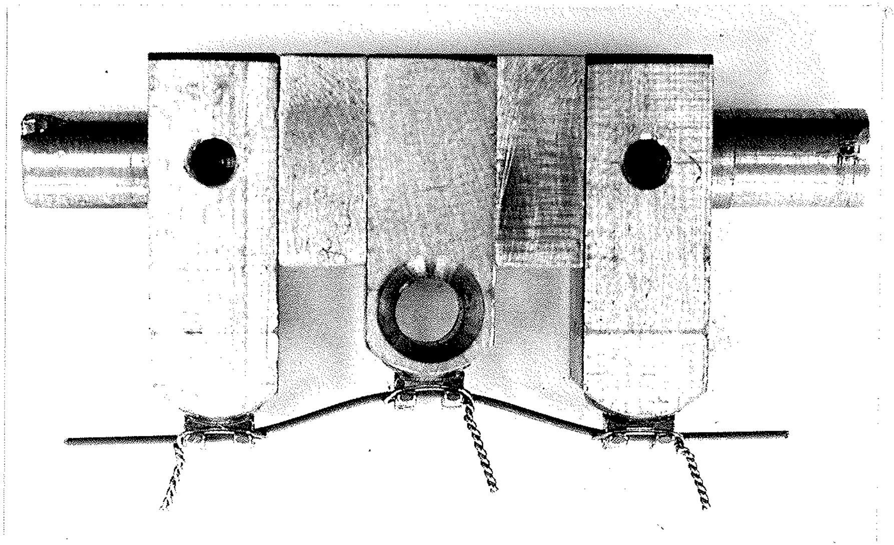
Each of the four subgroups was ligated at one sitting and all necessary experimental procedures on that subgroup were carried out consecutively on the same day.

---

* Unitek, Monrovia, California

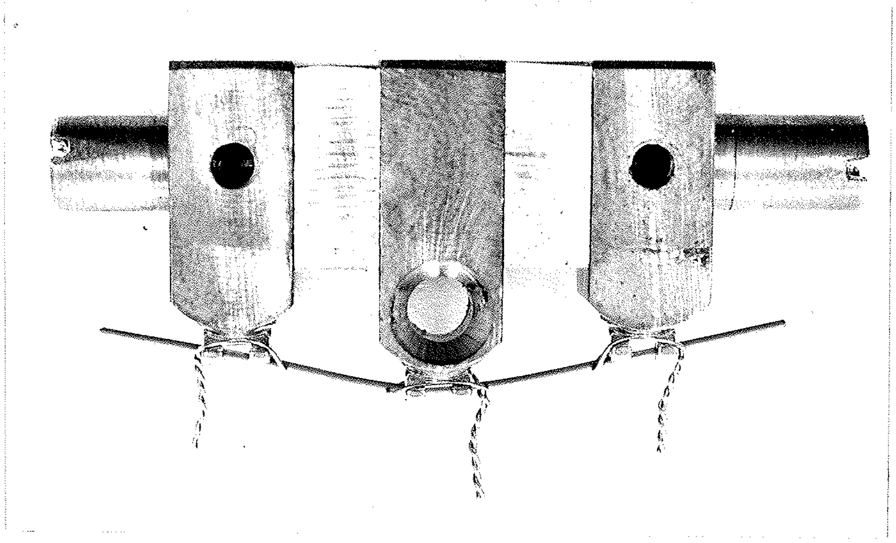


Buccal Malalignment

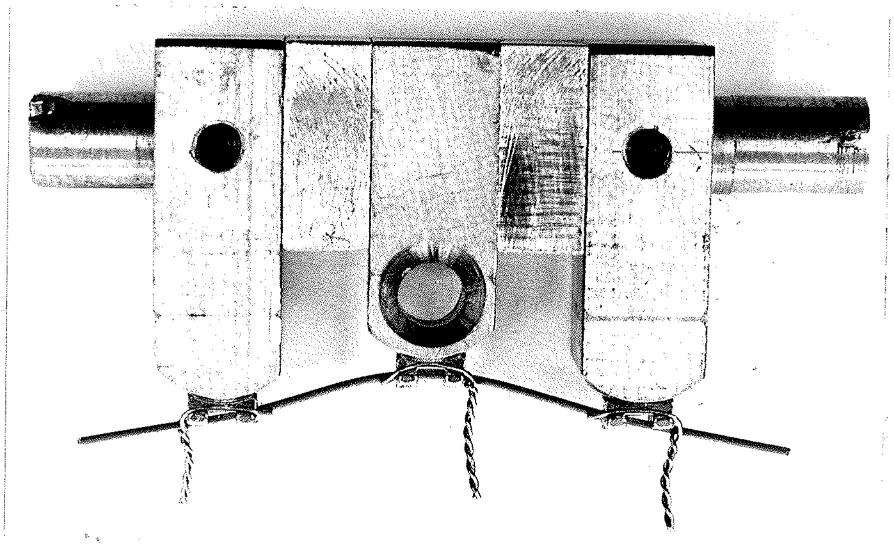


Lingual Malalignment

Figure 13: Three-tooth assembly with tightly ligated archwire.

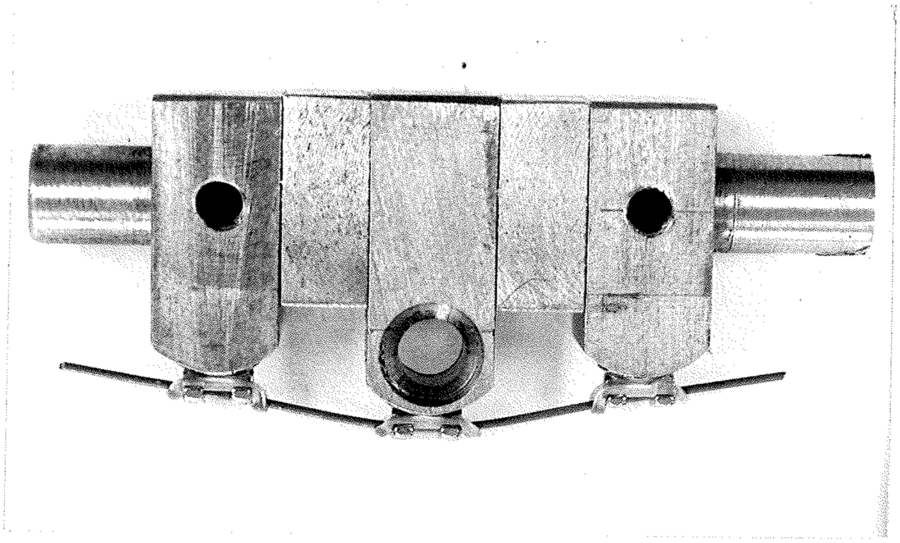


Buccal Malalignment

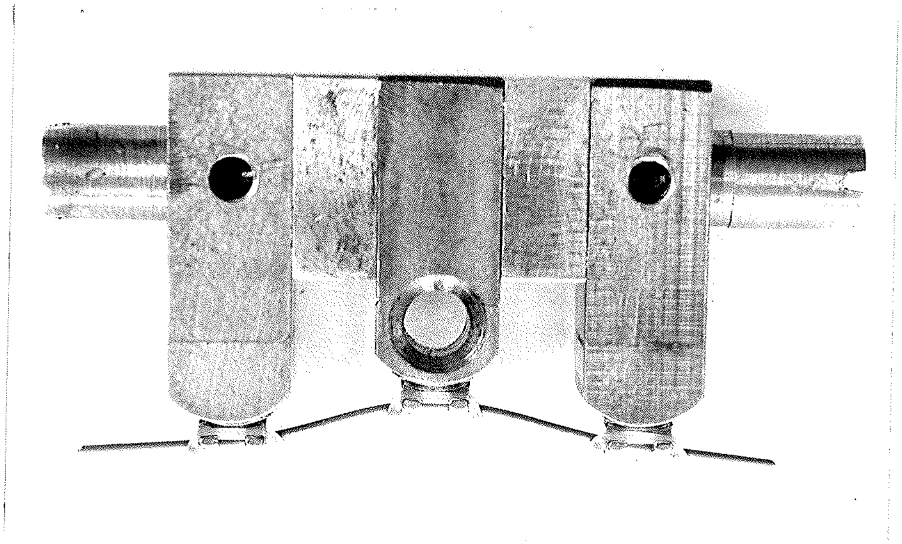


Lingual Malalignment

Figure 14: Three-tooth assembly with loosely ligated archwire.



Buccal Malalignment



Lingual Malalignment

Figure 15: Three-tooth assembly with elastically ligated archwire.

A series of trials using elastic ligation was also carried out. The individual elastic modules were removed from their storage cane and adapted around the bracket tie wings using a Mathieu needle holder while manually stabilizing the archwire. The preliminary investigation showed that elastic ligation produced very consistent force and moment characteristics when the same type of archwire was tested. Thus a series of ten consecutive elastic ligations was not performed. The manner in which the elastic ligature constrained the archwire within the tie wings of the bracket is illustrated in Figure 15.

The malaligned center tooth was brought into alignment with the end teeth by moving the activation assembly buccally or lingually 2 mm. in .2 mm. increments. Forces and moments at each interval were recorded on magnetic cassette tape. At the end of each run the segment of archwire was removed, labelled and stored for later observation.

Data Analysis

The computer programs described earlier, in conjunction with the data acquisition system, convert the output of the transducers to values of forces and moments acting at the center of resistance of the measured tooth.

The data analysis program was used to retrieve stored data and display it either graphically on the x-y plotter or on the line printer.

A number of relationships were plotted and investigated. The horizontal axis for the various plots always represented the direction of activation, while the vertical axis represented either force or moment:

(1) Px/Ax: the force to activation ratio (buccal-lingual).

(2) Py/Ax: the force to activation ratio (occlusal-apical).

(3) Pz/Ax: the force to activation ratio (mesial-distal).

(4) Mx/Ax: the moment to activation ratio (around the buccal-lingual axis).

(5) My/Ax: the moment to activation ratio (around the occlusal-apical axis).

(6) Mz/Ax: the moment to activation ratio (around the mesial-distal axis).

By examining these relationships, the three dimensional tooth movement likely to result from the forces and moments delivered at various activations could be studied.

CHAPTER 4

RESULTS

RESULTS

The objective of this study was to investigate the influence of ligation technique on orthodontic force systems. A number of different experimental conditions were tested in an attempt to elucidate the characteristics of the ligation process. A majority of the tests measured the forces and moments acting on the center tooth in a three-tooth segment. This tooth was initially buccally or lingually malaligned in most of the tests. A small number of tests involved a three-tooth segment in which all teeth were initially aligned. In a limited number of trials only two adjacent teeth of the three-tooth segment were ligated to the archwire and the forces and moments acting on one of the teeth were recorded. Controlled ligation techniques including tight steel, loose steel, and elastic (described in Materials and Methods) were applied in these various orthodontic situations.

To facilitate reading of the discussion the three-tooth segment in which the center tooth was buccally malaligned by 2 mm. will be referred to as BUCCAL. The three-tooth segment in which the center tooth was lingually malaligned by 2 mm. will be referred to as LINGUAL. The three-tooth segment in which all three teeth were initially aligned will be referred to as ALIGNED. Trials in which tightly ligated stainless steel ligatures were used will be referred to as TIGHT. Those involving loosely ligated stainless steel ligatures will be referred to as LOOSE. Trials involving elastomeric ligation will be referred to as ELASTIC.

Data Presentation

Sample data representative of the range of experimental trials are presented graphically in this section. The graphs in this thesis fall into two broad categories. The first type represents an average of ten experimental runs in which the conditions being tested (initial malalignment, range of activation, archwire size and material, ligature tension and material) were kept constant. The mean values of forces and/or moments are plotted against activation. Each point is extended in the vertical direction to indicate plus and minus one standard deviation (n-1 weighting). Each point represents the mean of ten data points recorded at that particular activation. Graphs of this type include Figures 16 to 19. The second type of graph represents the data obtained from an individual experimental trial. This type of graph (Figure 20 to 31) allows a more accurate assessment of the correlation between various force and moment parameters without the smoothing effect present in graphs of mean values.

All graphs in this thesis share certain characteristics. The horizontal axis of the plot represents activation/deactivation distance (Ax) and is marked off in divisions of .4 mm. or .8 mm. depending on the total activation range. The vertical axis represents both force and moment. Force is marked at intervals of 200 gm., while moment is marked in increments of 4000 gm.mm. The plots in this thesis are photocopies of the original computer plots provided by the programs described in Materials and Methods.

The primary goal in aligning a buccally or lingually malposed tooth was to provide a buccolingual force (Px) possessing appropriate characteristics to achieve this goal. Since only round wires were tested this force was accompanied by a corresponding moment (Mz) around the mesial-distal axis. Thus Px/Ax and Mz/Ax are plotted together on one set of axes.

Extraneous forces and moments such as Pz, Mx and My were also present, although typically were of a much lesser magnitude than Px or Mz. As a result of the experimental method the initial values for Pz, Mx and My were occasionally influenced in a random manner over a small level of magnitude. Consequently, plots for Pz/Ax, Mx/Ax and My/Ax are presented in two different forms. In one form their actual values are plotted. In the second form the initial values of Pz, Mx and My are made equal to zero and the magnitude of their relative values is multiplied by a factor of five. This second manner of presentation for Pz/Ax, Mx/Ax and My/Ax eases visual interpretation of these relationships and trends.

Plots for Pz/Ax, Mx/Ax and My/Ax whether presented as actual values or with their initial values shifted to zero, are graphed with a common vertical axis. However, each of Pz/Ax, Mx/Ax and My/Ax are plotted relative to separate horizontal axes to prevent overlapping.

As anticipated the values for Py are very small and are insignificant. One plot of the relationship Py/Ax is presented on a separate set of axes (Fig. 27).

The graphs in Figures 16 to 31 represent data that is referred to in the Discussion. These figures mainly represent plots of Px/Ax and Mz/Ax for various experimental conditions (Figures 16 to 26). For the sake of brevity not all plots of Pz/Ax, Mx/Ax and My/Ax are presented in the Results. Only those of BUCCAL TIGHT (Figures 28 and 29) and of two-tooth trials (Figures 30 and 31) are included in the Results. However, for completeness, plots of Pz/Ax, Mx/Ax and My/Ax for all the experimental conditions discussed are presented in the Appendix, along with all of the corresponding plots of Px/Ax and Mz/Ax.

In plots involving malaligned teeth the initial values represent the most malaligned condition. With deactivation the teeth were brought into alignment. Graphically this is represented by a solid line. The teeth were then returned to their malaligned condition. The return set of activations is plotted with a dotted line. Although this return would not be performed clinically it was useful to demonstrate certain characteristics of the force system, such as hysteresis. Results from lingual malalignments are plotted to the left of the vertical axis (for example, see Figure 18) and results from buccal malalignments are plotted to the right of the vertical axis (for example, see Figure 16).

For graphs involving three-tooth segments in which the teeth were initially aligned the solid line plots represent the teeth moving into a position of malalignment. Dotted line plots represent the teeth returning to a position of alignment. For initially aligned teeth plots to the left of the vertical axis represent the center tooth buccally malaligned and plots to the right of the vertical axis represent lingual malalignment (for example, see Figure 25).

Archwire Tested

Initial attempts at using .445 mm. (.0175 inch) Triflex archwires confirmed Sullivan's findings (1982) that this multistranded wire was prone to large frictional effects. It was felt that the magnitude and irregularity of these frictional forces could mask the effects of ligation.

Tests were also carried out on Nitinol archwires in .406 mm. (.016 inch) and .457 mm. (.018 inch) sizes. Wire of this size and type was only available in arch blanks. In the larger size it was difficult to obtain a straight 35 mm. length of wire. For both sizes the large number of wire samples required for this study, coupled with the form in which this wire was available, made its use impracticable.

Preliminary tests were also carried out using .336 mm. (.014 inch) Truchrome stainless steel archwire. This wire exhibited a tendency towards permanent deformation when tightly ligated into the three-tooth segments at the interbracket dimensions used in this investigation.

Initial experiments included trials with .457 mm. (.018 inch) TMA as the test archwire. Both .406 mm. (.016 inch) TMA and .457 (.018 inc) TMA are available in straight lengths from the manufacturer. The larger size of TMA had a greater tendency to plastically deform when tight, stainless steel ligation was used.

As a result of these findings, .406 mm. (.016 inch) TMA archwire was used in the experiments that comprise this investigation into the influence of ligation on orthodontic force systems.

Data Interpretation

To aid interpretation of the data presented, one of the plots will be described in some detail. The mean values of Px/Ax and Mz/Ax for the BUCCAL LOOSE series are presented in Figure 16. The plot of Px/Ax originates below the horizontal axis and represents a lingually directed force. At Ax=0 (initial malalignment), the initial mean value of Px is 135 gm. With deactivation the teeth are brought into alignment and the value of Px gradually falls to zero at Ax=2.0 mm. The plot of Mz/Ax originates above the horizontal axis and represents lingual crown tipping. At Ax=0 the initial mean value of Mz is 1650 gm.mm. With deactivation this value also falls to zero. For both Px/Ax and Mz/Ax the plots for activation (dotted lines) correspond very closely to those of deactivation (solid lines).

It can be seen from Figures 16 to 20 that an increase in ligation tension is generally accompanied by an increase in the magnitude of Px and Mz for both buccal and lingual malalignments. Figures 16 to 26 demonstrate the influence of experimental variables on a number of characteristics such as load deflection rate, propensity for bracket alignment as well as force and moment magnitude. These characteristics will be elaborated upon in the Discussion.

Summary

The results in this thesis represent the forces and moments achieved by applying .406 mm. (.016 inch) TMA and a variety of ligation techniques to a number of different orthodontic situations. A determination of test repeatability was not appropriate since an objective of this investigation was to assess the variability associated with ligation.

A number of graphs representing various test conditions follow. The graphs are presented in the format described above and will be referred to in subsequent discussion of the relevant findings.

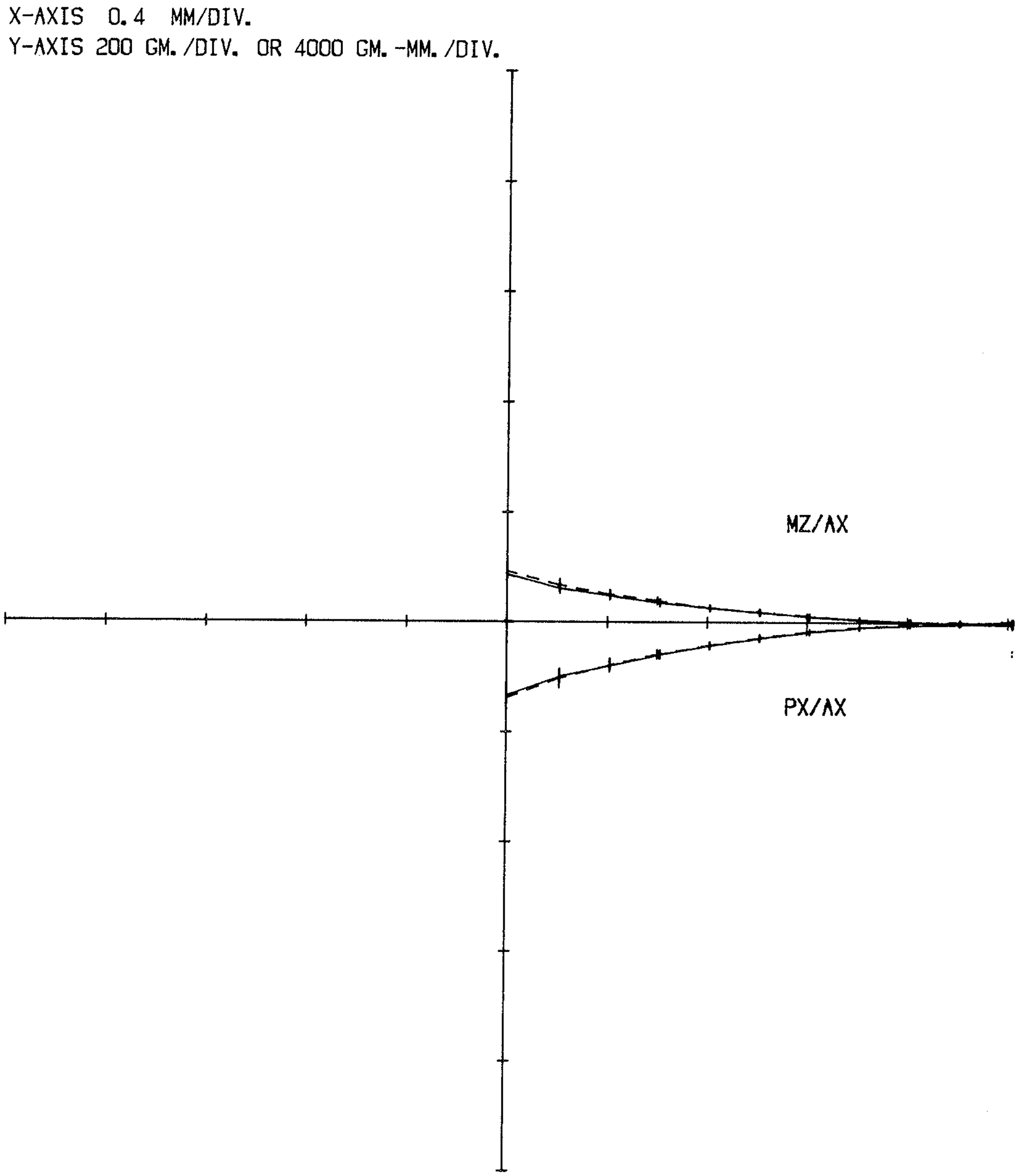


Figure 16: BUCCAL LOOSE: plots of Px/Ax and Mz/Ax

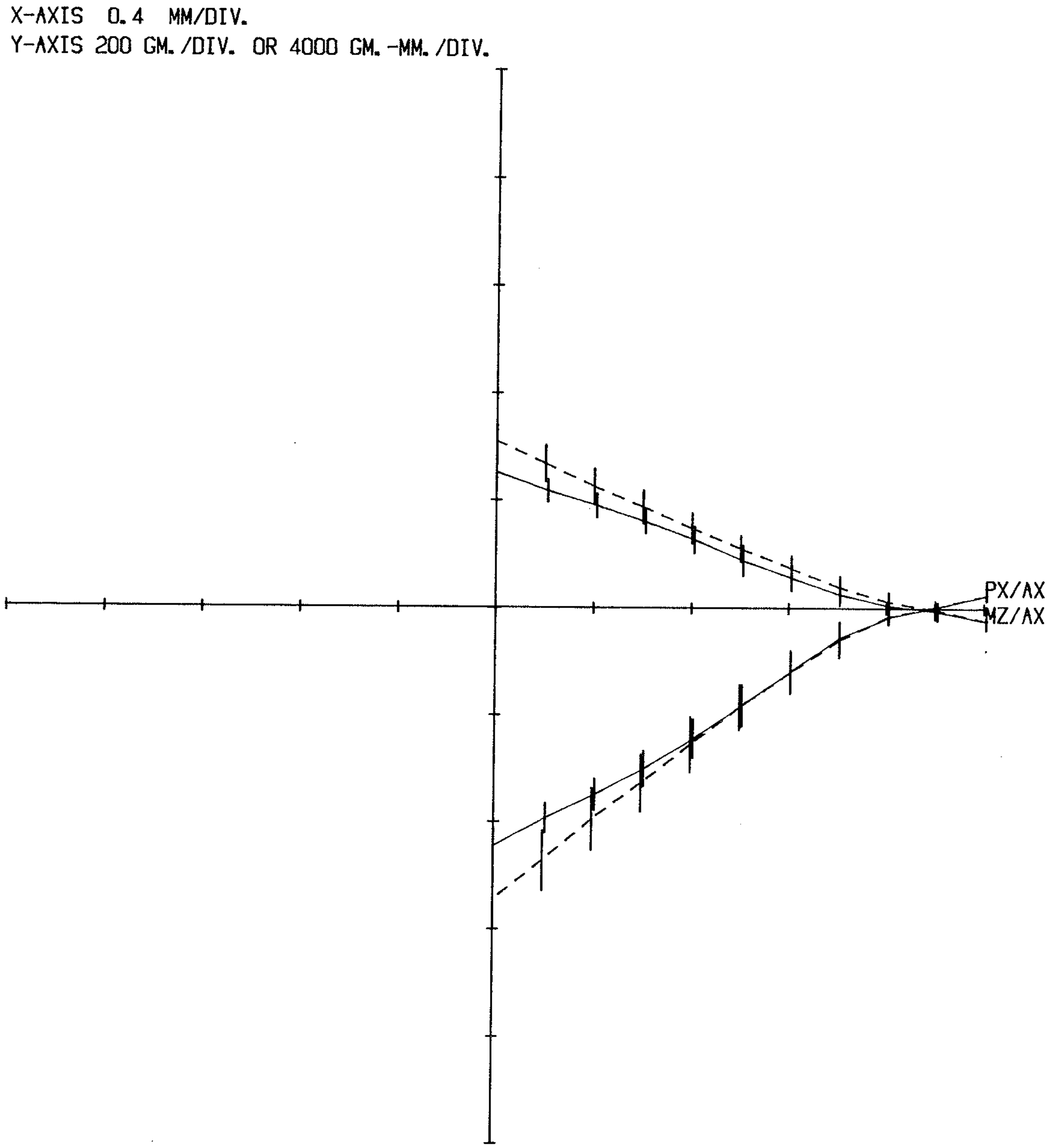


Figure 17: BUCCAL TIGHT: plots of Px/Ax and Mz/Ax

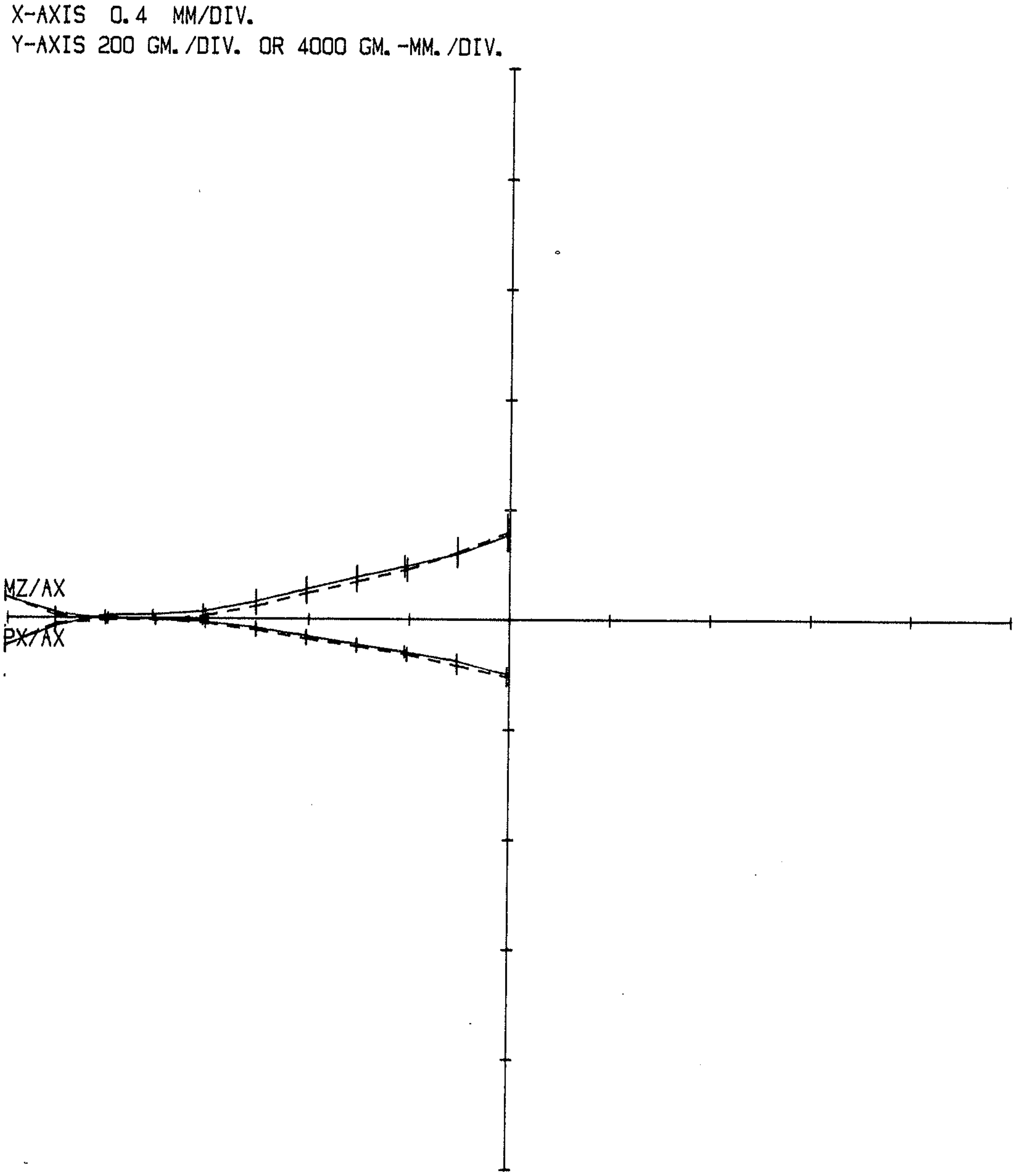


Figure 18: LINGUAL LOOSE: plots of Px/Ax and Mz/Ax

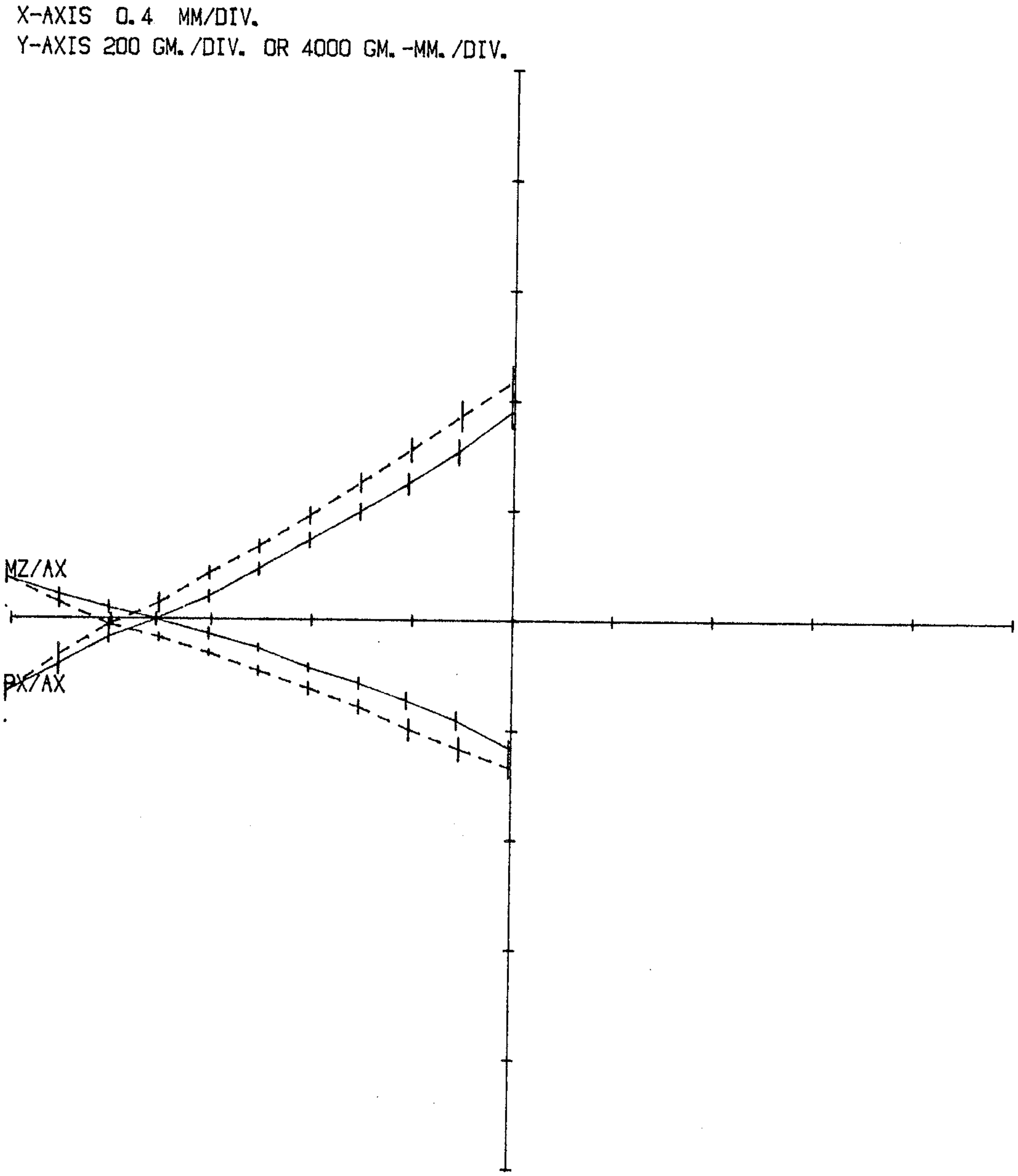


Figure 19: LINGUAL TIGHT: plots of Px/Ax and Mz/Ax

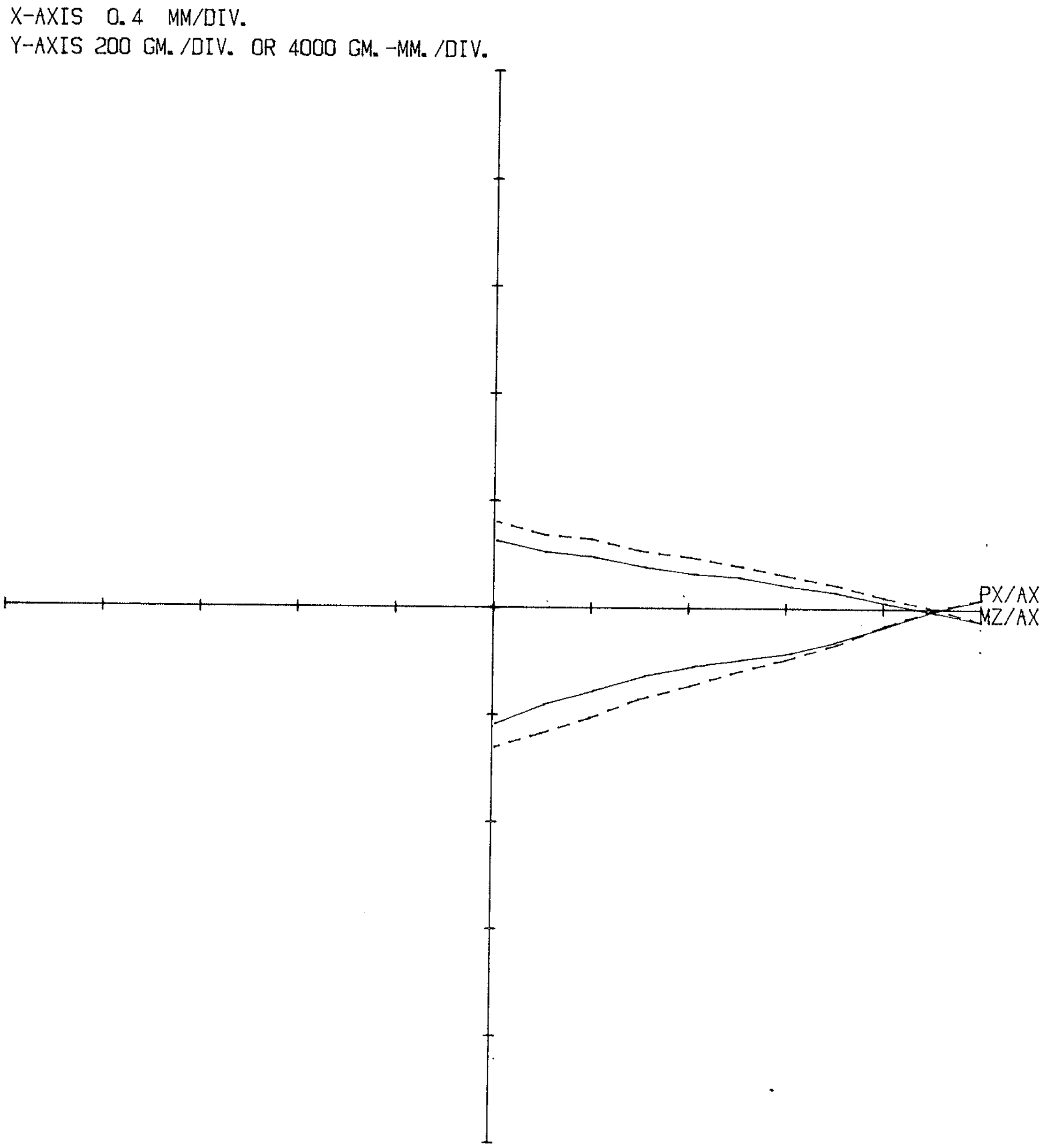


Figure 20: BUCCAL ELASTIC: plots of Px/Ax and Mz/Ax

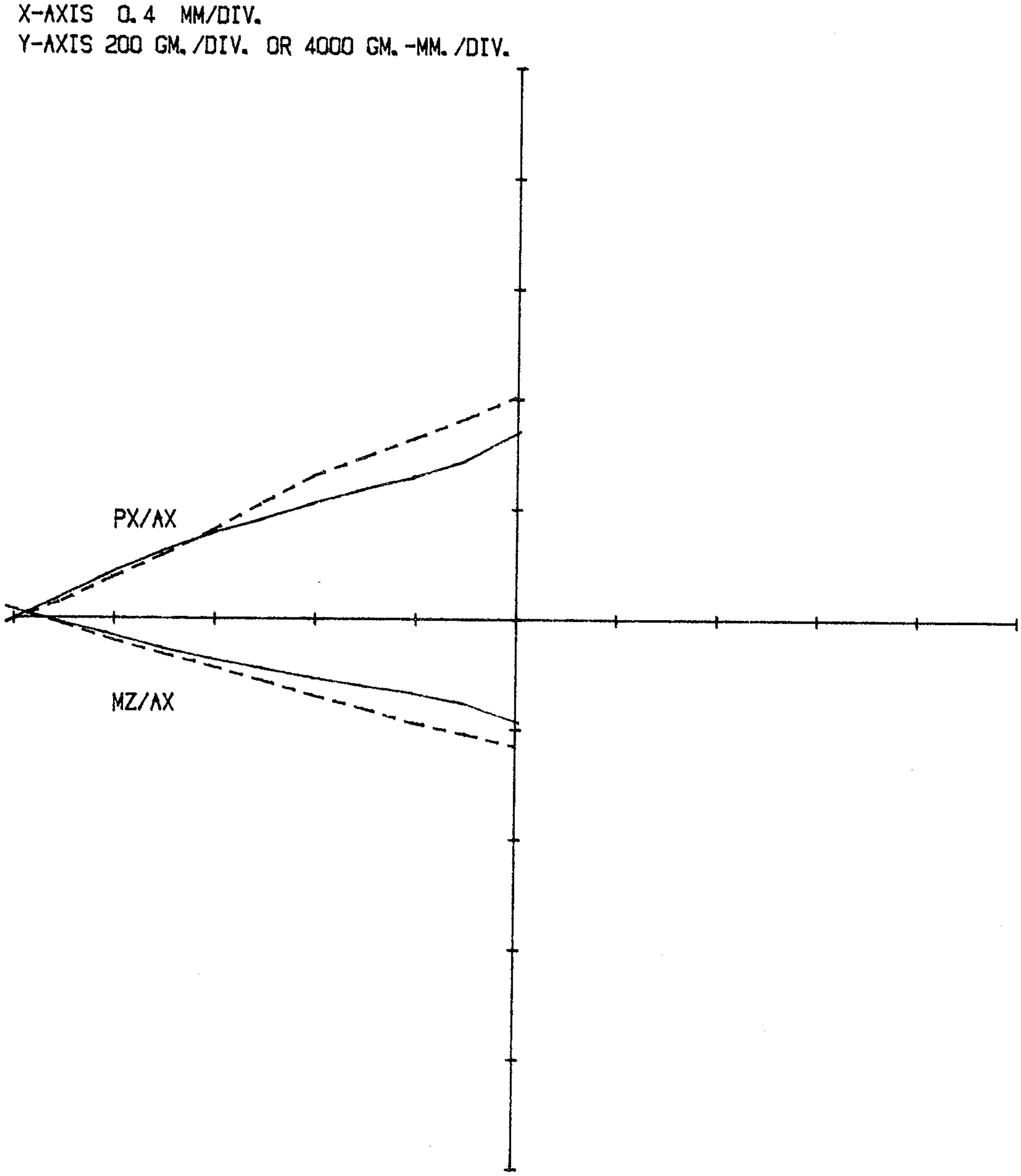


Figure 21: LINGUAL ELASTIC: plots of Px/Ax and Mz/Ax

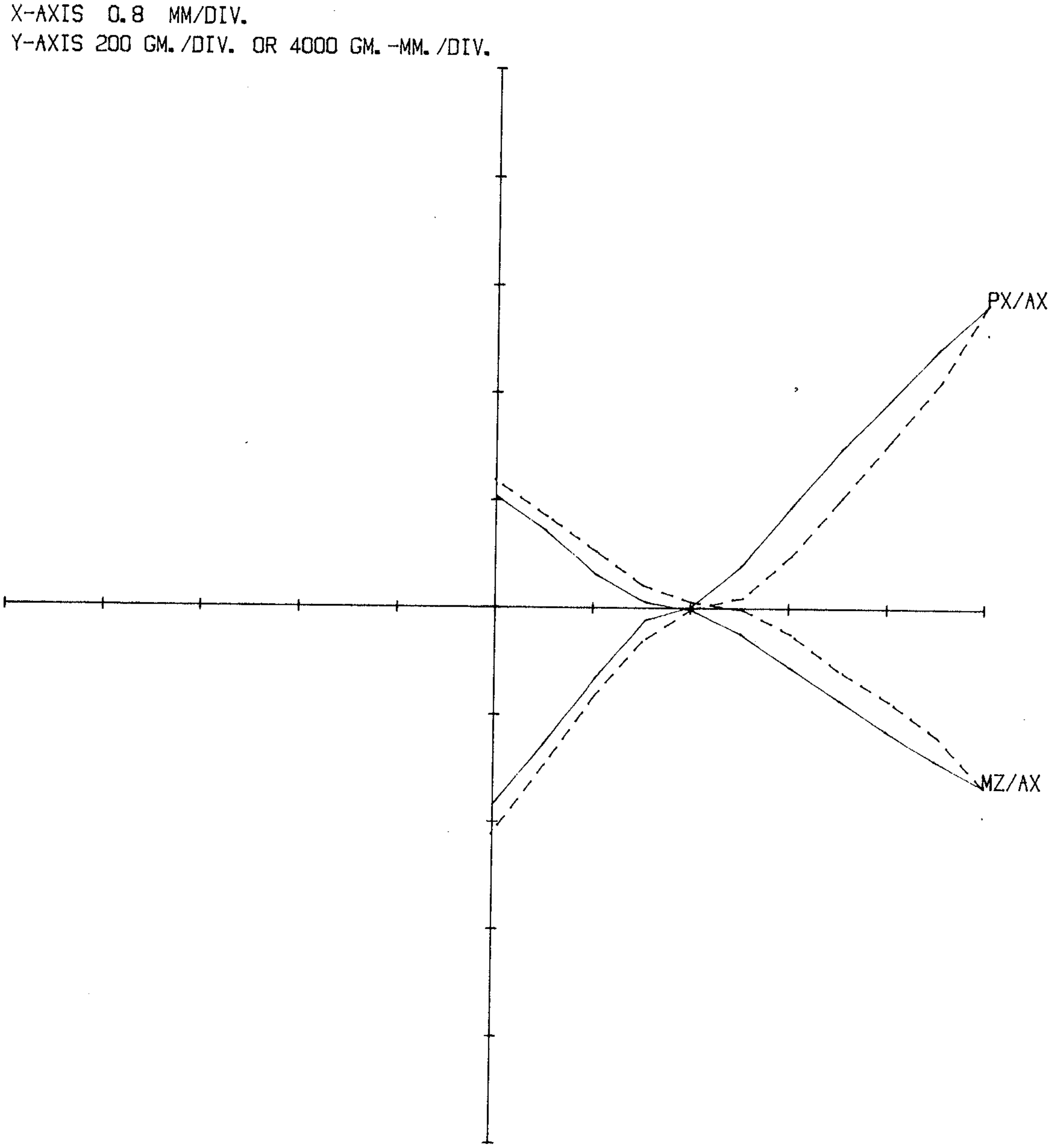


Figure 22: 4 mm. activation of BUCCAL TIGHT: plots of Px/Ax and Mz/Ax

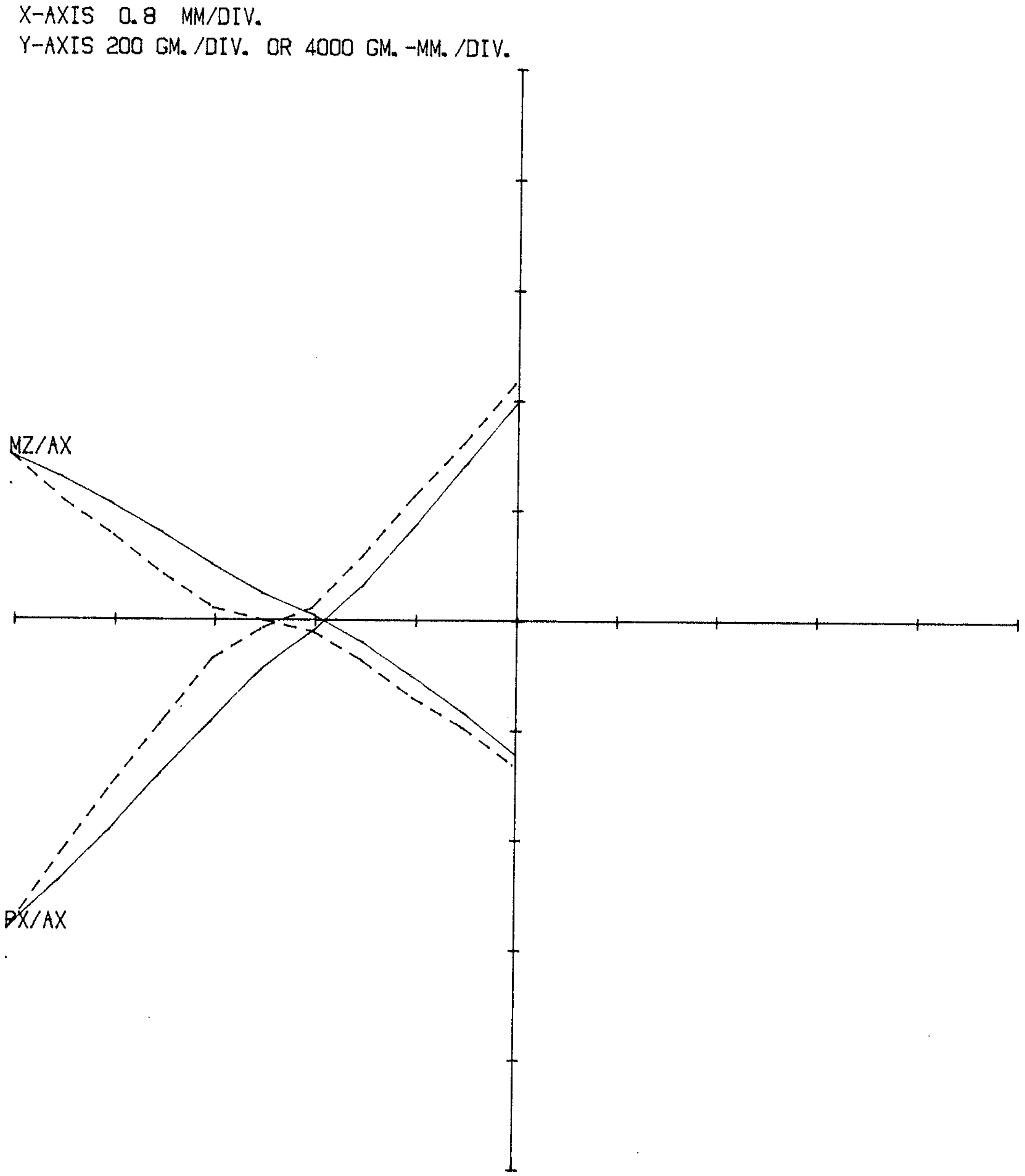


Figure 23: 4 mm. activation of LINGUAL TIGHT: plots of Px/Ax and Mz/Ax

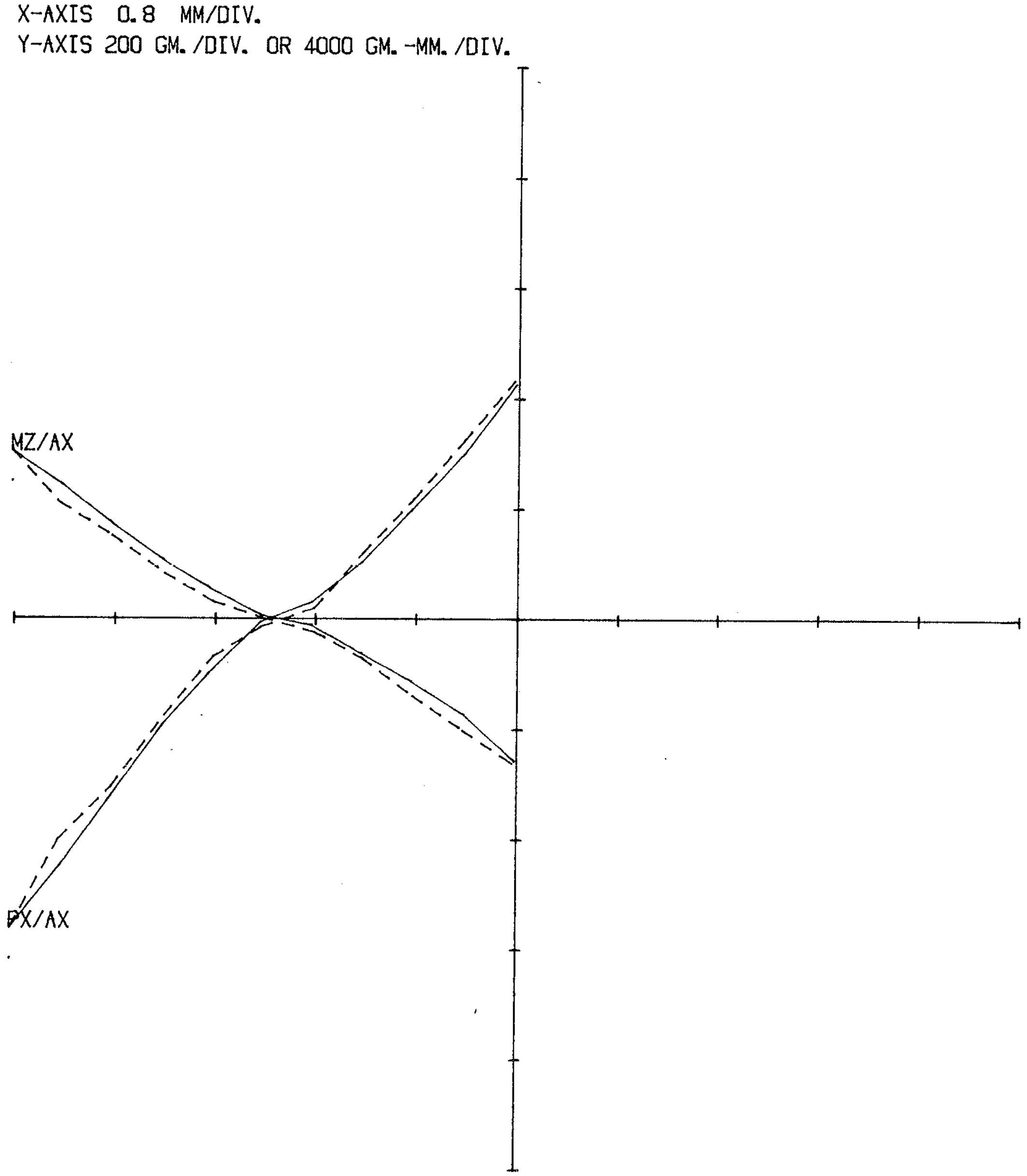


Figure 24: 4 mm. activation LINGUAL TIGHT: plots Px/Ax and Mz/Ax (2nd activation)

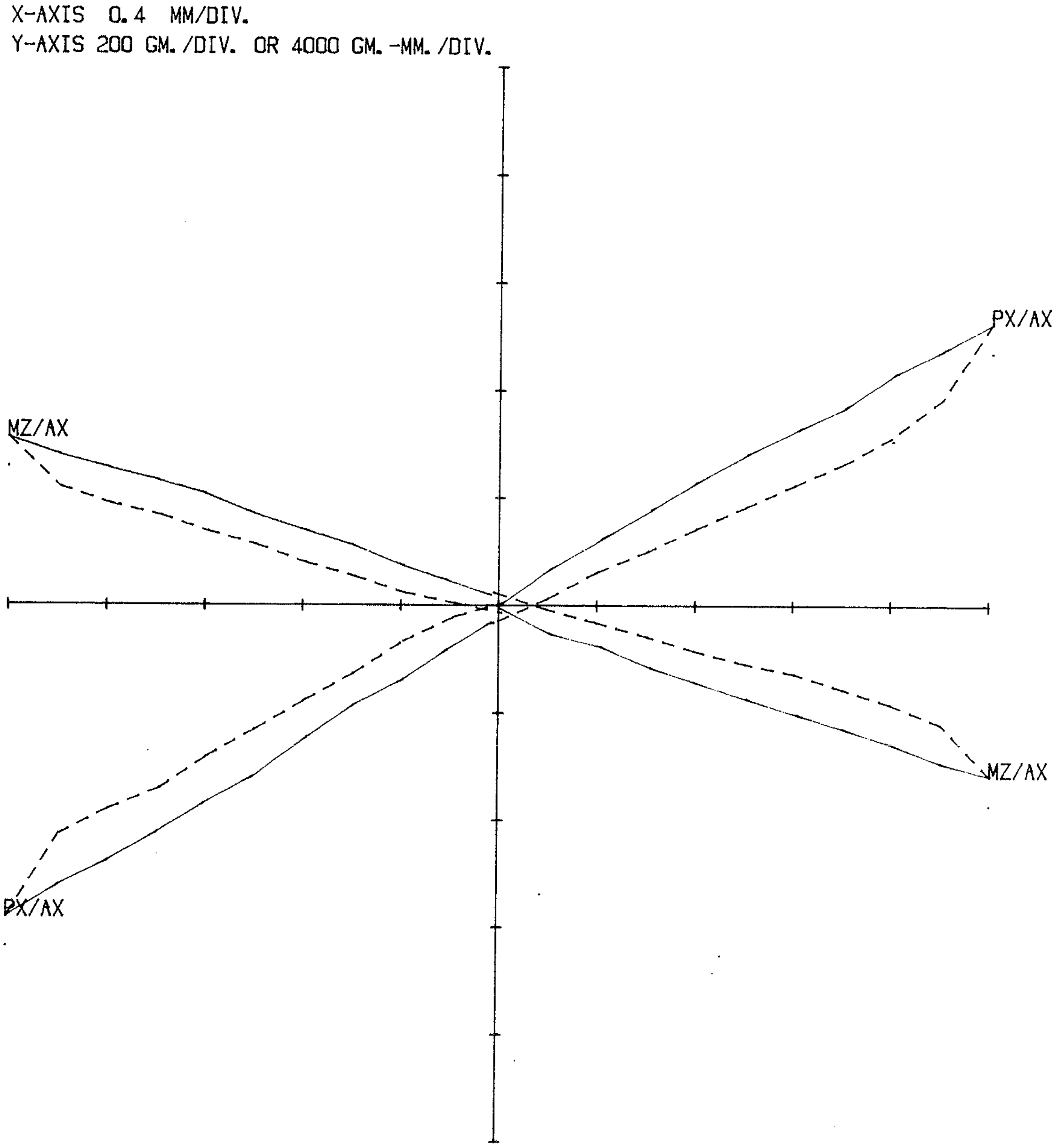


Figure 25: ALIGNED TIGHT: 2 mm. activation buccally and lingually: plots of Px/Ax and Mz/Ax

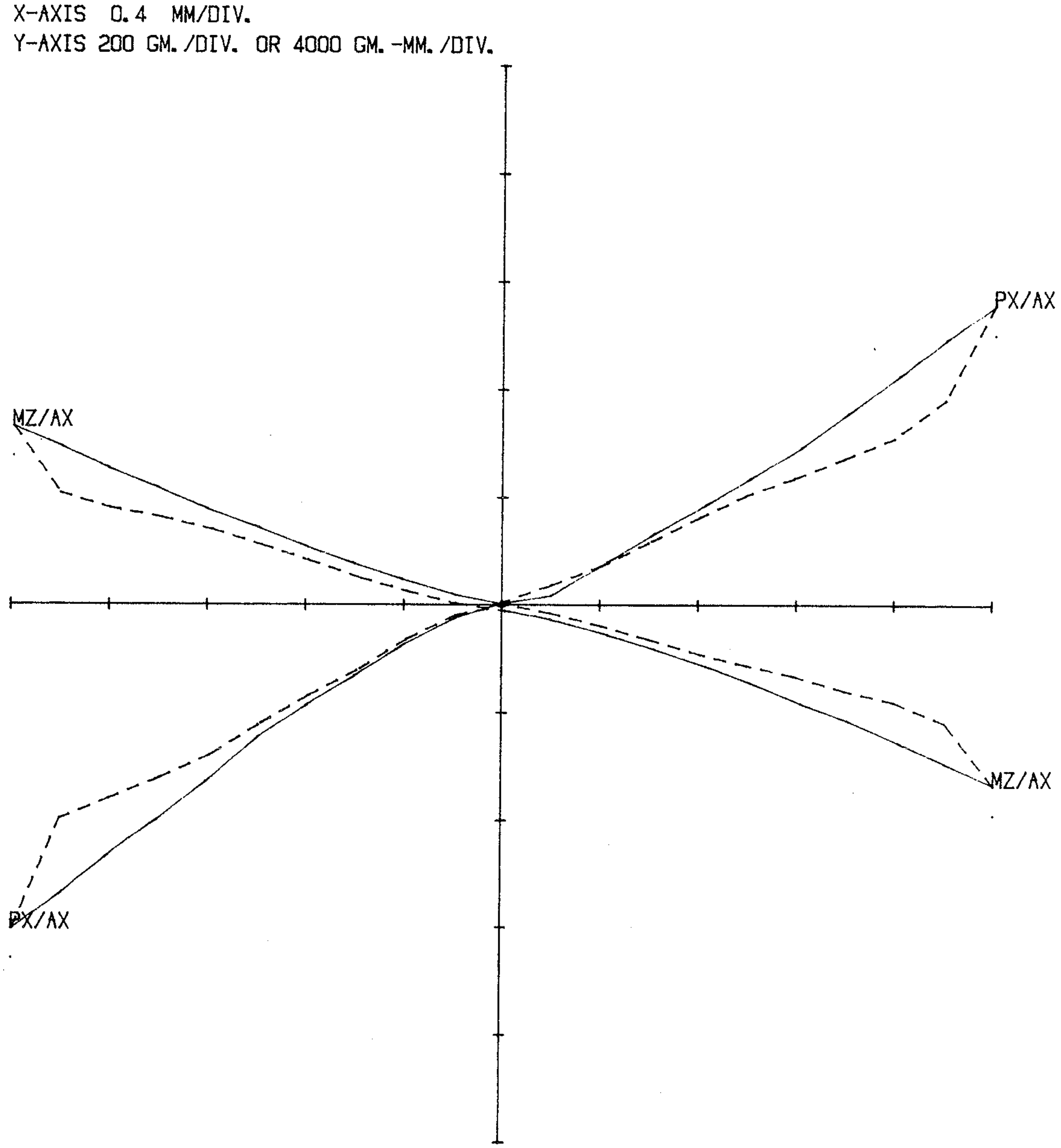


Figure 26: ALIGNED TIGHT: 2 mm. activation buccally and lingually: plots of Px/Ax and Mz/Ax (2nd activation)

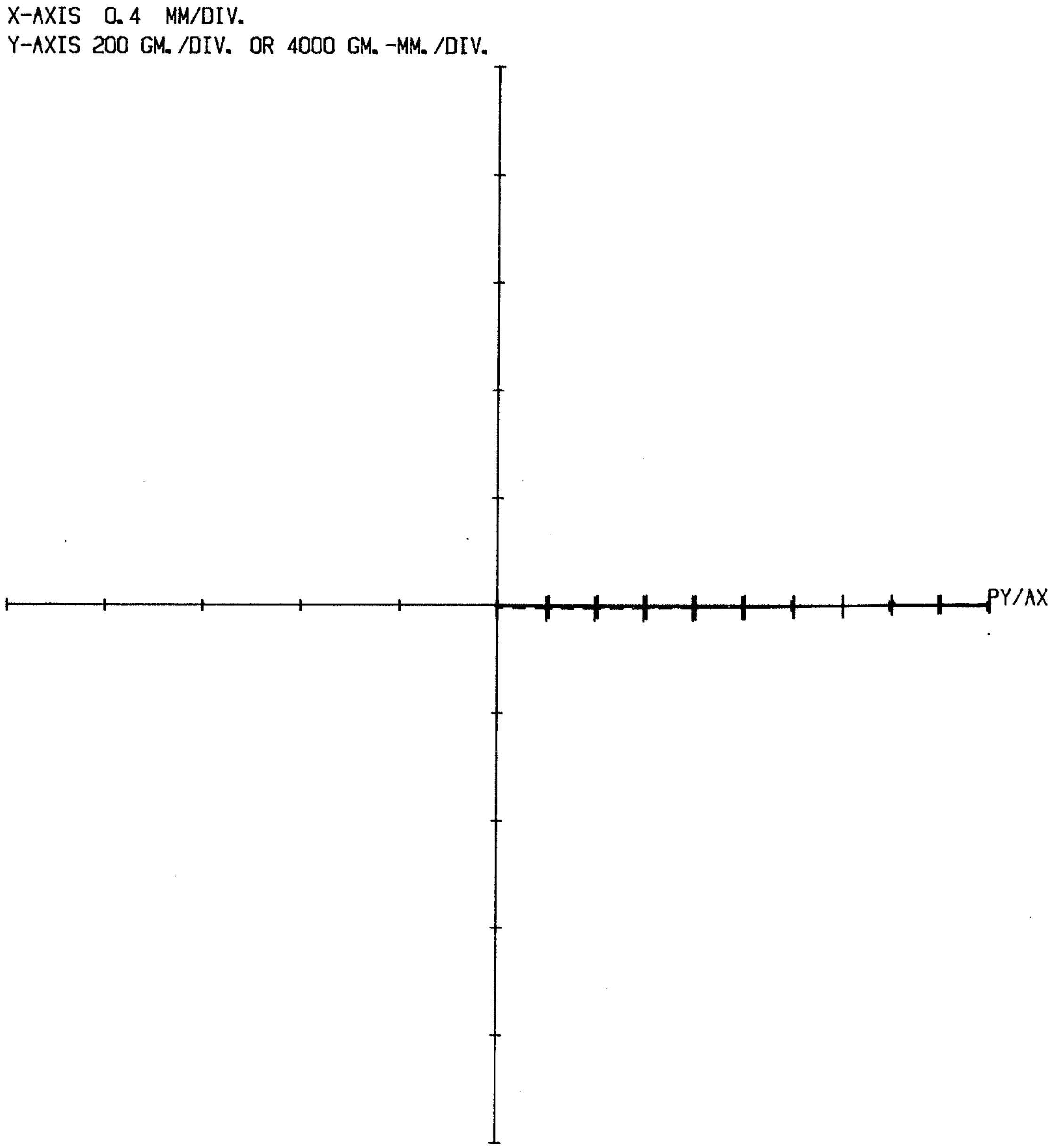


Figure 27: BUCCAL TIGHT: plot of Py/Ax

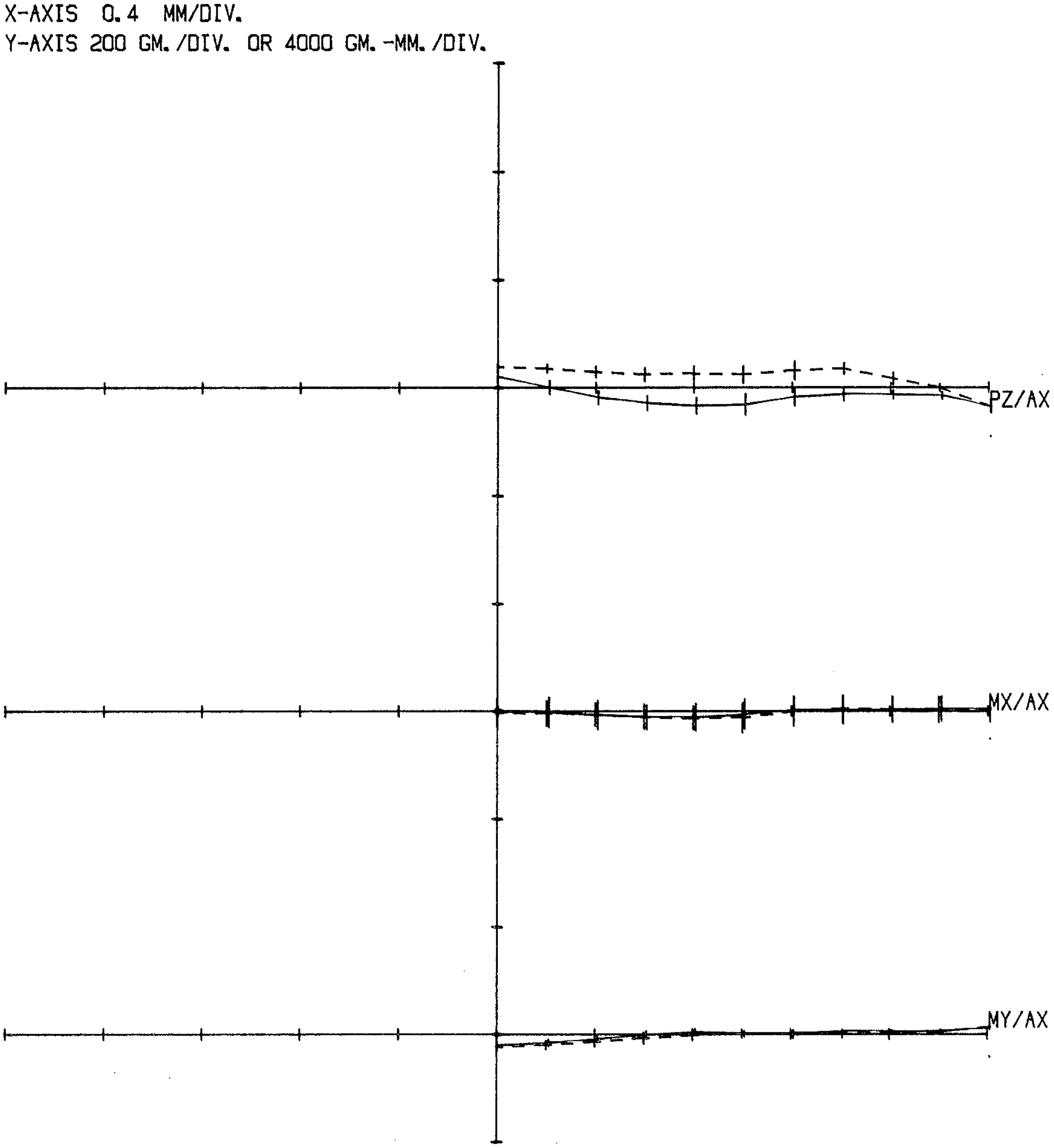


Figure 28: BUCCAL TIGHT: plots of Pz/Ax, Mx/Ax and My/Ax

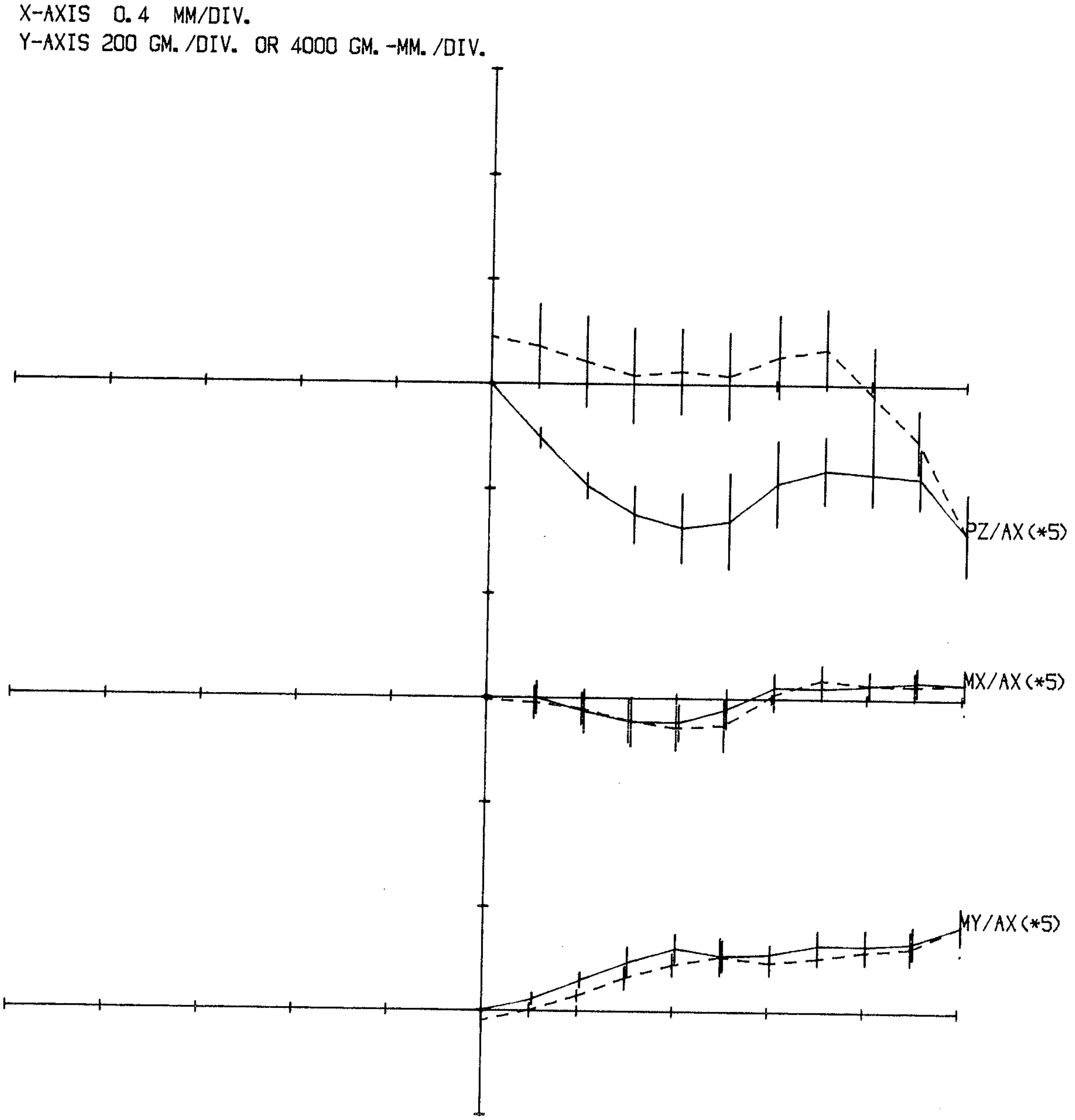


Figure 29: BUCCAL TIGHT: plots of Px/Ax, Mx/Ax and My/Ax (with zero shift and multiplication)

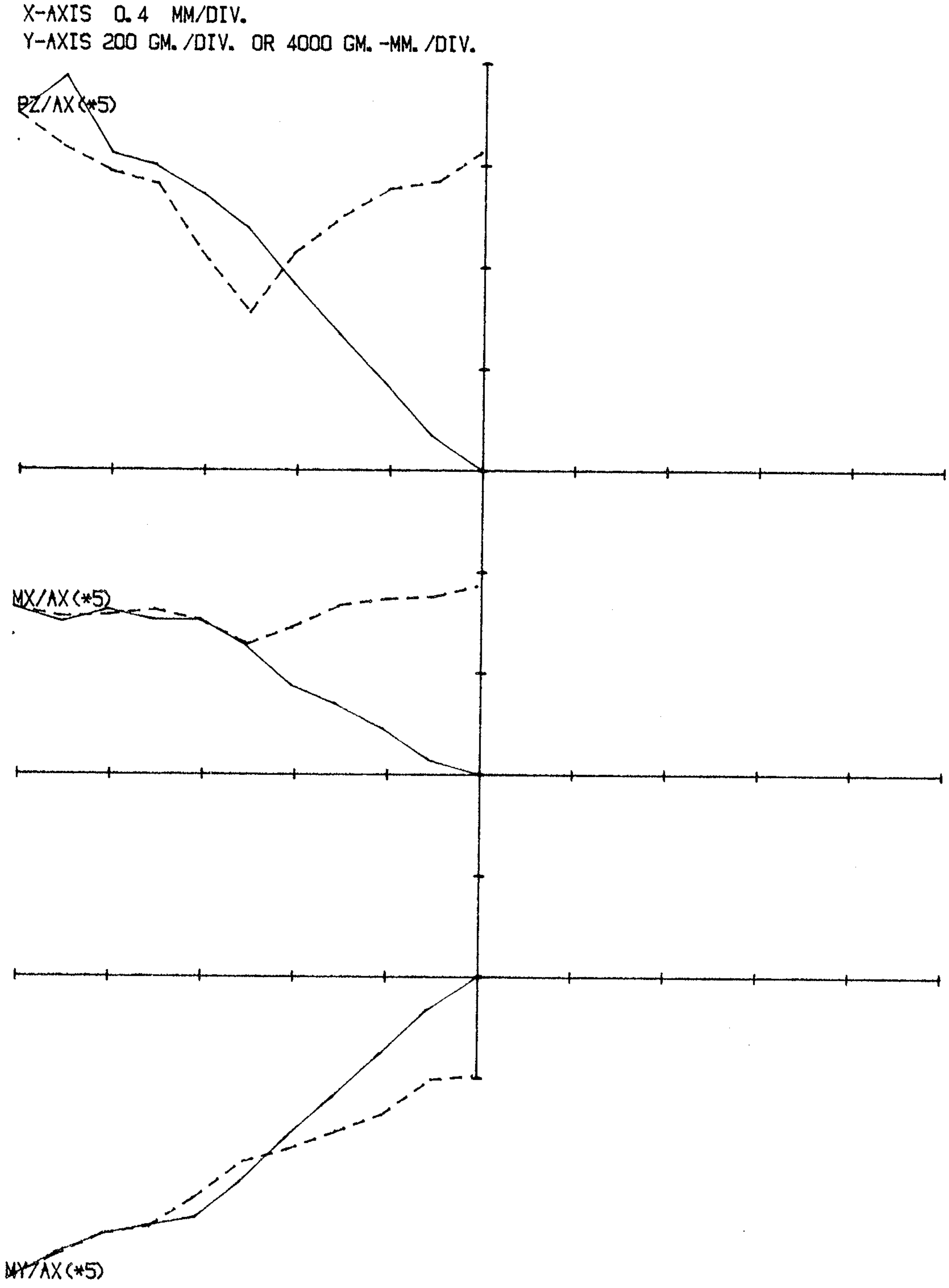


Figure 30: Two-tooth trial (left tooth and center tooth): plots of Pz/Ax, Mx/Ax and My/Ax (zero shift and multiplication)

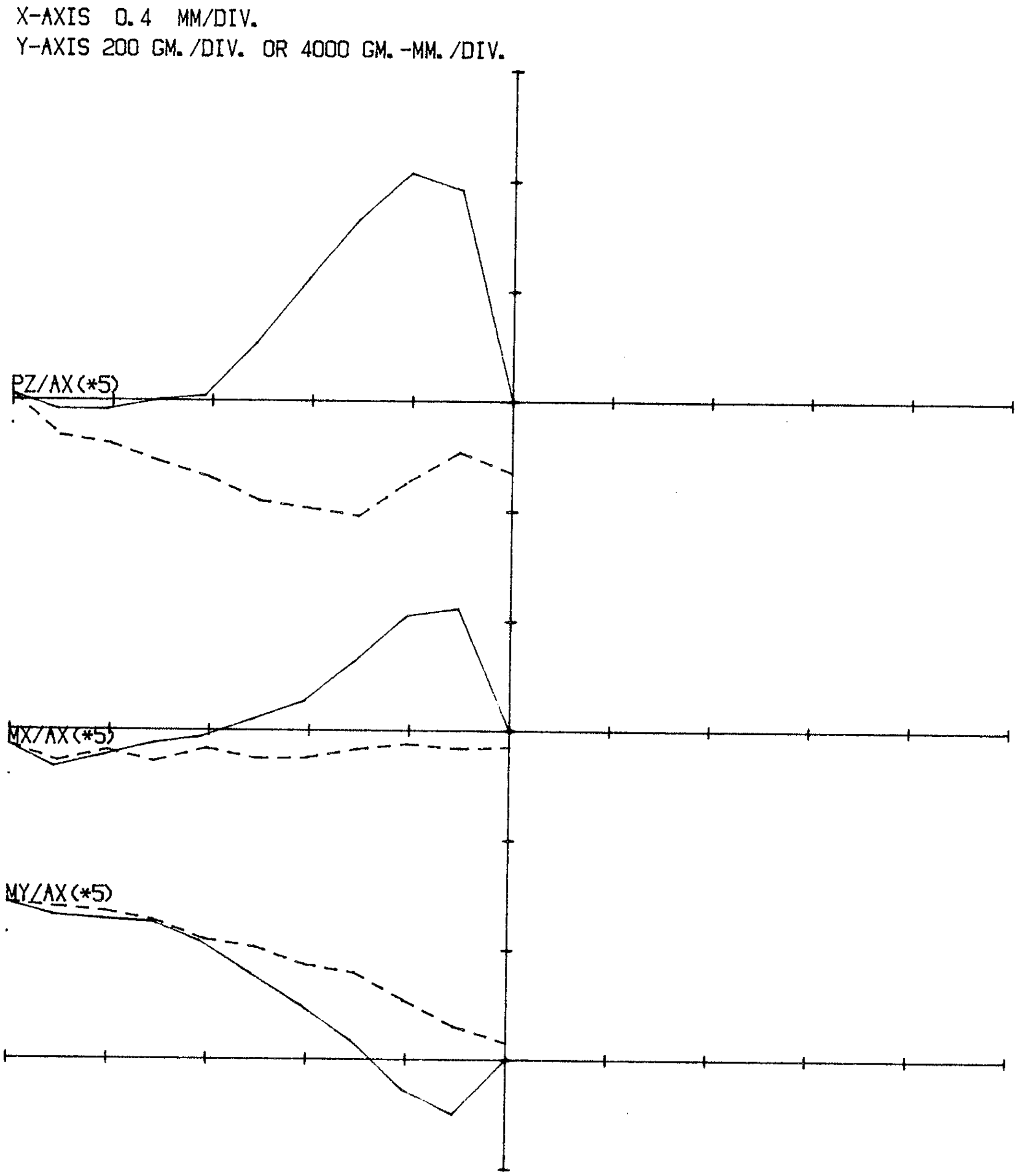


Figure 31: Two-tooth trial (right tooth and center tooth): plots of Pz/Ax, Mx/Ax and My/Ax (zero shift and multiplication)

CHAPTER 5

DISCUSSION

DISCUSSION

Introduction

The purpose of this investigation was to study the influence of ligation technique on the delivery of orthodontic forces and moments. A large proportion of orthodontic therapy involves alignment of teeth, thus, the effects of ligation on an orthodontic force system typically employed clinically to correct malalignment was studied. Forces and moments were simultaneously measured in three dimensions using instrumentation previously developed at the University of Manitoba. The discussion initially considers the characteristics of the force system associated with achieving tooth alignment. This is followed by an examination of significant secondary relationships generated by the alignment forces studied. Consideration of the significance of the findings to clinical orthodontics concludes the discussion.

Tooth Alignment

The method used in this investigation typically involved the center tooth of a three-tooth segment that was either buccally or lingually malaligned. All teeth were aligned occlusogingivally. The objective of the force system delivered by the archwire was to provide a force in the appropriate buccolingual direction (Px) to align the center tooth with the end teeth. Ideally the end teeth, assumed to be straight and in alignment with the remainder of the dental arch, would not be subjected to forces that might cause them to move. This investigation found that the archwires applied to the malaligned three-tooth segments were capable of initiating bracket alignment in the x direction. However this was accompanied by a number of other effects.

As expected, the .406 mm. (.016 inch) TMA archwire segments delivered an alignment force (Px) with all forms of ligation studied in both BUCCAL and LINGUAL situations. However the results suggest that the center tooth would not always be brought into complete alignment, regardless of the threshold required for tooth movement. The data also reveals that in all situations the Px was accompanied by a significant Mz or tendency to tip buccally or lingually around a mesiodistal axis. The Mz recorded is due to the Px acting at a distance 11 mm. from the center of resistance of the tooth.

The displacement of 2 mm. used in the BUCCAL and LINGUAL set-ups was considered typical of several orthodontic clinical situations. Although, the interbracket distance of 6.7 mm. used in this investigation is greater than that usually found intra-orally it could represent the clinical situation of not initially banding and bonding all teeth in an arch. The larger interbracket distance also ensured easy access to the brackets to achieve a controlled ligation technique.

The .406 mm. (.016 inch) TMA archwire delivered an initial Px of an appropriate direction for alignment of all BUCCAL and LINGUAL set-ups tested, regardless of the type of ligation used.

The discussion will indicate the activation distance at which this alignment force falls to zero. From the literature review it can be seen that some investigators suggest that tooth movement may cease when the force applied falls below a certain threshold (eg. Smith and Storey, 1952; Jarabak and Fizzell, 1972; Burstone, 1981). Jarabak and Fizzell have suggested a threshold value of approximately 40 gm. for lower bicuspid tooth movement. Typically the literature pertaining to optimal force considers 20 gm. to be a light force. The activation distance at which Px falls to these values (40 gm. and 20 gm.) will be indicated where appropriate in the discussion.

In the course of this discussion it will be necessary to comment on hysteresis and on changes in slope of the various plots. Therefore these terms will be elucidated.

Hysteresis refers to a failure of coincidence during two associated events. Hysteresis can be said to occur when behaviour during deflection in one direction is not the same as when it returns. An example is seen in Figure 25 where the plots of Px/Ax and Mz/Ax for deactivation and activation from an ALIGNED state do not coincide. Hysteresis results whenever friction is present in combination with a spring. Friction results along the longitudinal axis of the archwire (z dimension) as the archwire is moved through the bracket slot and makes contact with any part of the slot or the ligature strands.

A change in the slope of the plots Px/Ax represents a change in load deflection rate. This effect is distinct and separate from that of hysteresis. Slope change represents a change in archwire constraint and a change in shape of the archwire. As the teeth become aligned the configuration of the archwire changes from curved to straight. This is associated with a change in constraint and archwire stiffness. These changes result in a different slope of the plot Px/Ax. An example of this change in slope, or non-linearity of the Px/Ax curve, is present in Figure 24.

The phenomena of slope change and hysteresis will be referred to throughout the discussion and the independent factors responsible for their existence should be kept in mind.

Test Conditions

The discussion will now consider the behaviour of Px and Mz for the various malalignment conditions and ligation techniques examined.

BUCCAL LOOSE

The mean values of Px/Ax and Mz/Ax for the BUCCAL LOOSE series are presented in Figure 16. The plot of Px/Ax originates below the horizontal axis representing a lingually directed force. At Ax=0, the initial mean value of Px is 135 gm. with deactivation the value of Px gradually falls to zero (at Ax=2.0 mm.). The mean value of Px is less than 40 gm. at .9 mm. of deactivation and less than 20 gm. at 1.2 mm. of deactivation. The plot of Mz/Ax (Fig. 16) originates above the horizontal axis and represents lingual crown tipping. At Ax=0, the initial mean value of Mz is 1650 gm.mm. As expected, the plot of Mz/Ax closely mirrors the Px/Ax plot. The plot Px/Ax is nonlinear overall, however, certain slope characteristics can be applied to segments of the graph. The value of Px decreases most rapidly between Ax=0 and Ax=.2 mm. (Fig. 16). Between Ax=.2 and Ax=1.2, the slope of Px/Ax is reduced as compared to its initial value. From Ax=1.2 to Ax=2.0 (full deactivation) the Px/Ax plot displays a very low slope. The plots of deactivation and activation nearly superimpose along their entire course. This suggests a minimal amount of hysteresis in this series of trials.

BUCCAL TIGHT

The mean values of Px/Ax and Mz/Ax for the BUCCAL TIGHT series are presented in Figure 17. The plot of Px/Ax originates below the horizontal axis representing a lingually directed force. At Ax=0 the mean initial value of Px=450 gm. With deactivation the value of Px is reduced and reaches zero when Ax=1.8 mm. In other words a lingually directed force is no longer present when the teeth are still .2 mm. out of alignment (40 gm. at 1.5 mm; 20 gm. at 1.6 mm.). At complete deactivation (Ax=2.0 mm.) there is a small buccally directed force present. Clinically this buccally directed force would not occur, since tooth movement would cease when the lingually directed force fell to zero or below the threshold necessary to move the tooth. The plot of Mz/Ax (Fig. 17) originates above the horizontal axis and represents lingual crown tipping. The mean initial value for Mz is 5100 gm.mm. and the plot of Mz/Ax closely mirrors that of Px/Ax. The deactivation plot of Px/Ax is essentially nonlinear although slope trends can be recognized along its path. The value of Px decreases at a fairly uniform rate between Ax=0 and Ax=.8 mm. The slope of Px/Ax is greater between Ax=.8 mm. and Ax=1.4 mm. and is then reduced from Ax=1.4 mm. to 1.6 mm. A further slope reduction is evident between Ax=1.6 mm. and Ax=2.0 mm. The activation plot of Px/Ax (dotted line in Fig. 17) is nearly identical to that of the deactivation plot (solid line in Fig. 17) between Ax=2.0 mm. and Ax=.8 mm. However, between Ax=.8 mm. and Ax=0 the Px/Ax activation plot is not coincident with the deactivation indicating, the presence of hysteresis.

The factors that can influence the changes in slope of the Px/Ax curves, the hysteresis occasionally present and the tendency for Px to reach zero before complete deactivation in the BUCCAL TIGHT sample will now be discussed.

The Px/Ax plot of BUCCAL LOOSE (Fig. 16) displays a fairly steady and gradual slope reduction coupled with an absence of hysteresis. Thus frictional forces do not significantly affect the buccolingual force in this situation. The slope reduction is likely due to a gradual reduction in beam constraint (k) (see page 8) as the teeth become aligned. The change in constraint occurs as the archwire achieves increasingly more freedom to move between the base of the bracket slot and the ligature wire.

The Px/Ax plot of BUCCAL TIGHT (Fig. 17) displays a more irregular series of slopes. The value of Px declines less rapidly from Ax=0 to Ax=.8 mm. than it does from Ax=.8 mm. to Ax=1.4 mm. This would suggest that the archwire has less stiffness over the initial stage of deactivation than through the intermediate stage. Greater frictional resistance encountered at the end teeth as the archwire tries to pass through the brackets of these teeth likely contributes to this reduction in stiffness. This follows from the fact that some energy that would otherwise have been used for tooth alignment was lost to friction. If friction was sufficiently great to inhibit any archwire movement the force on the center tooth would immediately fall to zero. Initially, when allowing the center tooth to deactivate, some of the energy stored in the archwire is absorbed by frictional losses at the end teeth. Thus, less energy is available to align the teeth and the effective archwire stiffness is reduced. With further deactivation the archwire enters the end teeth at less of an angle and the amount of friction encountered is reduced. This reduced level of friction allows more of the energy stored in the archwire to be available for alignment and the effective stiffness is increased. This increased stiffness is indicated by the increase in slope between Ax=.8 mm. and Ax=1.4 mm. (Fig. 17). The decrease in slope apparent after Ax=1.4 mm. and more pronounced after Ax=1.6 mm. is probably due to a decrease in constraint at the end teeth. As the archwire continues to straighten it has increased freedom to move between the bracket slot and the ligature wire. With greater freedom of movement in the end teeth and a decrease in constraint, the archwire stiffness is decreased.

The activation plot of Px/Ax for BUCCAL TIGHT (dotted line, Fig. 17) displays the same slope changes as the deactivation plot (solid line, Fig. 17) over the activation range Ax=2.0 mm. to Ax=.8 mm. However between Ax=.8 mm. and Ax=0 the activation plot displays greater stiffness than the deactivation plot. This hysteresis is accounted for by frictional effects at the end teeth. With increased activation (betweeen Ax=.8 mm. and Ax=0) the archwire must be drawn increasingly tighter against the ligatures on the end teeth. The friction produced by these ligatures reinforces the stiffness of the archwire as the center tooth moves further out of alignment. This increased stiffness results in an increased slope of the activation plot Px/Ax between Ax=.8 mm. and Ax=0 as compared to that between Ax=1.4 mm. and Ax=0.

Thus friction produced by ligation at the end teeth is responsible for an initial decrease in stiffness during deactivation and an increase in stiffness during the final stages of activation for BUCCAL TIGHT. This frictional effect accounts for the hysteresis present in Px/Ax in this situation. It is noteworthy that if the common slope of the deactivation and activation plots between Ax=.8 mm. and Ax=1.4 mm. is extrapolated back to the vertical axis the resulting line would almost perfectly bisect the existing plots of deactivation and activation. An extrapolated line of this nature might represent the archwire stiffness between Ax=0 and Ax=.8 mm. if frictional forces associated with ligation were not present at the end teeth. The near perfect bisection of the deactivation and activation plots suggests that friction played a nearly equivalent role in altering the stiffness of each plot.

The plot of Px/Ax for BUCCAL LOOSE does not display any appreciable hysteresis. This is likely due to the absence of significant friction at the end teeth. Loose ligation in this situation does not result in any appreciable binding of the archwire against the bracket slot of the end teeth.

It is interesting to consider what factors result in Px falling to zero before the teeth are aligned, (as occurs in BUCCAL TIGHT). Two separate influences can contribute to this phenomenon. Firstly, when the center tooth is ligated tightly the archwire can be pulled to a position lingual to the bracket slot as it leaves each end of the bracket (Fig. 32). Secondly, if this occurs the passive position of the center tooth will exist when the ends of the archwire are slightly lingual to the center tooth and, hence, Px=0 when the center tooth is slightly buccal of the end teeth. If the archwire is permanently distorted when the end teeth are ligated the passive position of the center tooth will be influenced. With permanent distortion the archwire will not provide a load when the teeth occupy a position corresponding to the kink present in the wire. This will occur before the center tooth is aligned with the end teeth.

The plots of Px/Ax and Mz/Ax for BUCCAL LOOSE and BUCCAL TIGHT (Figs. 16 and 17) demonstrate the influence of ligature tension on orthodontic force and moment delivery. The corresponding plots for lingual malalignment will now be discussed.

LINGUAL LOOSE

The mean values of Px/Ax and Mz/Ax for the LINGUAL LOOSE series are presented in Figure 18. The plot of Px/Ax originates above the horizontal axis representing a buccally directed force. At Ax=0 the

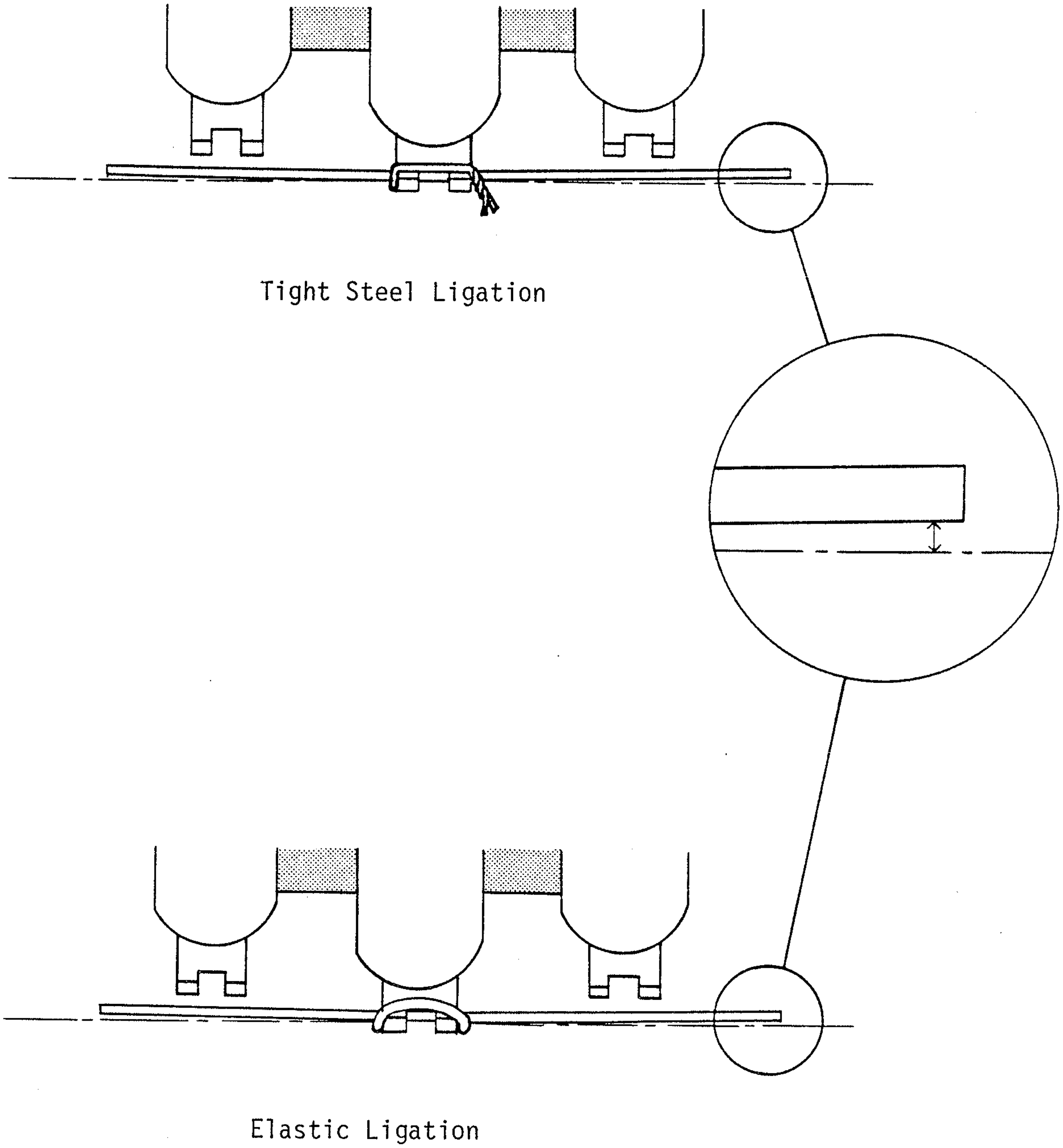


Figure 32: Potential influence of center tooth ligation on archwire bias.

initial mean value of Px is 150 gm. With deactivation the value of Px is reduced and reaches zero when Ax=1.65 mm. (40 gm. at .9 mm.; 20 gm. at 1.15 mm.). At complete deactivation (Ax=2.0 mm.) a lingually directed force is present. Such a force would not occur clinically since tooth movement would cease when the buccally directed force fell to zero or below the threshold necessary to move the teeth. The plot of Mz/Ax (Fig. 18) originates below the horizontal axis and represents buccal crown tipping. The mean initial value of Mz is 2000 gm.mm. and the plot of Mz/Ax closely mirrors the plot of Px/Ax. The deactivation plot of Px/Ax is essentially nonlinear, however, certain slope trends are recognizable. The value of Px decreases fairly rapidly from Ax=0 to Ax=.2 mm. From Ax=.2 mm. to Ax=1.2 mm. the slope of Px/Ax is fairly consistent but less than its initial value. From Ax=1.2 mm. to Ax=1.6 mm. the slope of the Px/Ax plot is close to zero. Its slope gently increases from Ax=1.6 mm. to 1.8 mm. and then increases quite markedly from Ax=1.8 mm. to Ax=2.0 mm. The activation plot of Px/Ax (dotted line in Fig. 18) closely resembles the deactivation plot (solid line in Fig. 18). The two plots do not completely superimpose, suggesting the presence of a small degree of hysteresis.

Factors previously discussed can be shown to exert their influence when considering the phenomena presented in the Px/Ax plot for LINGUAL LOOSE (Fig. 18). Slope changes are likely due to changes in archwire constraint provided by the ligatures. During deactivation the archwire achieves greater freedom of movement between bracket slot and ligature wires in the end teeth and constraint is reduced. This results in the initial reduction of archwire stiffness and slope changes of the Px/Ax curve. The very flat portion of the Px/Ax plot between Ax=1.2 mm. and Ax=1.6 mm. likely represents a reduction in constraint provided by ligation at the center tooth or all three teeth. The archwire has considerable freedom of movement between the bracket slot and ligature wire at the center tooth. As the tooth is brought buccally beyond this activation range the archwire begins to load against the bracket slot. This, once again, provides constraint to the archwire at the center tooth. As a result, archwire stiffness increases again and the slope of the Px/Ax curve is increased from Ax=1.6 mm. to 1.8 mm. and more especially from Ax=1.8 mm. to 2.0 mm..

The amount of hysteresis present in the Px/Ax plots of deactivation and activation for LINGUAL LOOSE never exceeds 10 gm. of force. This relatively small difference can be attributed to slight changes in friction encountered by the archwire during deactivation and subsequent activation and is not of great significance.

The factors contributory to Px=0 before complete deactivation are also similar to those previously discussed. For LINGUAL LOOSE Px=0 at Ax=1.65 mm. (Fig. 18). After ligation is initially performed on the lingually malaligned center tooth, the archwire enters the end teeth at a considerable angle. The portion of the archwire between the center tooth and the end teeth is in a position lingual to the bracket slot of the end teeth. The ligatures on the end teeth are capable of maintaining this bias in the position of the archwire. Once the end teeth are ligated this archwire bias will be present whether or not the center tooth is ligated (Fig. 33). As a result of this bias in the archwire created by the ligatures on the end teeth, the passive

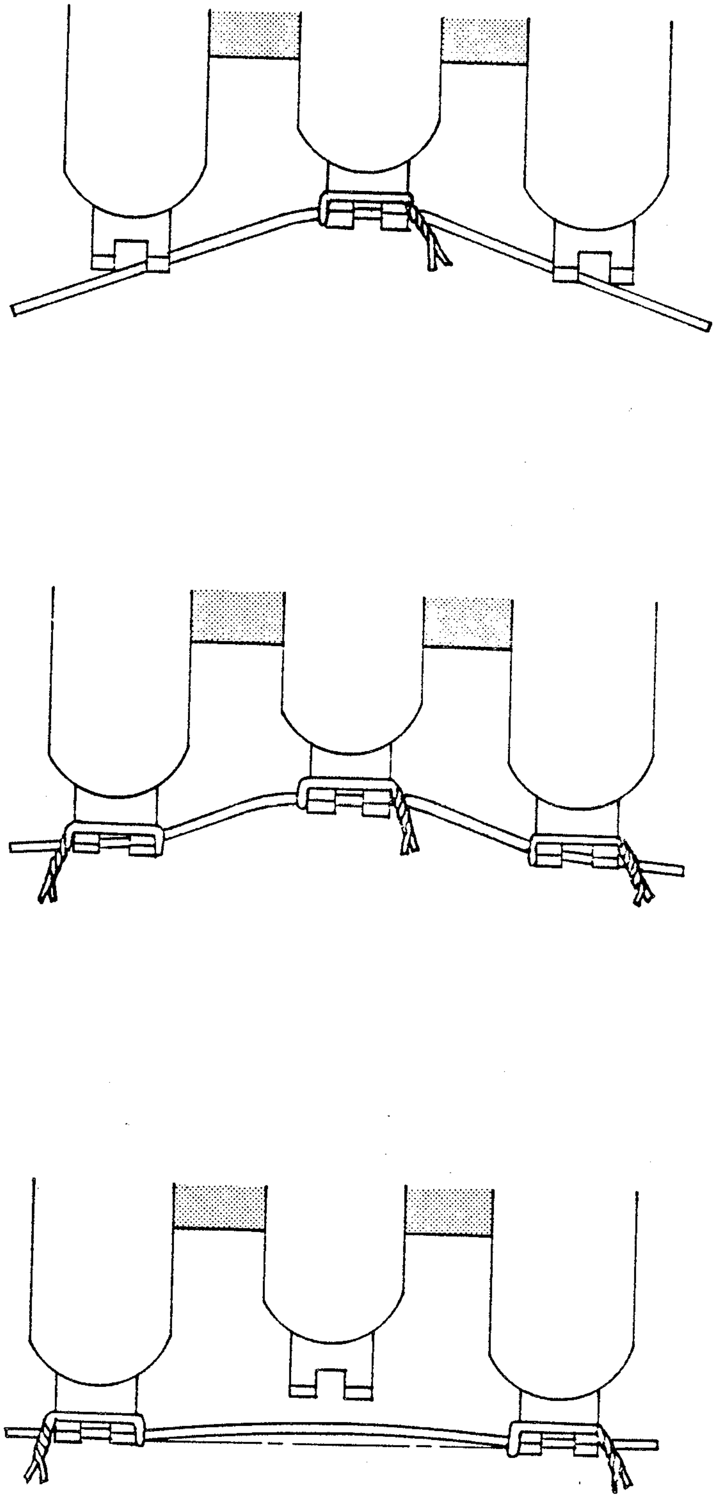


Figure 33: Potential influence of end teeth ligation on archwire bias.

position of the archwire will occur before the center tooth is aligned. Permanent distortion of the archwire could also contribute to this early loss of buccally directed force. However visual inspection of the archwire segments used in the LINGUAL LOOSE series suggests that permanent distortion did not occur to any marked extent. Thus archwire bias resulting from the ligatures on the end teeth contributes most strongly to elimination of buccally directed force before complete deactivation for the LINGUAL LOOSE series. The archwire bias also contributes to the increased slope of the Px/Ax plot between Ax=1.6 mm. and Ax=2.0 mm. As described earlier, when the center tooth moves buccally in this activation range the archwire is loaded against the bracket slot. Due to the biased position of the archwire this loading occurs before Ax=2.0 mm. Thus constraint is increased and the slope of plot Px/Ax increases.

LINGUAL TIGHT

The mean values of Px/Ax and Mz/Ax for the LINGUAL TIGHT series are presented in Figure 19. The plot of Px/Ax originates above the horizontal axis representing a buccally directed force. At Ax=0 the mean initial value of Px=380 gm. With deactivation the value of Px is reduced and reaches zero when Ax=1.4 mm. (40 gm. at 1.2 mm., 20 gm. at 1.3 mm.). At complete deactivation (Ax=2.0 mm.) a lingually directed force is present. Clinically this would not occur, but rather tooth movement would cease when the buccally directed force fell to zero or below the threshold necessary to move the teeth. The plot of Mz/Ax (Fig. 19) originates below the horizontal axis and represents buccal crown tipping. The mean initial value of Mz is 4600 gm.mm. and the plot of Mx/Ax closely mirrors that of Px/Ax. The deactivation plot of Px/Ax is nonlinear overall, however, slope trends are recognizable along its path. The value of Px decreases most rapidly between Ax=0 and Ax=.2 mm. The slope of Px/Ax is relatively constant between Ax=.2 mm. and Ax=1.2 mm. and is less than during the initial deactivation step. Between Ax=1.2 mm. and Ax=1.6 mm. the slope is consideralby less. This portion of the plot includes the activation point (Ax=1.4 mm.) at which Px=0. The slope of the plot from Ax=1.6 mm. to Ax=2.0 mm. increases (similar to the slope from Ax=.2 mm. to Ax=1.2 mm.). The activation plot of Px/Ax (dotted line in Fig. 19) displays similar slope characteristics as the deactivation plot (solid line in Fig. 19). However between Ax=.2 mm. and Ax=0 the Px/Ax activation plot maintains the slope displayed between Ax=1.2 mm. and Ax=.2 mm. The activation and deactivation plots are noncoincident over the entire range of activation indicating the presence of hysteresis.

Once again factors previously discussed largely account for the phenomena present in the Px/Ax curve for LINGUAL TIGHT. The slight decrease in slope of the deactivation plot between Ax=.2 mm. and Ax=1.2 mm. as compared to the initial step of deactivation is likely due to a small reduction in constraint associated with a slight increase in archwire freedom under the ligatures of the end teeth and/or the center tooth. The more apparent slope reduction between Ax=1.2 mm. and Ax=1.6 mm. likely represents a reduction in constraint provided by the ligature at the center tooth. The subsequent increase in slope and archwire stiffness between Ax=1.6 mm. and Ax=2.0 mm. results from the archwire loading against the bracket slot of the center tooth.

The archwire bias discussed earlier when describing LINGUAL LOOSE and presented in Figure 33 accounts for some aspects of the Px/Ax plot for LINGUAL TIGHT (Fig. 19). It contributes to Px falling to zero at Ax=1.4 mm. and is partly responsible for the increased slope of the deactivation plot between Ax=1.6 mm. and Ax=2.0 mm. since the archwire bias results in contact between the archwire and the bracket slot of the center tooth before Ax=2.0 mm.

Visual inspection of the archwire segments used in the LINGUAL TIGHT tests revealed that permanent distortion regularly occurred. This plastic deformation resulted in an archwire kink that also contributed to Px reaching zero at an earlier activation distance than had occurred with LINGUAL LOOSE. Permanent distortion also contributed to the earlier contact of the archwire with the bracket slot of the center tooth and the subsequent slope increase between Ax=1.6 mm. and Ax=2.0 mm. The permanent distortion induced by tight ligation also limited the increase in the initial Px for LINGUAL TIGHT (380 gm.) compared to LINGUAL LOOSE (150 gm.).

There is considerable hysteresis displayed in Px/Ax plot for LINGUAL TIGHT (Fig. 19). This can be attributed to friction associated with the ligatures on the end teeth. Owing to the geometry of the lingual malalignment and the resulting archwire bias, the friction provided by the ligature strands on the side of the end teeth closer to the center tooth does not easily dissipate. With deactivation the archwire continues to load against these ligature strands. Hence, the friction achieved by tight ligation of the end teeth influences archwire stiffness over the entire range of deactivation. Consequently the plots for deactivation (solid line, Fig. 19) and activation (dotted line, Fig. 19) are essentially noncoincident.

BUCCAL ELASTIC

Plots of Px/Ax and Mz/Ax for a typical BUCCAL ELASTIC run are presented in Figure 20. The plot of Px/Ax originates below the horizontal axis and represents a lingually directed force. At Ax=0 the initial value of Px=215 gm. With deactivation the value of Px is reduced and reaches zero when Ax=1.8 mm. (40 gm. at 1.55 mm.; 20 gm. at 1.7 mm.). At complete deactivation a small buccally directed force is present. Clinically this would not occur since tooth movement would cease when the lingually directed force fell to zero or below the threshold necessary for tooth movement. The plot of Mz/Ax (Fig. 20) originates above the horizontal axis and represents lingual crown tipping. The initial value of Mz is 2500 gm.mm. and the plot of Mz/Ax closely mirrors the plot of Px/Ax. The deactivation plot of Px/Ax is nonlinear but does display certain slope characteristics. Between Ax=0 and Ax=1.2 mm. the slope of Px/Ax is generally decreasing. From Ax=1.2 mm. to Ax=2.0 mm. slope of Px/Ax is constant and greater than for previous deactivation steps. The activation plot of

Px/Ax (dotted line in Fig. 20) closely resembles the deactivation plot of Px/Ax (solid line in Fig. 20) between Ax=2.0 mm. and Ax=1.2 mm. However, between Ax=1.2 mm. and Ax=0 the activation plot is not coincident with the deactivation plot indicating hysteresis.

The phenomena present in the plots for BUCCAL ELASTIC have been encountered previously. Friction associated with ligation on the end teeth is responsible for the hysteresis present in the Px/Ax plot. As compared to BUCCAL TIGHT the hysteresis in BUCCAL ELASTIC is present over a longer range of activation but is of lesser magnitude at Ax=0. The elastic nature of the ligatures enables them to maintain contact with the archwire and, hence, exert their frictional influence over a greater range of deactivation and activation then tight steel ligatures. However, the tight steel ligatures initially exert a greater frictional effect on the archwire.

The elastic ligature on the center tooth results in the archwire bias described previously for BUCCAL TIGHT and illustrated in Figure 32. This results in Px=0 before complete deactivation.

The slope of the Px/Ax plot for BUCCAL ELASTIC (Fig. 20) displays less change than it does for other ligation techniques. For example with BUCCAL TIGHT (Fig. 17) the changes in slope during deactivation are much greater. The more constant slope associated with BUCCAL ELASTIC suggests that elastic ligation provides a more constant manner of constraint than does steel ligation.

LINGUAL ELASTIC

Plots of Px/Ax and Mz/Ax for a typical LINGUAL ELASTIC run are presented in Figure 21. The plot of Px/Ax originates above the horizontal axis and represents a buccally directed force. At Ax=0 the initial value of Px=340 gm. With deactivation the value of Px is reduced and essentialy reaches zero when Ax=2.0 mm. (40 gm. at 1.8 mm.; 20 gm. at 1.9 mm.). The plot of Mz/Ax originates below the horizontal axis and represents buccal crown tipping. The initial value of Mz is 3800 gm.mm. and the plot of Mz/Ax closely mirrors the plot of Px/Ax. The deactivation plot of Px/Ax is essentially nonlinear, however, slope characteristics are similar to those of BUCCAL ELASTIC. A generally decreasing slope is present between Ax=0 and Ax=0.8 mm. Between Ax=0.8 mm. and Ax=1.2 mm. slope increases and from Ax=1.2 mm. to Ax=2.0 mm. the slope of Px/Ax is constant and greater than for previous deactivation steps. Once again, the activation plot of Px/Ax (dotted line in Fig. 21) closely resembles the deactivation plot of Px/Ax (solid line in Fig. 21) between Ax=2.0 mm. and Ax=1.2 mm. and is dissimilar between Ax=1.2 mm. and Ax=0.

Friction associated with ligation on the end teeth is responsible for the hysteresis present in the Px/Ax plot. Compared to the steel ligatures of LINGUAL TIGHT, the elastic ligatures provide friction over a reduced activation range. This would indicate that the friction achieved by elastic ligatures dissipates more readily as the archwire becomes aligned with the end teeth.

The absence of archwire bias in LINGUAL ELASTIC is apparent since

Px=0 at Ax=2.0 mm. (total deactivation). This sharply constrasts with LINGUAL LOOSE and LINGUAL TIGHT where lingual archwire bias resulted in Px=0 before complete deactivation.

The absence of slope reduction as Px approaches zero (Fig. 21) suggests that the elastic ligature is capable of providing a relatively constant manner of constraint. This is contrasted, for example by LINGUAL LOOSE (Fig. 18) where the slope of Px/Ax changes considerably as Px approaches zero.

For both buccal and lingual malalignments elastic ligation provided a more constant load deflection rate than steel ligation was capable of. As a result the sudden changes in alignment force present with steel ligation did not occur when elastic were used.

4 mm. Trials

Experimental trials were carried out in which the activation range was increased to 4 mm. Figure 22 represents a BUCCAL TIGHT trial in which the center tooth was brought to a position of lingual malalignment before returning to its original position. Characteristic slope change, loss of alignment force before tooth alignment and hysteresis are evident.

Figures 23 and 24 represent two consecutive LINGUAL trials in which the center tooth was brought into buccal malalignment before being returned to its original position. In Figure 23 the steel ligatures are tight and considerable hysteresis is evident. The ligatures were not replaced or tightened for the trial shown in Figure 24. Due to the reduction in ligature tension there is considerably less hysteresis in Figure 24 than in Figure 23. Slope reduction in the area where Px reaches zero is more dramatic due to the loosened ligation at the center tooth.

These 4 mm. trials help confirm observations discussed earlier. In all three trials Px reaches zero before the brackets are aligned, indicative of archwire bias and/or permanent distortion. Slope reduction as Px approaches zero followed by a subsequent slope increase as malalignment reoccurs lends credence to ligation's influence over archwire stiffness. The effects at reduced ligation tension on friction, hysteresis and constraint are also illustrated.

Initially Aligned Trials

Trials were also carried out in which the teeth were initially aligned and subsequently brought into lingual or buccal malalignment. In Figure 25 the archwire was tightly ligated into an aligned set-up and initially the center tooth was taken into lingual malalignment (to the right of the vertical axis) and then into buccal malalignment (to the left of the vertical axis). Figure 26 represents a consecutive trial performed in an identical fashion without changing or tightening the ligatures. The reduction in ligature tension results in less hysteresis over part of the activation range and a more noticeable slope change as Px reaches zero. Even with the reduction in ligature tension hysteresis is still present at the extremes of activation. Due to the archwire entering the end teeth at a considerable angle with increased activation the ligatures are able to exert a significant frictional effect.

The trials involving initially aligned teeth confirm some previously discussed phenomena. A reduction in ligature tension is shown to influence friction, hysteresis and archwire constraint. Further, the bias effect associated with ligation of malaligned teeth is largely absent in these trials. The bias effect of reducing $\dot{P}x$ to zero before bracket alignment is only evident once, at the completion of lingual deactivation during the initial trial (dotted line, right side of Fig. 25). This may have occurred when the relatively tight ligatures on the end teeth engaged the archwire while the teeth were malaligned at the beginning of the deactivation. No evidence of bias effect is present for any other trial involving initially aligned teeth. This further confirms the contribution of initial malalignment towards creating archwire bias with ligation.

By comparing the trials involving initially aligned teeth and the 4 mm. trials the difference between hysteresis and change in slope can be readily observed. Examining the second activation of ALIGNED TIGHT (Fig. 26) it is apparant from the noncoincidence of the activation and deactivation plots that considerable friction was present as the teeth became nonaligned. The energy lost to friction was not available for tooth alignment and hysteresis resulted. By contrast, the second activation of the 4 mm. trial involving LINGUAL TIGHT (Fig. 24) displays very little hysteresis. In spite of the minimal friction present the Px/Ax plot displays a considerable change in slope as Px approaches zero. This change in slope is due to a change in constraint associated with straightening of the archwire as the teeth become aligned. Thus Figures 24 and 26 clearly demonstrate that hysteresis and slope change associated with Px/Ax are independent of each other.

There were no signs of irregularities caused by indentation of the archwire by the ligature strands (due to the ligature seating itself into the indentation). Effects that could have been caused by this were not present in any trials.

Orthodontic tooth alignment forces are significantly influenced by ligation. The stiffness of the archwire and hence the load deflection rate is altered by ligation tension. This occurs due to changes in constraint at the bracket slot. Similarly, ligation tension influences the magnitude of the initial alignment force. Archwire bias and a tendency for the alignment force to reach zero before complete deactivation are influenced by ligation and the geometric effect of the initial tooth malalignment. These also contribute to the possibility of permanent distortion of the archwire. Ligation results in friction and consequent hysteresis. This suggests the presence of forces acting in mesial-distal and/or occlusal-gingival directions. Moments around the x and y axes may also result from frictional effects. These secondary forces and moments will now be discussed.

Secondary Forces and Moments

Force in the occlusal-gingival direction (Py) was not expected to be of significance. A plot of Py/Ax for BUCCAL TIGHT (Fig. 27) confirms the linearity and low magnitude of Py.

Plots of Pz/Ax, Mx/Ax and My/Ax are presented as absolute values (Fig. 28) and relative values with zero shift and multiplication (Fig. 29) for BUCCAL TIGHT. Considering friction forces acting on the center tooth of a three-tooth segment it is important to realize that the net effect of friction at both end teeth is involved. Additionally, frictional characteristics associated with center tooth ligation can influence measurement of Pz, Mx and My in the three-tooth segment. Plots of Pz/Ax, Mx/Ax and My/Ax for the assorted ligation conditions discussed earlier are presented in the Appendix.

To illustrate these secondary forces and moments more clearly trials were performed in which only two teeth were ligated. The LINGUAL assembly was used for these two-tooth trials. By only ligating two teeth a clearer understanding of the interrelationships of Pz/Ax, Mx/Ax and My/Ax was possible. The values of Pz, Mx and My presented likely represent the effects that would occur at the end tooth of a three-tooth segment.

In the first two tooth trial the center tooth and end tooth to the left of the center tooth were tightly ligated. The measured (center) tooth would thus correspond to a tooth on the distal side of a buccally malaligned tooth. Plots of Pz/Ax, Mx/Ax are presented in Figure 30. Their initial values have been shifted to zero and the magnitude of their values increased by a factor of five. As the brackets become aligned the required archwire length between them decreases. The curved slope of the tightly ligated archwire at malalignment as compared to its relatively straight configuration at alignment accentuates the change in interbracket length it must undergo. With deactivation, the archwire is pushed through both brackets. Initially Pz at the measured tooth is strongly negative, however, in Figure 30 this value is arbitrarily shifted to zero. With deactivation the value of Pz becomes less negative and is represented by a positive plot of Pz/Ax. On activation (dotted line in Fig. 30) the plot of Pz/Ax follows a considerably different pathway indicating the variability of the frictional effect. The plot of Mx/Ax closely resembles that of Pz/Ax. This suggests that Pz is largely responsible for the presence of Mx. The value of My is influenced by the angle between the archwire's initial position and the buccal surface of the bracket. The couple introduced at the measured tooth when the archwire is ligated into the bracket slot introduces a large positive My. With deactivation My becomes negative relative to its initial value as the archwire becomes aligned with bracket slot. This is the general trend displayed by the plot of My/Ax in Figure 30. However, Pz can also be seen to influence My. Where Px has a positive relative value (during initial deactivation) it contributes to My becoming increasingly negative. Where Px has a less positive tendency (during later stages of deactivation) it inhibits the tendency of My to become negative. During activation (dotted line in Fig. 30) where Pz/Ax remains relatively positive, My/Ax remains negative.

In the second two-tooth trial the center tooth and the end tooth to the right of the center tooth were tightly ligated. The measured (center) tooth would thus correspond to a tooth on the mesial side of a buccally malaligned tooth. Plots of Pz/Ax, Mx/Ax and My/Ax are presented in Figure 31. Their initial values have been shifted to zero and the magnitude of their values increased by a factor of five. For reasons previously described the archwire is pushed through both brackets during deactivation. The value of Pz/Ax increase sharply and then declines during the latter stages of deactivation. This represents a different frictional pattern than that which occurred in the first two-tooth trials (Fig. 30). Upon activation the plot of Pz/Ax (dotted line in Fig. 31) is considerably different than during deactivation (solid line in Fig. 31). This further illustrates the variability of the frictional effect. The plot of Mx/Ax closely resembles that of Pz/Ax suggesting a stong influence of Pz on Mx. The value of My is influenced by the angle between archwire and bracket slot prior to ligation. The couple introduced at the measured tooth when the archwire is ligated into the bracket slot introduces a large negative My. With deactivation the value of My will become relatively positive as the archwire is aligned with the bracket slot. However a positive value for Pz will contribute to a negative My and counteract the effect of archwire alignment. In Figure 31 this interrelationship is clearly evident. During the initial stages of deactivation (Ax=0 to Ax=.5 mm.) the strongly positive Pz prevents My from becoming relatively positive. Over this range of deactivation My is actually made increasingly negative by the positive Pz. As the value of Pz becomes less positive during later stages of deactivation My becomes positive as the archwire and bracket slot become parallel.

The two tooth trials represented in Figures 30 and 31 suggest that the tooth adjacent to a malaligned tooth would display considerable movement.

This discussion will now consider some of the clinical implications of these trials and earlier three-tooth segment experiments.

Clinical Significance

The results of this thesis indicate that ligation technique will significantly influence orthodontic force and moment delivery.

The goal when ligating a low modulus archwire into a malaligned tooth is to move that tooth into alignment. Frequently, however, the alignment force (Px) fell to zero, or below a threshold level well before the teeth were aligned. This tendency can be attributed to archwire bias and/or plastic deformation of the archwire associated with ligation. Tight steel ligation appeared to increase these effects.

With steel ligatures, failure of tooth alignment would likely occur more readily with lingual than buccal malalignment. When the lingually malaligned tooth is ligated before other teeth the propensity for archwire bias seems greatly increased. If the aligned teeth had been ligated first, archwire bias and the risk of permanent distortion of the archwire would have been reduced. Clinically, if steel ligation is to be used, buccally positioned teeth should be ligated initially and care should be taken not to introduce archwire bias during the ligation process.

Elastic ligation appeared to greatly reduce the tendency for rapid force decay before tooth alignment. With lingual malalignment, elastic ligation maintained an alignment force until the brackets were essentially aligned. This represents considerably greater deactivation range than occurred with steel ligation. For buccal malalignment elastic ligation maintained an alignment force until the center tooth was within .2 mm. of alignment. This is comparable to the deactivation achieved with tight steel ligation. Depending upon the threshold necessary to move teeth intra-orally, tooth movement may have ceased slightly before this deactivation distance. For loose steel ligation with buccal malalignment the alignment force fell to very low levels at little more than 1.0 mm. of deactivation. Elastic ligation appears to be the most desirable ligation technique for achieving maximum deactivation with low modulus archwires.

Ligation can also influence the rate at which force decreases with deactivation or the load deflection rate (LDR) of the archwire. It has been suggested (Burstone 1961, 1981) that a relatively steady rate of force application is more desirable than an abrupt change in applied force. Thus a relatively constant low slope of the Px/Ax plot is most desirable. For both buccal and lingual malalignments loose steel ligation results in a lower LDR than tight steel ligation. The overall LDR achieved with elastic ligation is intermediate to that of loose and tight steel ligation. However, during the course of alignment elastic ligatures maintain a more constant force over a greater range of archwire deactivation than either form of steel ligation. When low modulus archwires are used clinically elastic ligation is most effective at delivering a constant force to the teeth during alignment.

The initial alignment forces in these experiments frequently exceeded the magnitude suggested as being ideal or optimal (Reitan, 1960, Burstone, 1962a, Gianelly and Goldman, 1971, Jarabak and Fizzell, 1972). The interbracket distances used in this study were greater than typically encountered clinically. This implies that even higher forces may commonly occur when low modulus archwires are used intra-orally for tooth alignment and is in general agreement with Sullivan's findings in 1982. Loose steel ligation was capable of delivering a fairly low initial force for both buccal and lingual malalignments. This lower force was accompanied by a considerably reduced effective range of deactivation. Clinically the initial low modulus archwire and loose ligation would not likely result in tooth alignment. However, if tighter ligation or a higher modulus archwire is used in an attempt to achieve complete tooth alignment, excessive force or reduced activation due to archwire bias and plastic deformation may result. Several solutions can be considered in an attempt to overcome these problems. A reduction in stiffness by decreasing the modulus of elasticity of the archwire will lower initial force levels. However this will likely be accompanied by plastic deformation of the archwire if the teeth are considerably malaligned. Reduced interbracket distances will increase the tendency towards permanent archwire deformation. An increase in the effective range of deactivation can be achieved if offset bends are incorporated into the archwire as suggested by Burstone (1981). However, exploratory experiments as part of this work suggest that the increased activation range may be accompanied by larger initial forces and the possibility of the malaligned tooth overshooting its intended position of alignment. A more practical solution to achieving low initial alignment force and complete deactivation of the archwire may be achieved by multilooped archwires. When loops in the archwire provide energy storage for tooth alignment there is much less tendency for permanent distortion regardless of the manner of ligation. Additionally, with a looped archwire there is much less tendency for archwire bias as is associated with ligating a straight archwire into malaligned teeth. Finally, since ligation tension is not likely to be as critical to the performance of a multilooped archwire the alignment forces delivered would be more predictable. The variability possible with different ligation techniques would not greatly influence the alignment forces provided by a looped archwire.

In all of the experimental conditions studied the alignment force was accompanied by a buccal or lingual tipping tendency (Mz). This tipping action is inherent with all round archwires due to geometry associated with the bracket slot location in relation to the center of resistance of the tooth. This tipping tendency is generally not desirable when aligning teeth. Rectangular archwires are necessary to control this tipping tendency by providing a moment (Mz) of opposite sign and magnitude. Recent findings by Olsen (1983) suggest tight ligation is appropriate to reduce the play, or slop of rectangular archwires in the bracket slot. Thus rectangular looped archwires, tightly ligated, maybe the ideal technique for tooth alignment.

Hysteresis, related to frictional influences, and changes in load deflection rate, associated with changes in archwire constraint and configuration , were evident in a number of trials. If interbracket distance was less than the 6.7 mm. used in this study these effects would be greatly increased. An initial malalignment greater than the one used experimentally (2 mm.) would also augment these effects. Clinically, interbracket distances of less than the 6.7 mm. and tooth malalignments of more than 2 mm. are frequently encountered.

Frictional effects were present in a number of trials and appear to be related to ligation. The magnitude of the frictional effect increased with lingual malalignments. Elastic ligation was associated with frictional effects over a considerable range of deactivation for both buccally and lingually malaligned teeth.

Frictional effects cause variations in tooth alignment forces and this variability will increase with greater ligature tension. Frictional force (Pz) also influences the tendency of adjacent teeth to rotate and tip as the teeth become aligned.

Mesial-distal tipping (Mx) is largely influenced by friction, expressed as Pz. Hence, it will be variable and largely dependent on ligature tension. Adjacent teeth will likely tip when non-looped low modulus archwires are used to achieve tooth alignment.

Tooth rotation about the occlusal apical axis (My) is affected by the angular relationship between the bracket slot and the archwire and by frictional force. The influence of friction will vary and will be related to ligature tension. The extent to which rotation occurs because of the initial archwire angulation relative to the bracket slot is determined by the degree of tooth malalignment and the width of the bracket. For a given tooth displacement a decrease in bracket width would achieve less My. However a narrower bracket would result in some loss of three dimensional control.

In this study the secondary effects on adjacent teeth were found to be considerable. During tooth alignment, these spurious effects could result in unwanted movement of the adjacent teeth. At the completion of alignment these teeth could readily occupy a position not intended at the beginning of treatment. The extent to which this could occur would be variable, dependent partly on ligation technique. If a multilooped archwire was substituted for a straight low modulus archwire these spurious effects may be reduced.

A tendency for adjacent teeth to move buccally or lingually in response to the alignment force was not included in this study. Earlier work by Sullivan (1982) has demonstrated this tendency.

Summary

This investigation of the influence of ligation on orthodontic force and moment delivery provided insight into the interaction between various elements of mechanotherapy.

The results indicate that variation in ligation technique can result in very significant changes in the performance of low modulus archwires used for tooth alignment (see Table I). The forces of alignment encountered were frequently in excess of what is considered "optimal". This occurred with malalignments not greater than those commonly encountered clinically and with greater than typical inter-bracket distance. Ligature tension influenced the magnitude of the initial alignment by a factor of more than 3:1 and altered load deflection rate by more than a 2:1 ratio. Variation in ligation technique significantly altered the deactivation range over which an effective alignment force would be delivered. Consequently, ligature technique affected the extent to which the low modulus archwire could correct the initial malalignment.

The results also demonstrated the presence of secondary forces not intended when achieving tooth alignment. These spurious forces were largely influenced by ligature tension and friction. These secondary forces would result in unwanted movement of the adjacent teeth such as rotation and tipping about the occlusal-apical and mesial-distal axes. Forces present in the mesiodistal direction would also result in "wedging" of the teeth as alignment occurred.

Ligation has been shown to contribute considerable variability to mechanical factors influencing tooth movement. In view of the variation possible when ligating archwires into malaligned teeth, subsequent variability in the biological response demonstrated is not surprising. Mechanical variability may be largely responsible for the range of effects that are achieved with apparently similar types of mechanotherapy.

TABLE I: Summary of Experimental Findings.

Types of Ligation	Px (initial)	Mz (initial)	Ax where Px=0
BUCCAL LOOSE	135 gm.	1650 gm.mm.	2.0 mm.
BUCCAL TIGHT	450 gm.	5100 gm.mm.	1.8 mm.
BUCCAL ELASTIC	215 gm.*	2500 gm.mm.*	1.8 mm.*
LINGUAL LOOSE	150 gm.	2000 gm.mm.	1.65 mm.
LINGUAL TIGHT	380 gm.	4600 gm.mm.	1.4 mm.
LINGUAL ELASTIC	340 gm.*	3800 gm.mm.*	2.0 mm.*

Note: All data presented is mean of 10 trials except where noted by *.

Modifications to the three dimensional measuring system used in this investigation proved most satisfactory. Through the use of edgewise brackets and ligation new insight into archwire behaviour was possible.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The purpose of this investigation was to examine the influence of ligation techniqe on orthodontic force and moment delivery. Modifications to the existng three dimensional analysis technique used previously by Sullivan were carried out to achieve this study. From the results obtained it was concluded that:

(1) The use of edgewise brackets and ligation as used in this investigation has provided insight into the behaviour of orthodontic archwires.

(2) The various model tooth assemblies used provided evidence for variation in orthodontic force systems depending upon the nature of the initial tooth alignment.

(3) The low modulus archwires tested frequently achieved excessively high initial alignment forces.

(4) Variation in ligation tension influenced the initial alignment force by a factor of between 2:1 and 3:1 depending upon the geometry of the initial malalignment.

(5) Variation in ligation tension significantly altered the load deflection rate of the low modulus archwire studied.

(6) The alignment force provided by the low modulus archwire often fell to zero or a subthrehold level before the teeth were aligned. Ligation technique and initial malalignment geometry influenced this tendency.

(7) Secondary, or spurious forces frequently encountered during tooth alignment resulted in a loss of three dimensional control over tooth position. These secondary forces were largely influenced by ligation tension.

(8) Ligation tension and to a lesser extent initial malalignment geometry influenced the presence of friction.

(9) Frictional forces typically encountered when ligating low modulus archwires were capable of influencing the effective tooth alignment force.

(10) Elastomeric ligation provided the best overall performance with the low modulus archwires tested.

(11) Under controlled conditions consistent ligation was possible. Intraorally, however, the variability associated with ligation may be greater and would be contributed to by differences in interbracket dimension and initial tooth malalignment.

Recommendations for Future Research

The results of this investigation have suggested a number of other research topics. These are outlined below:

(1) An assessment of inter operator variability in ligation technique using the method established in this investigation.

(2) An investigation into the effects of additional constraint provided by edgewise brackets in a five-tooth segment.

(3) An investigation of the influence of ligation on orthodontic force systems using assorted interbracket widths.

(4) A comparison of .457 x .635 mm. (.018 x .022 inch) brackets to .559 x .711 mm. (.022 x .028 inch) brackets.

(5) A comparison of force and moment control between low modulus and round and rectangular multilooped archwires when used for tooth alignment.

CHAPTER 7

BIBLIOGRAPHY

BIBLIOGRAPHY

Ackerman, J.L., Sager, C.R., Del Priore, R.C. and Bramante, M.A. (1969) A controlled light continuous force technique. Am. J. Orthod. 56: 233-251.

Andreason, G.F. and Johnson, P. (1967) Experimental findings on tooth movements under two conditions of applied force. Angle Orthod. 37: 9-12.

Andreason, G.F. and Quevedo, F.R. (1970) Evaluation of friction forces in the .022 x .028 edgewise bracket _in vitro_. J. Biomechanics 3: 151-160.

Andreason, G.F. and Zwanziger, D. (1980) A clinical evaluation of the differential force concept as applied to the edgewise bracket. Am. J. Orthod. 78: 25-40.

Andrews, L.F. (1975) _The Straight Wire Appliance_. Syllabus of philosophy and techniques. Edition 2.

Begg, P.R. (1956) Differential force in orthodontic treatment. Am. J. Orthod. 42: 481-510.

Boester, C.H. and Johnston, L.E. (1974) A clinical investigation of the concepts of differential and optimal force in canine retraction. Angle Orthod. 44: 113-119.

Brantley, W.A., Augat, W.S., Myers, C.L. and Winders, R.V. (1978) Bending deformation studies of orthodontic wires. J. Dent. Res.

57: 609-615.

Brumfield, R.C. (1937) An experimental check on edgewise arch computations. Int. J. Orthod. 23: 687-688.

Burstone, C.J. (1962a) Rationale of the segmented arch. Am. J. Orthod. 48: 805-822.

Burstone, C.J. (1962b) The biomechanics of tooth movement. In: Kraus, B.S. and Reidel, R.A. (Eds) Vistas in Orthodontics. Philadelphia: Lea and Febiger, pp. 197-213.

Burstone, C.J. (1975) Application of bioengineering to clinical orthodontics. In: Graber, T.M. and Swain, B.F. (Eds) Current Orthodontic Concepts and Techniques, Vol. I, Ch. 3, Philadelphia: W.B. Saunders Co.

Burstone, C.J. (1981) Variable-modulus orthodontics. Am. J. Orthod. 80: 1-16.

Burstone, C.J. and Goldberg, A.J. (1980) Beta titanium: A new orthodontic alloy. Am. J. Orthod. 77: 121-132.

Burstone, C.J. and Groves, J.H. (1960) Threshold and optimum force values for maxillary anterior tooth movement. J. Dent. Res. 39: 695 (Abstract).

Burstone, C.J. and Koenig, H.A. (1974) Force systems from an ideal arch. Am. J. Orthod. 65: 270-289.

Burstone, C.J., Baldwin, J.J. and Lawless, D.T. (1961) The application of continuous forces to orthodontics. Angle Orthod. 31: 1-14.

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

Carey, C.W. (1944) Force control in the movement of dental structures. Angle Orthod. 14: 47-66.

Creekmore, T.D. (1976) The importance of interbracket width in orthodontic tooth movement. J. Clin. Orthod. 10: 530-534.

Creekmore, T.D. (1979) On torque. J. Clin. Orthod. 13: 305-310.

DeFranco, J.C., Koenig, H.A. and Burstone, C.J. (1976) Three-dimensional large displacement analysis of orthodontic appliances. J. Biomech. 9: 793-801.

Dellinger, E.L. (1978) A scientific assessment of the straight wire appliance. Am. J. Orthod. 73: 290-299.

Drake, S.R., Wayne, D.M., Powers, J.M. and Asgar, K. (1982) Mechanical properties of orthodontic wires in tension, bending and tension. Am. J. Orthod. 82: 206-210.

Drenker, E.W. (1956) Forces and torques associated with second order bends. Am. J. Orthod. 42: 766-773.

Fish, G.D. (1917) Some engineering principles of possible interest to orthodontists. Dent. Cosmos. 59: 881-889.

Fogel, M.S. and Magill, J.M. (1976) The modular self-locking appliance system: A variation in the combination technique. J. Clin. Orthod. 10: 653-660.

Frank, C.A. and Nikolai, R.J. (1980) A comparative study of frictional resistances between orthodontic bracket and archwire. Am. J. Orthod. 78: 593-609.

Gianelly, A.A. and Goldman, H.J. (1971) <u>Biologic Basis of Orthodontics</u>. Philadelphia: Lea and Febiger, Chapter 4.

Greif, R., Coltmand, M. and Shapiro, E. (1978) Computer analysis of orthodontic force system. J. Dent. Res. I.A.D.R. 57: 361 (Abstract).

Haack, D.C. (1963) The science of mechanics and its importance to analysis and research in the field of orthodontics. Am. J. Orthod. 49: 330-344.

Halderson, H. (1957) Routine use of minute forces. Am. J. Orthod. 43: 750-768.

Halderson, Holly (1961) Routine use of minute forces. Am. J. Orthod. 47: 707-708 (Abstract).

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

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

Hanson, G.H. (1980) The SPEED System: A report on the development of a new edgewise appliance. Am. J. Orthod. 78: 243-264.

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

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

Hixson, M.E., Brantley, W.A., Pincsak, J.J. and Conover, J.P. (1982) Changes in bracket slot tolerance following recycling of direct bond metallic orthodontic appliances. Am. J. Orthod. 81: 447-454.

Hocevar, R.A. (1981) Why edgewise? Am. J. Orthod. 80: 237-255.

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

Irish, R.E. (1927) Conscious constructive application of pressure. Int. J. Orthod. and Oral Surg. 13: 528-535.

Isaacson, R.J. and Burstone, C.J. (1976) Malocclusion and bioengineering. In: Ahinger, E. and Pakkol, P. (Eds.) The Relevance of Biomedical Engineering to Dentistry. Proceedings of the workshop held at the National Institute of Health, Bethesda, Maryland, February 2-4, 1976. Bethesda: U.S. Dept. of Health, Education and Welfare, Public Health Service, National Institute of Health.

Jarabak, J.R. and Fizzell, J.A. (1972) Technique and Treatment with the Light Wire Appliance. 2nd Edition, St. Louis: C.V. Mosby Co.

Johns, E.E. (1953) A study of the forces inherent in orthodontic appliances and the selection of forces for tooth movement. J. Can. Dent. Assoc. 19: 423-436.

Kamiyama, T. and Sasaki, T. (1973) Friction and width of brackets. J. Jpn. Orthod. Soc. 32: 286-289.

Koenig, H.A. and Burstone C.J. (1974a) Force system delivered by simple orthodontic appliances. J. Dent. Res. I.A.D.R. 53: 258 (Abstract).

Koenig, H.A. and Burstone, C.J. (1974b) Analysis of generalized curved beams for orthodontic applications. J. Biomech. 7: 429-435.

Lang, R.L., Sandrik, J.L. and Klapper, L. (1982) Rotation of rectangular wire in rectangular molar tubes. Pt. II. Pretorqued molar tubes. Am. J. Orthod. 81: 22-31.

Mahler, D.B. and Goodwin, L. (1967) An evaluation of small diameter orthodontic wires. Angle Orthod. 37: 13-17.

McLachlan, K.R. (1985) Personal communications.

Moyers, R.E. and Bauer, J.L. (1950) The periodontal response to various tooth movements. Am. J. Orthod. 36: 572-580.

Neuger, R.L. (1967) The measurement and analysis of moments applied by a light wire torquing auxiliary and how these moments change magnitude with respect to various changes in configuration and application. Am. J. Orthod. 53: 492-513.

Newman, G.V. (1963) A biomechanical analysis of the Begg light arch wire technique. Am. J. Orthod. 49: 721-740.

Oberg. E. and Jones, F.D. Machinery's Handbook, 12th Edition, New York: Industrial Press, 1944, pp. 374-390.

Olsen, D.L. (1983) A study of the relationship of ligation to available torque delivery of rectangular archwires in pretorqued and standard edgewise brackets. Msc. Thesis, Marquette University.

Oppenheim, A. (1936a) Biologic orthodontic therapy and reality. Angle Orthod. 6: 69-116.

Oppenheim, A. (1936b) Biologic orthodontic therapy and reality. Angle Orthod. 36: 153-183.

Oppenheim, A. (1944) A possibility for physiologic orthodontic movement. Theoretical part. Am. J. Orthod. 30: 277-328.

Orban, B. (1936) Biologic problems in orthodontia. J. Am. Dent. Assoc. 23: 1849-1870.

Paulich, F. (1939) Measuring of orthodontic forces. Am. J. Orthod. and Oral Surg. 25: 817-849,

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

Peyton, F.A. and Moore, G.R. (1933a) Flexibility studies on gold alloy wires and orthodontic appliances. Int. J. Orthod. 19: 779-794.

Peyton, F.A. and Moore, G.R. (1933b) Flexibility studies on gold alloy wires and orthodontic appliances. II Reflex springs and practical appliances. Int. J. Orthod. 19: 903-919.

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

Pryputniewicz, R.J., Burstone, C.J. and Bowley, W.W. (1978a) Determination of arbitrary tooth displacements. J. Dent. Res. 57: 663-674.

Pryputniewicz, R.J., Burstone, C.J. and Every, T.W. (1978b) Holographic determination of time effects of forces on tooth movements. J. Dent. Res. I.A.D.R. 57: 361 (Abstract).

Raphael, E., Sandrik, J. and Klapper, L. (1981) Rotation of rectangular wire in rectangular molar tubes. Part I. Am. J. Orthod. 81: 136-144.

Reitan, K. (1951) The initial tissue reaction incident to orthodontic tooth movement. Acta. Odont. Scand. Supp. 6.

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

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

Richmond, J.E. (1933a) Mild pressure and great force. J. Am. Dent. Assoc. 20: 1600-1606.

Richmond, J.E. (1933b) An appliance analysis with measured pressure. Int. J. Orthod. and Dent. for Children 19: 898-903.

Ricketts, R.M. Bench, R.W., Gugino, C.F., Hilgers, J.J. and Schulhof, R.J. (1979) Bioprogressive Therapy, Rocky Mountain Orthodontics, Denver, Colorado.

Riley, J.L., Garrett, S.G. and Moon, P.C. (1979) Frictional forces of ligated plastic and metal edgewise brackets. J. Dent. Res. I.A.D.R. 58: 98 (Abstract).

Rygh, P. (1972) Ultrastructural vascular changes in pressure zones of rat molar periodontium incident to tooth movement. Scand. J. Dent. Res. 80: 307-321.

Rygh, P. (1973) Ultrastructural changes in pressure zones of human periodontium incident to orthodontic tooth movement. Acta Odont. Scand. 31: 109-122.

Rygh, P. (1984) Personal communications.

Schrody, D.W. (1974) A mechanical evaluation of buccal segment reaction to edgewise torque. Angle Orthod. 44: 120-126.

Schwartz, H. (1967) The case against biomechanics. Angle Orthod. 37: 52-57.

Schwarz, A.M. (1932) Tissue changes incidental to orthodontic tooth movement. Int. J. Orthod. 18: 331-352.

Sebanc, J., Brantley, W.A., Pincsak, J.J. and Conover, J.P. (1984) Variability of effective root torque as a function of edge bevel on orthodontic arch wires. Am. J. Orthod. 86: 43-51.

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

Steiner, C.C. (1932) Force control in orthodontia. Angle Orthod. 2: 252-259.

Steyn, C.C. (1977) Measurement of edgewise torque force in vitro.

Am. J. Orthod. 71: 565-573.

Stoner, M.M. (1960) Force control in clinical practice. Am. J. Orthod. 46: 163-186.

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

Storey, E. and Smith, R. (1952) Force in orthodontics and its relation to tooth movement. Aust. J. Dent. 56: 11-18.

Strang, R.H. (1964) The value of a precision technique. Am. J. Orthod. 50: 113-124.

Stuteville, O.H. (1938) A summary review of tissue changes incident to tooth movement. Angle Orthod. 8: 1-20.

Sullivan, D. (1982) An investigation into the three dimensional force and movement characteristics of selected low modulus initial alignment archwires. Msc. Thesis, University of Manitoba.

Sved, A. (1937) The behaviour of arch wires in fixed attachments. Int. J. Orthod. 23: 683-686.

Sved, A. (1948) The treatment of malocclusion. Am. J. Orthod. 34: 549-578.

Sved, A. (1952) The application of engineering methods to orthodontics. Am. J. Orthod. 38: 399-421.

Thurow, R.C. (1982) <u>Edgewise</u> <u>Orthodontics</u>, 4th Edition, St. Louis:

C.V. Mosby Co., Chapters 1-2.

Utley, B.K. (1968) The activity of alveolar bone incident to orthodontic tooth movement as studied by oxytetracycline-incured flourescence. Am. J. Orthod. 54: 167-201.

Warnock, F.V. and Benhom, P.P. (1970) Mechanics of Solids and Strength of Materials, 2nd Edition, London: Pitman Press.

Waters, N.E. (1976) The mechanics of plain and looped arches: Part I. Br. J. Orthod. 3: 75-78.

Waters, N.E., Stephens, C.D. and Houston, W.J.B. (1975a) Physical characteristics of orthodontic wires and arch wires: Part I. Br. J. Orthod. 2: 15-24.

Waters, N.E., Stephens, C.D. and Houston, W.J.B. (1975b) Physical characteristics of orthodontic arch wires: Part II. Br. J. Orthod. 2: 73-83.

Waters, N.E., Houston, W.J.B. and Stephens, C.D. (1981) The characterization of archwires for the initial alignment of irregular teeth. Am. J. Orthod. 79: 373-389.

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

White, T.R., Caputo, A.A. and Chaconas, S.J. (1979) The measurement of utility archwire forces. Angle Orthod. 49: 272-281.

APPENDIX

Plots of forces and moments against activation.

Ligation conditions are given on each graph.

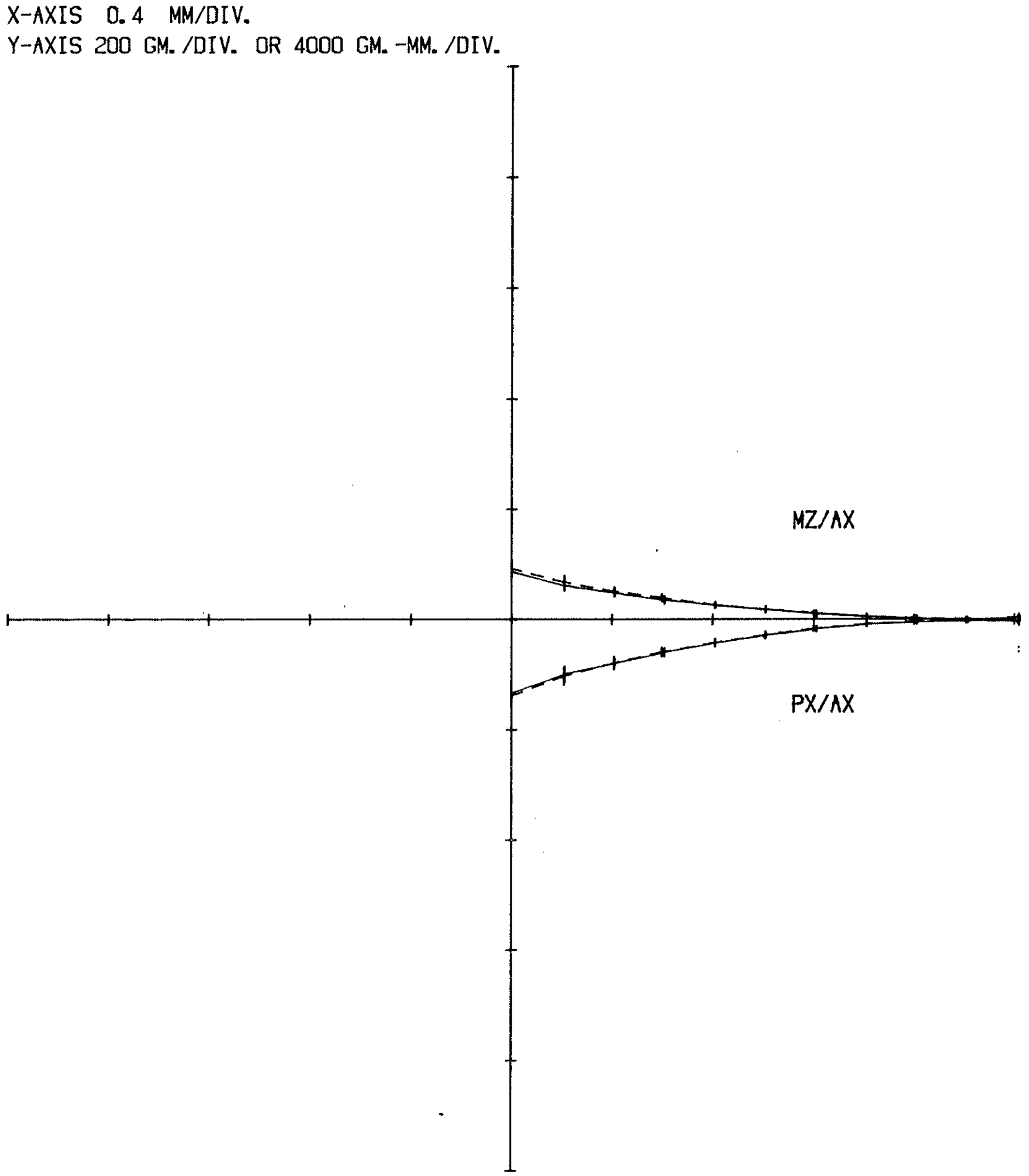


Figure A1: BUCCAL LOOSE: plots of Px/Ax and Mz/Ax

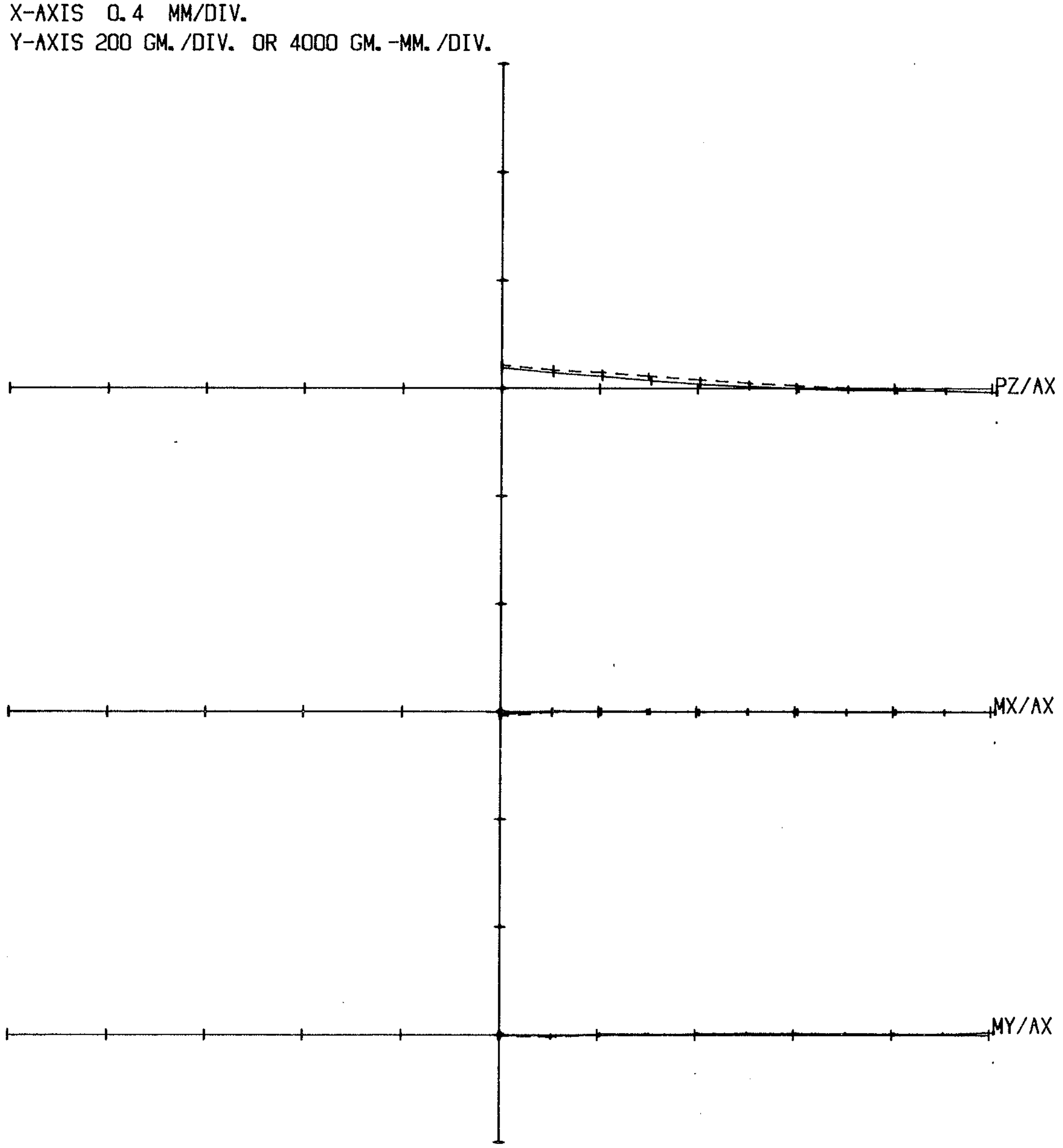


Figure A2: BUCCAL LOOSE: plots of Pz/Ax, Mx/Ax and My/Ax

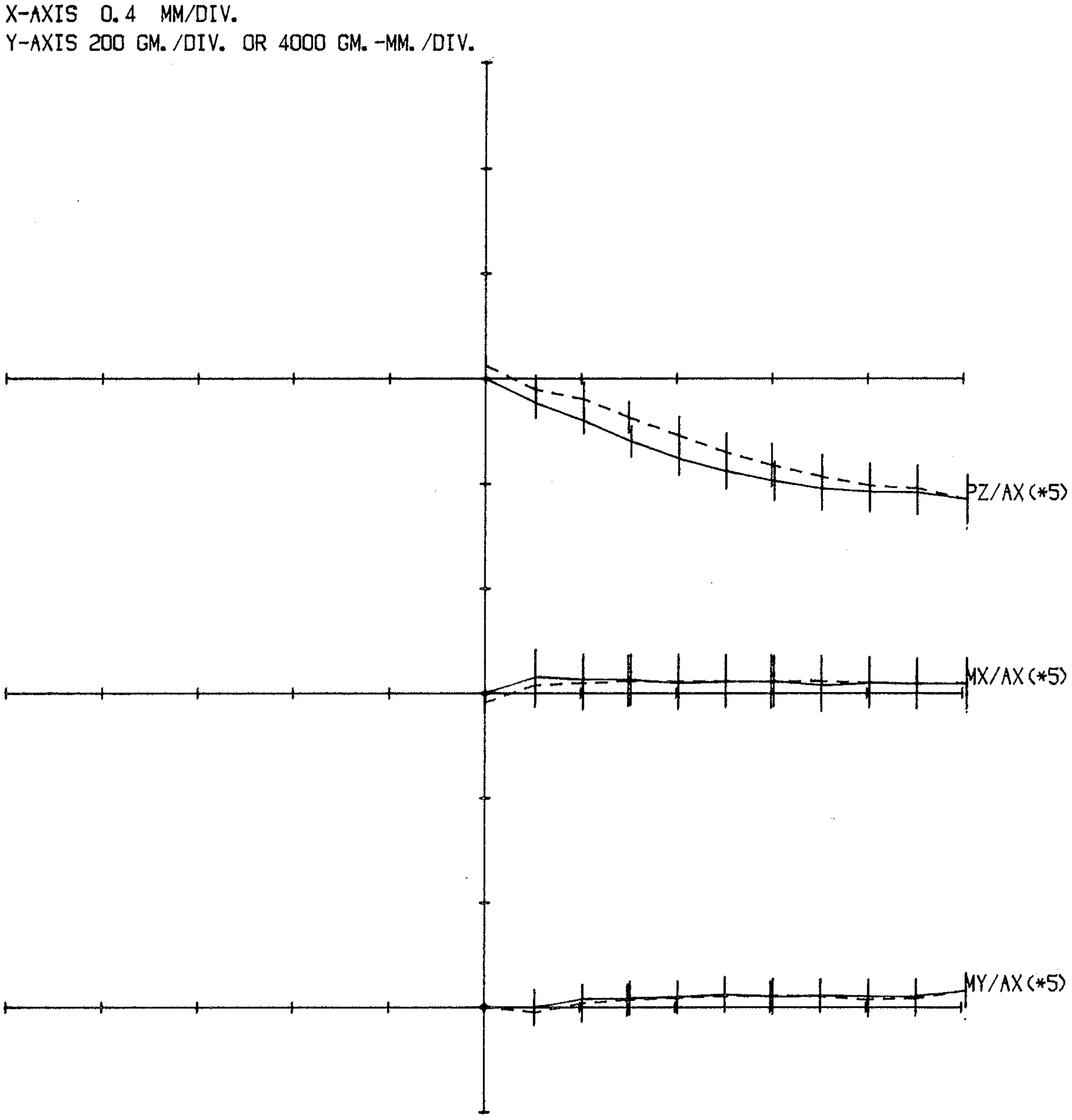


Figure A3: BUCCAL LOOSE: plots of Pz/Ax, Mx/Ax and My/Ax (with zero shift and multiplication)

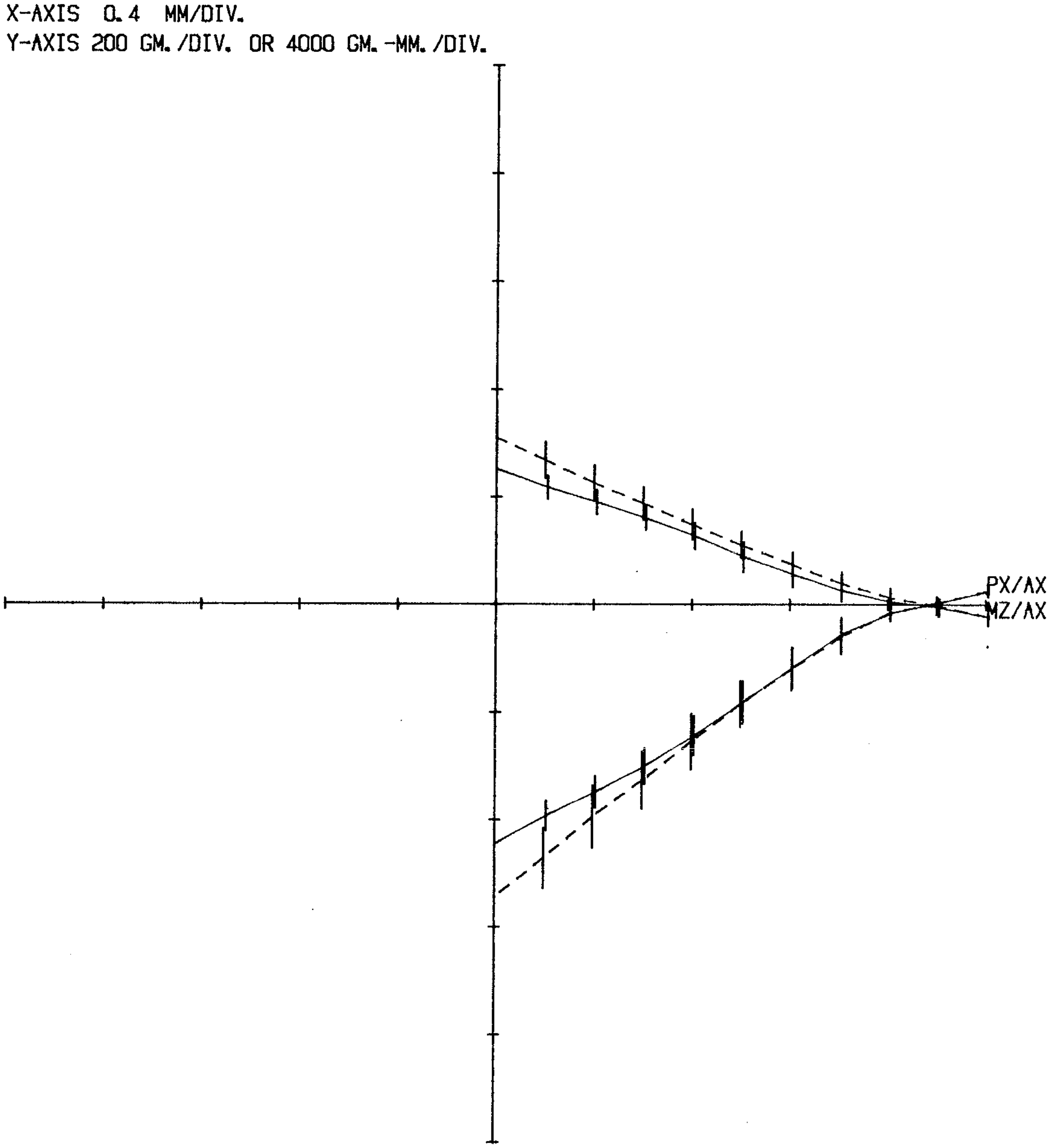


Figure A4: BUCCAL TIGHT: plots of Px/Ax and Mz/Ax

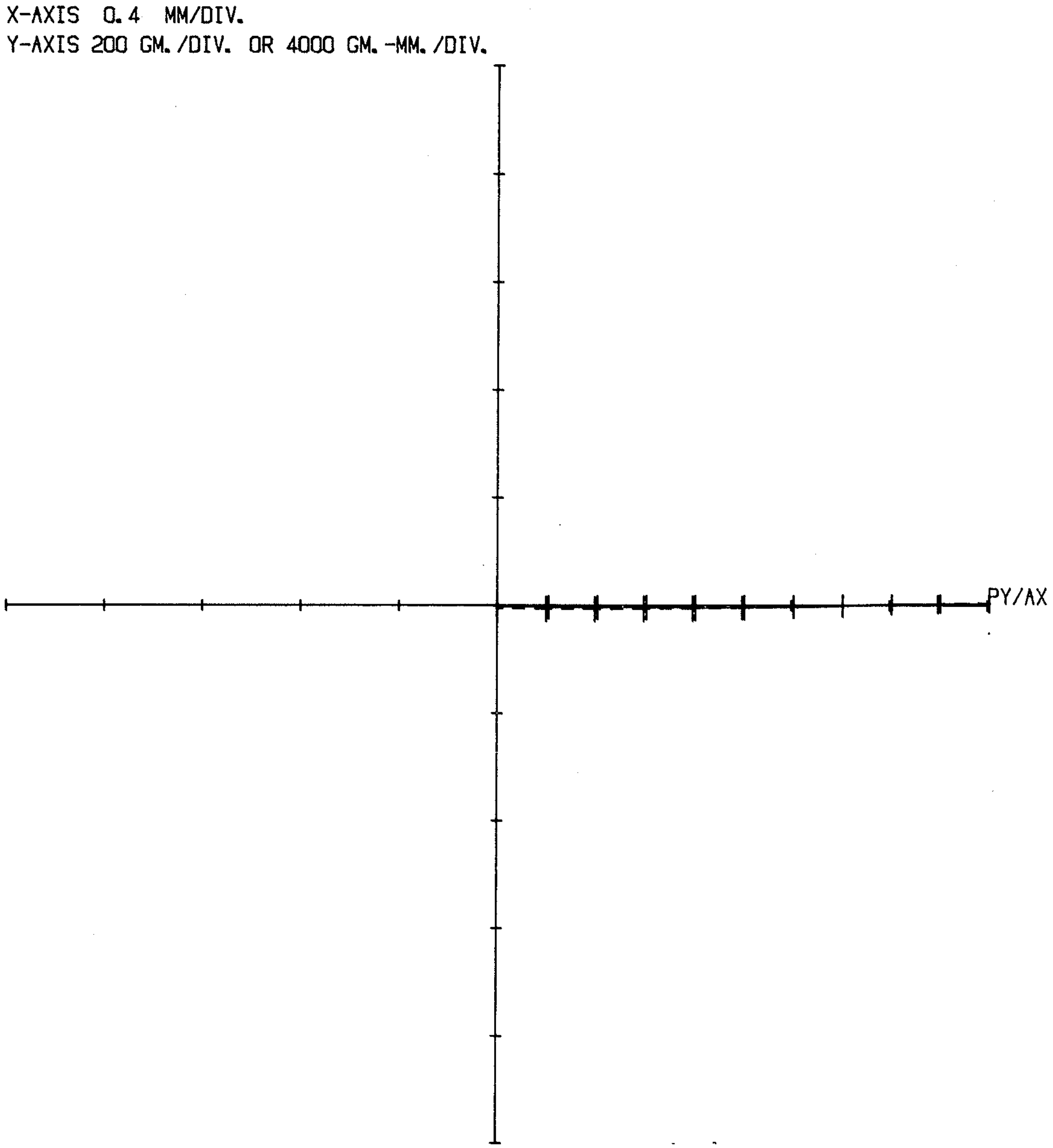


Figure A5: BUCCAL TIGHT: plot of Py/Ax

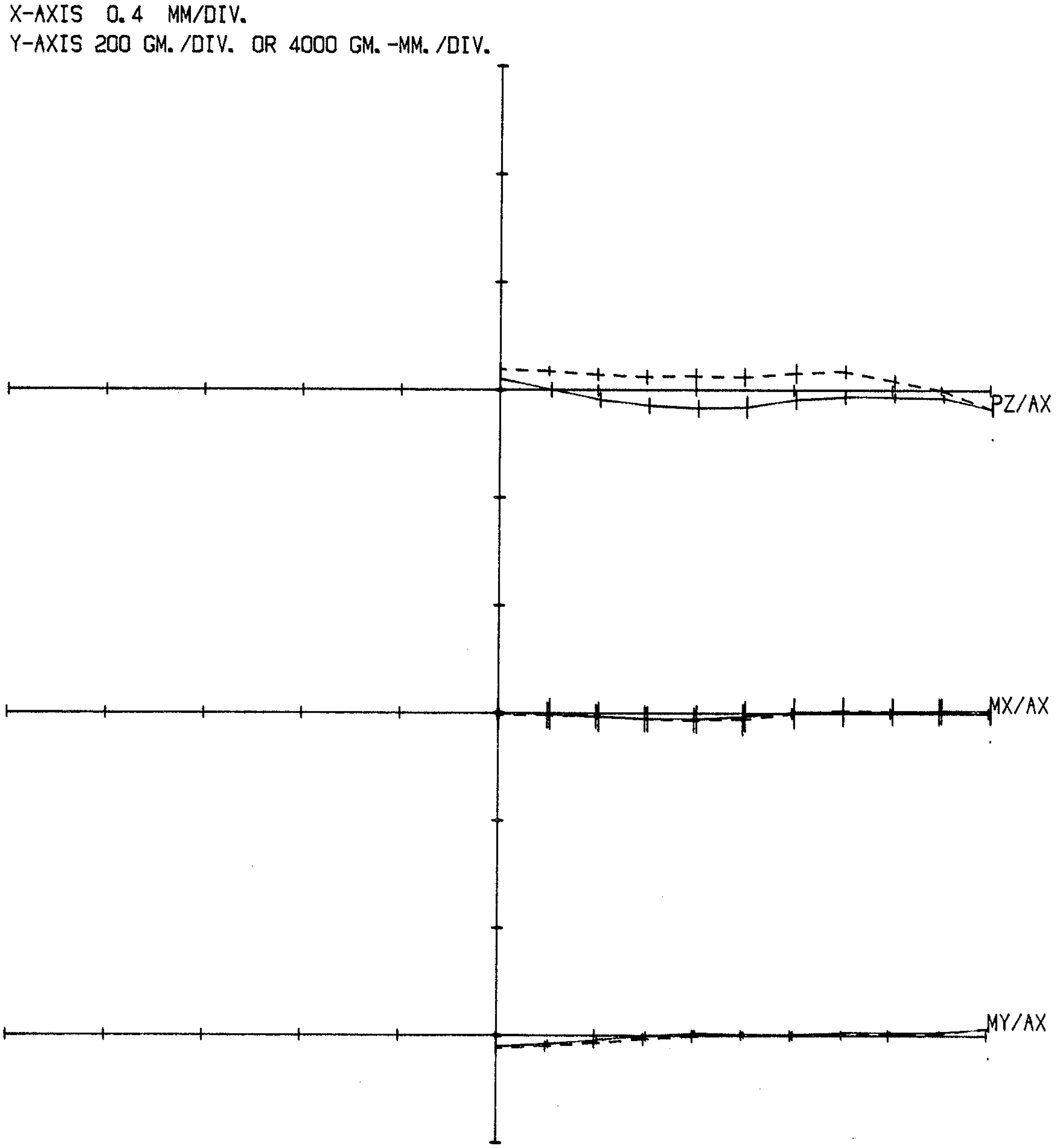


Figure A6: BUCCAL TIGHT: plots of Pz/Ax, Mx/Ax and My/Ax

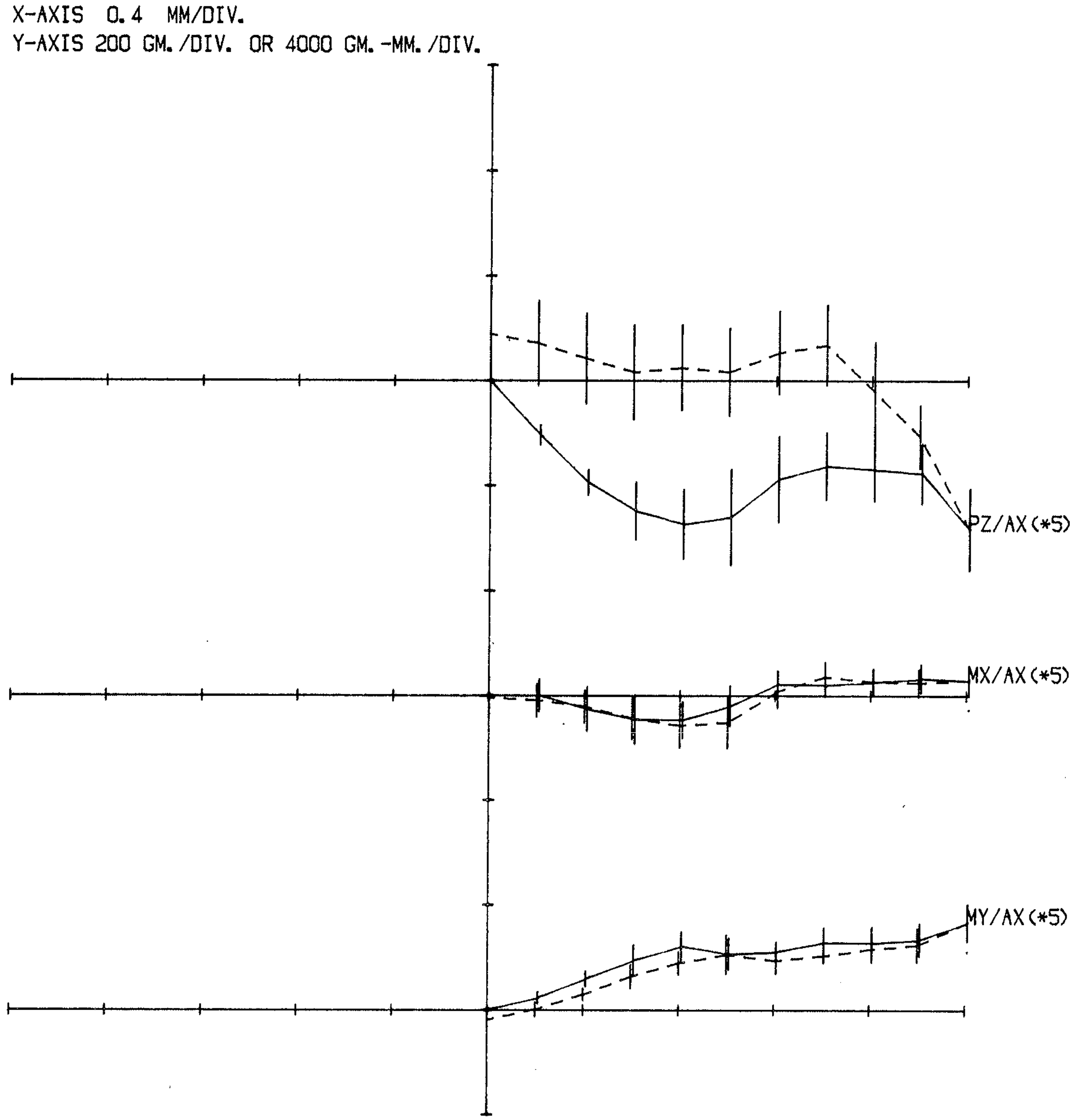


Figure A7: BUCCAL TIGHT: plots of Pz/Ax, Mx/Ax and My/Ax (with zero shift and multiplication)

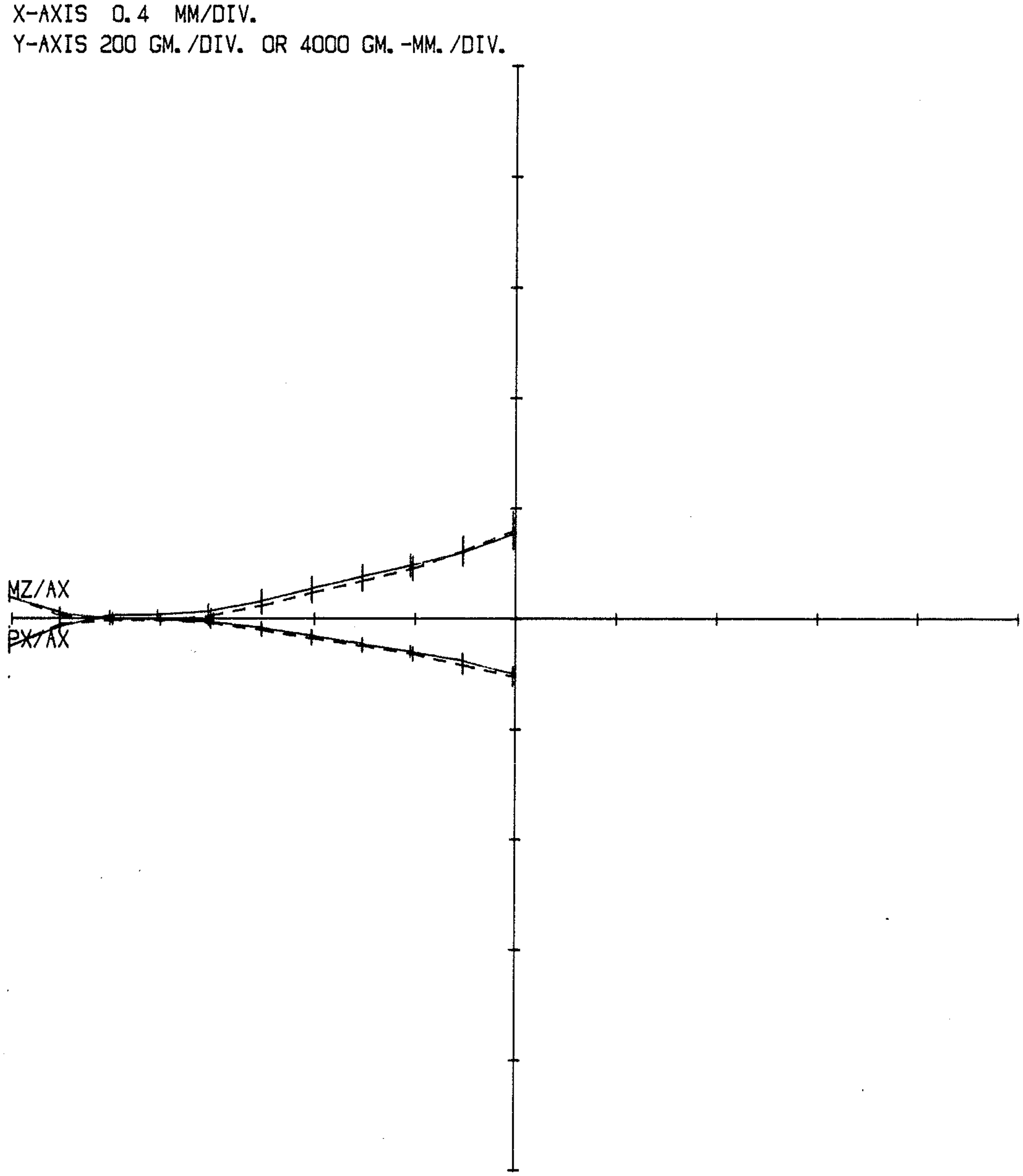


Figure A8: LINGUAL LOOSE: plots of Px/Ax and Mz/Ax

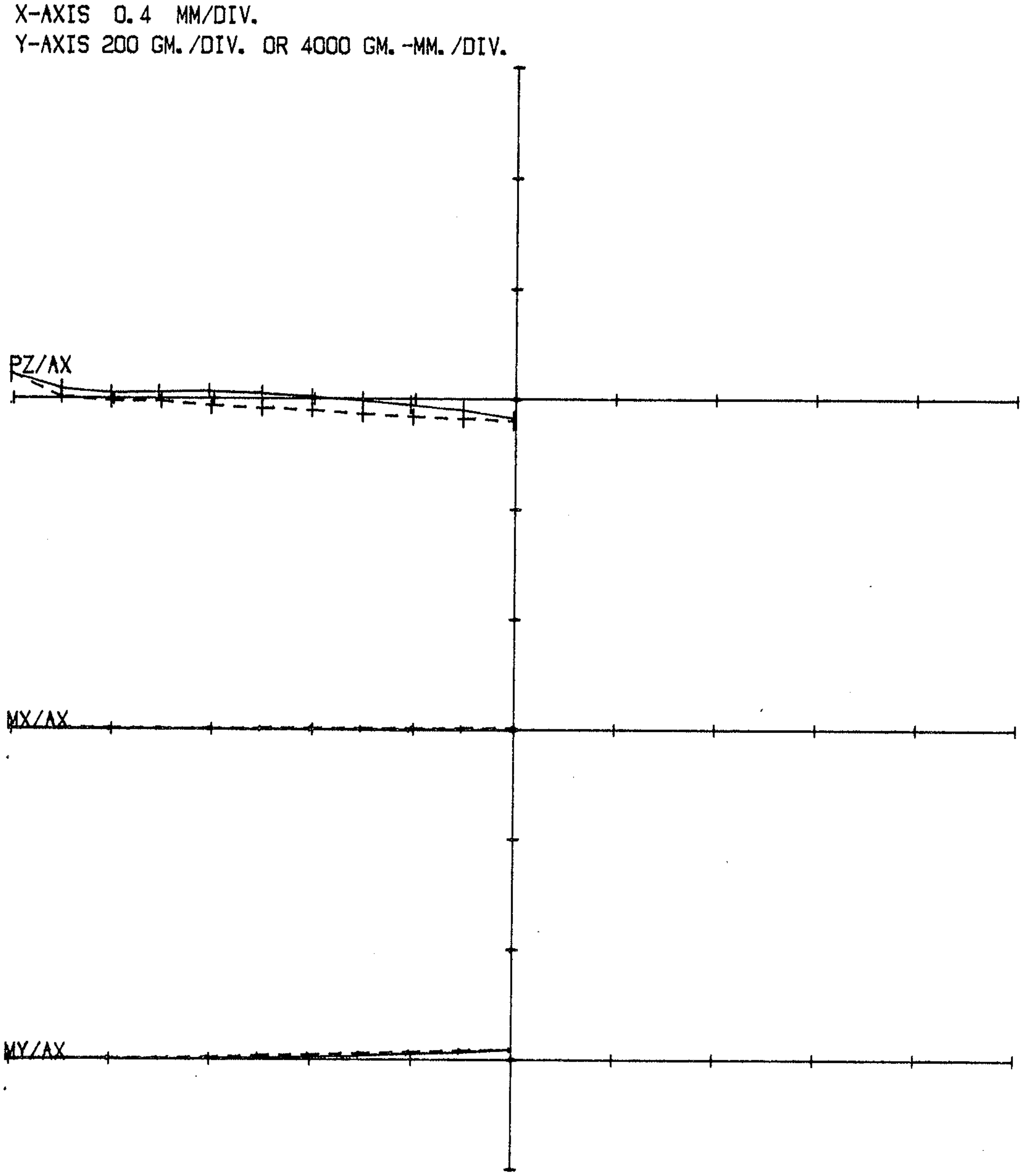


Figure A9: LINGUAL LOOSE: plots of Pz/Ax, Mx/Ax and My/Ax

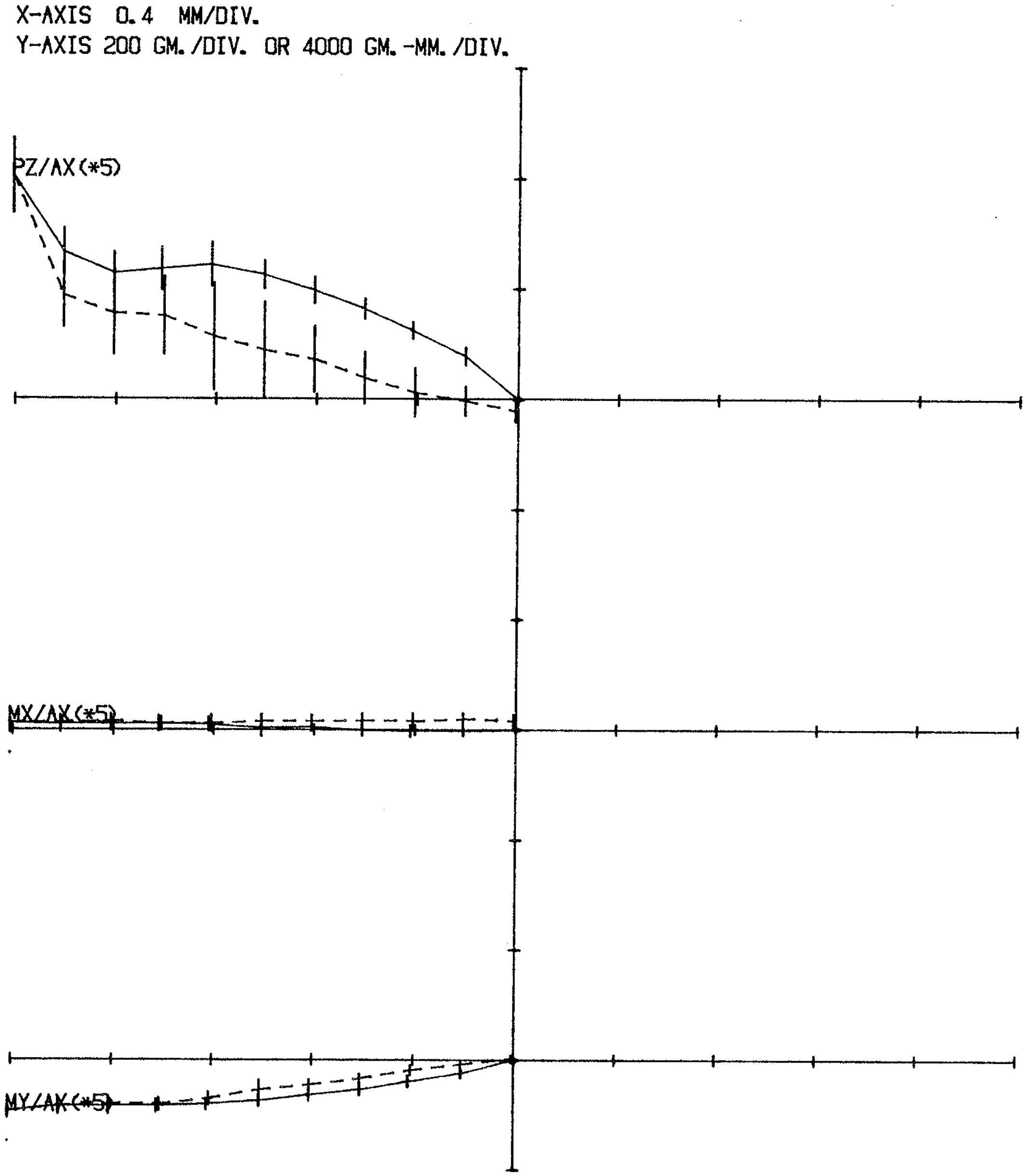


Figure A10: LINGUAL LOOSE: plots of Pz/Ax, Mx/Ax and My/Ax (with zero shift and multiplication)

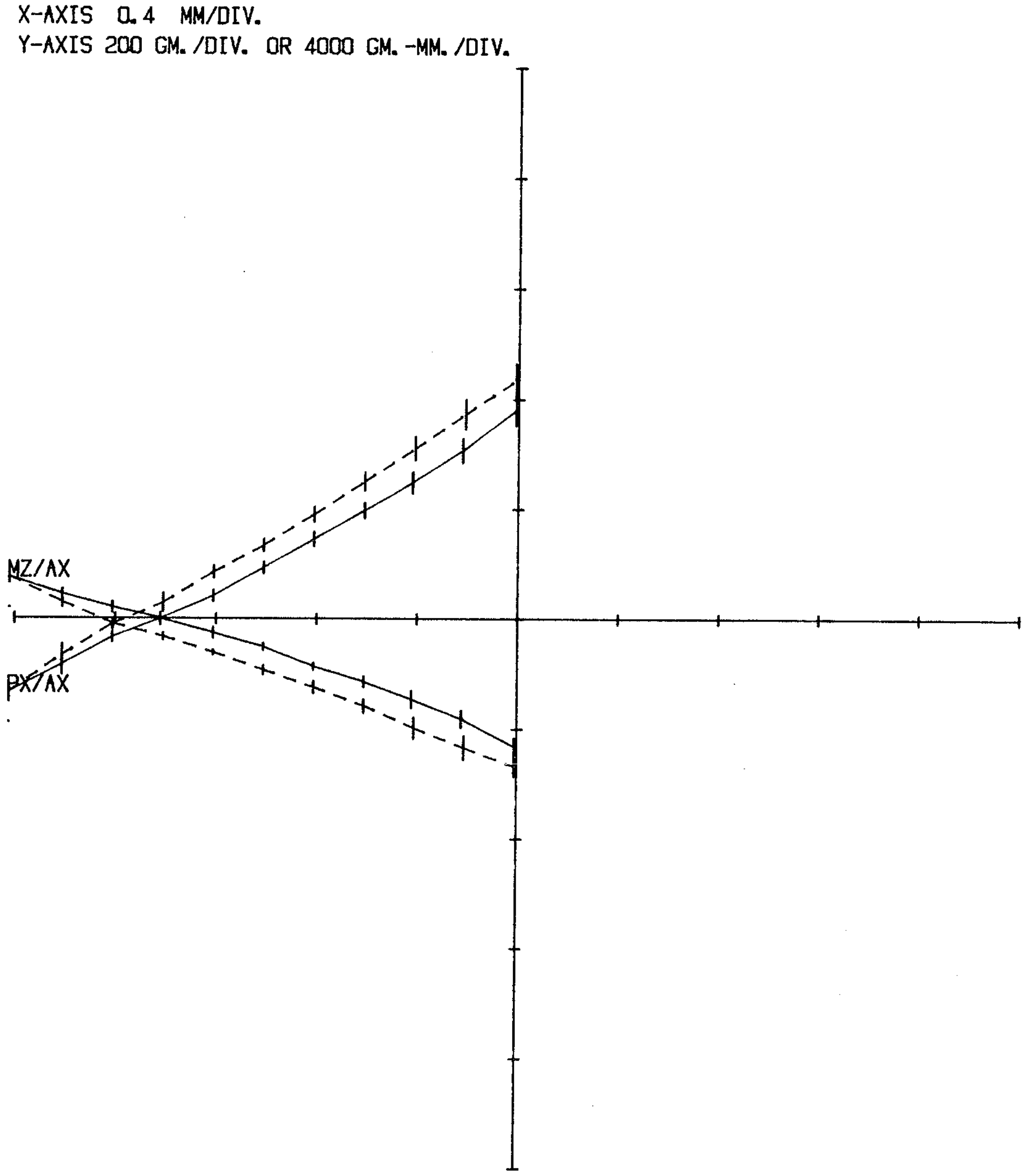


Figure A11: LINGUAL TIGHT: plots of Px/Ax and Mz/Ax

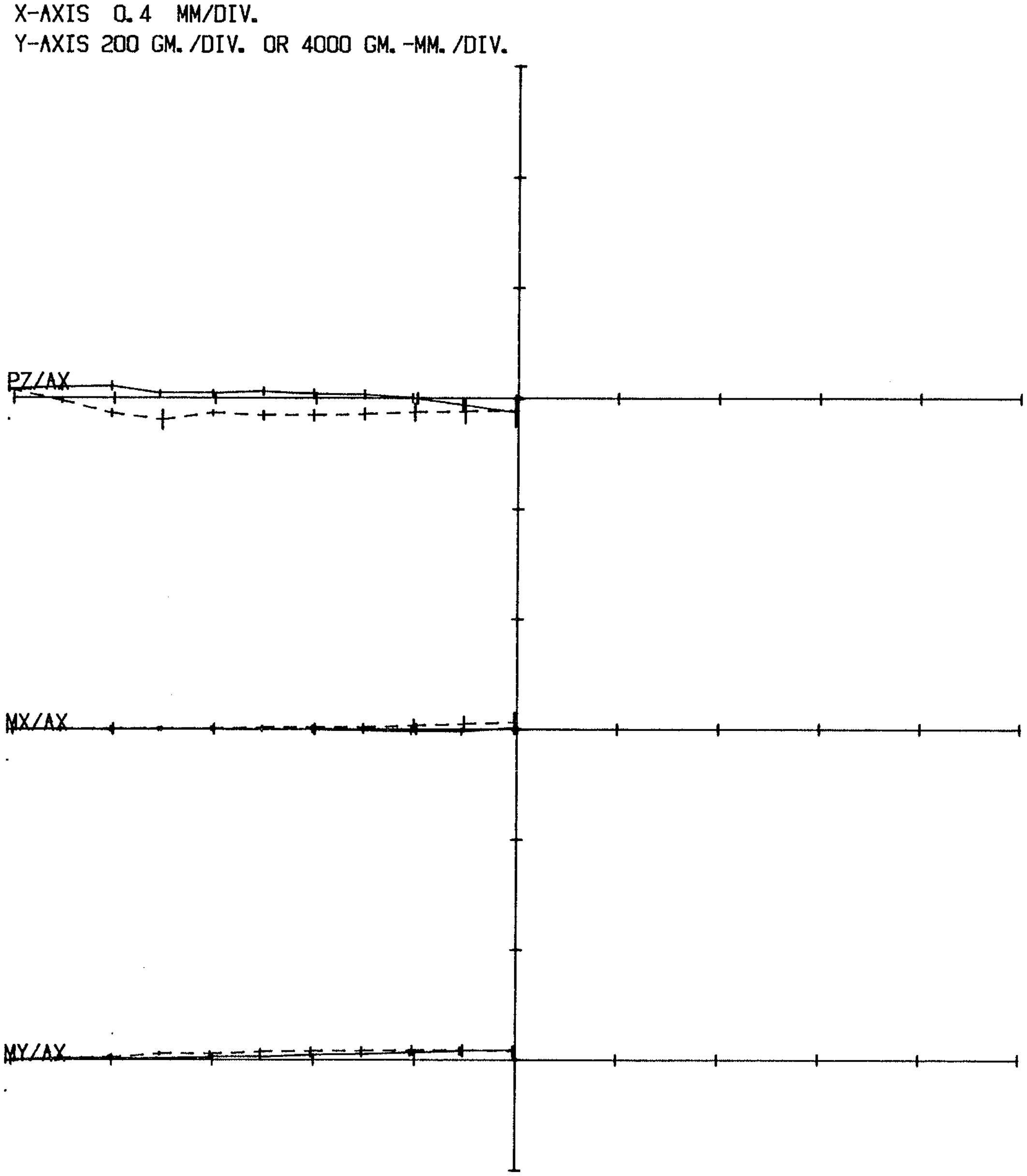


Figure A12: LINGUAL TIGHT: plots of Pz/Ax, Mx/Ax and My/Ax

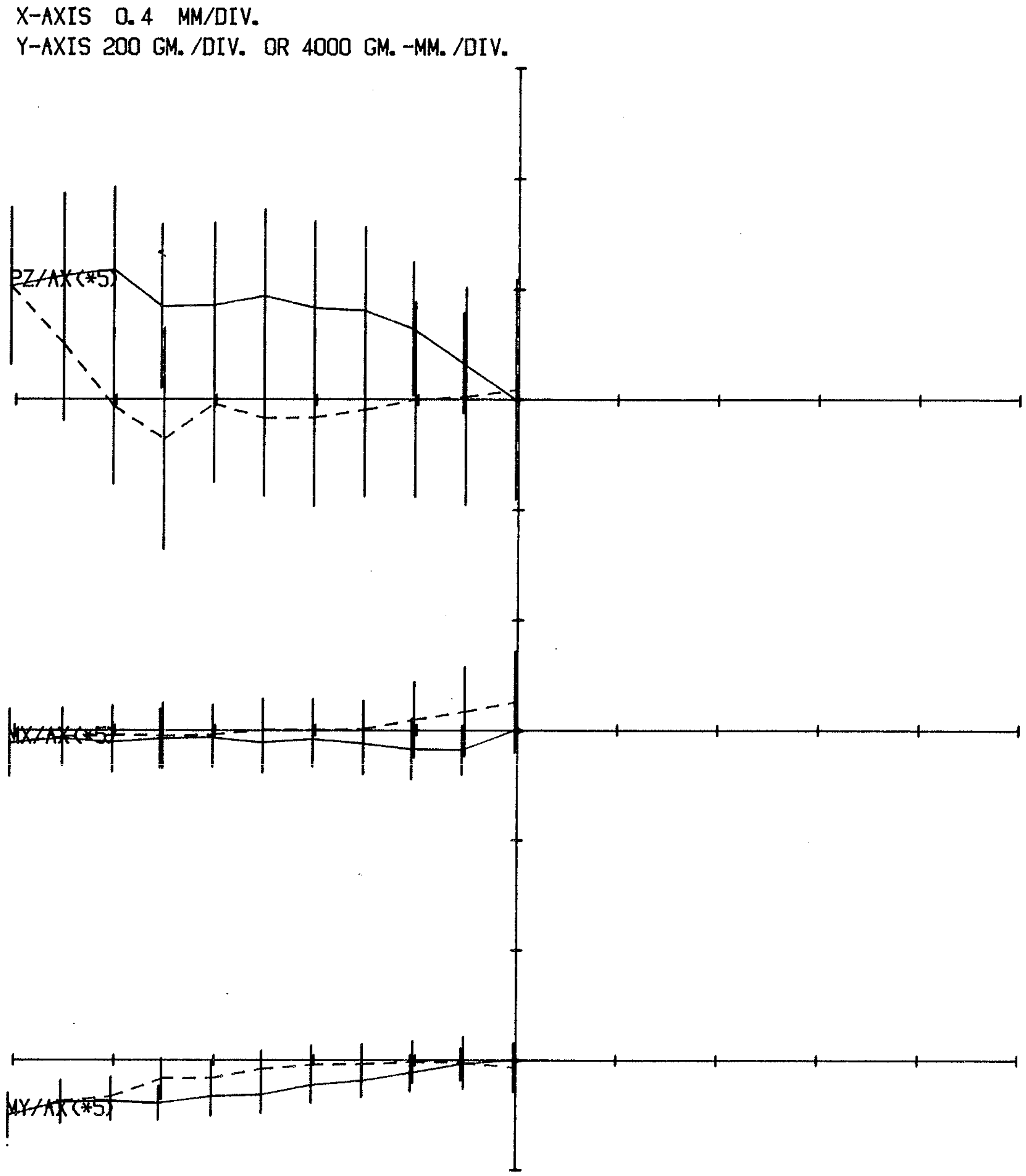


Figure A13: LINGUAL TIGHT: plots of Pz/Ax, Mx/Ax and My/Ax (with zero shift and multiplication)

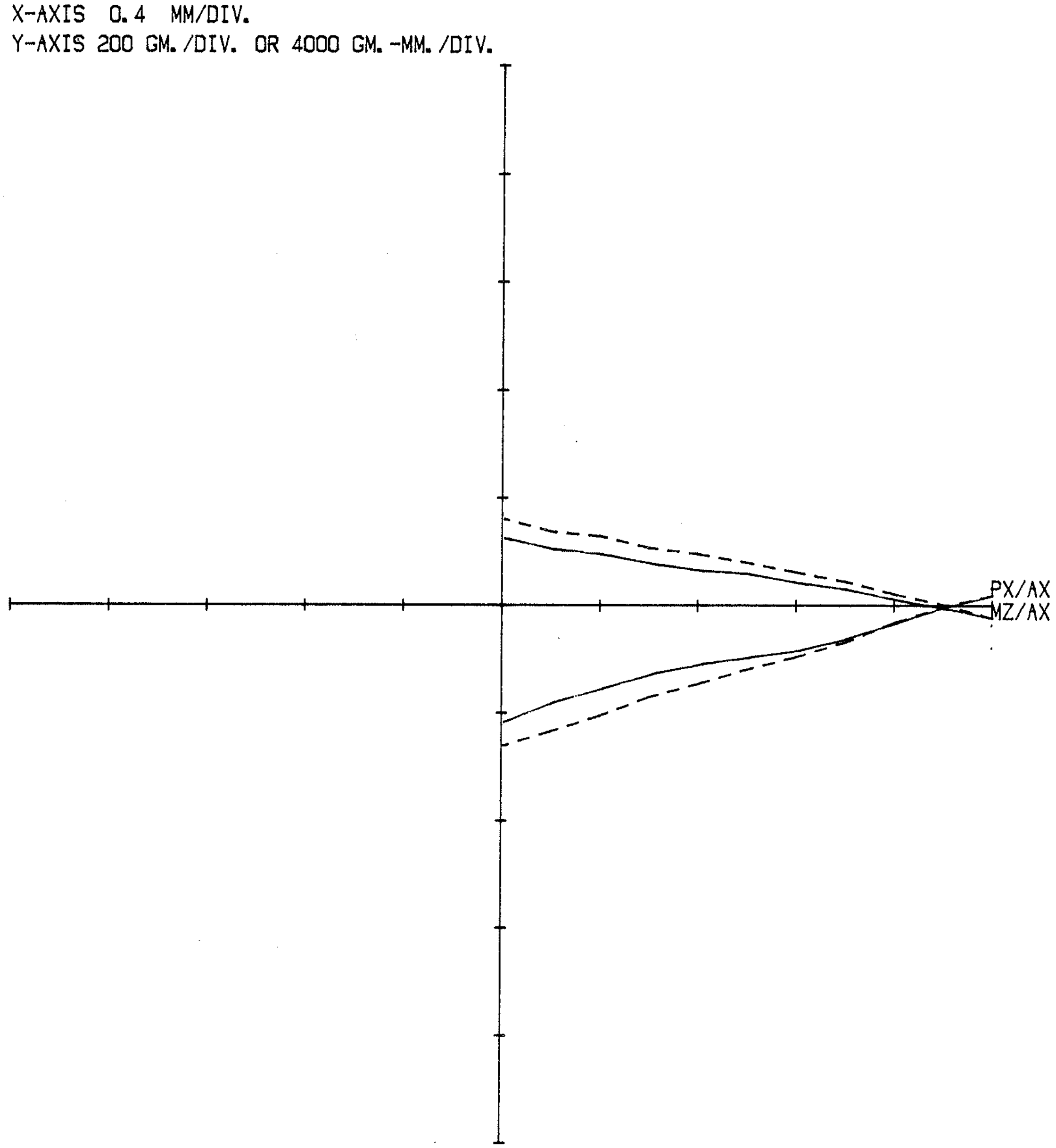


Figure A14: BUCCAL ELASTIC: plots of Px/Ax and Mz/Ax

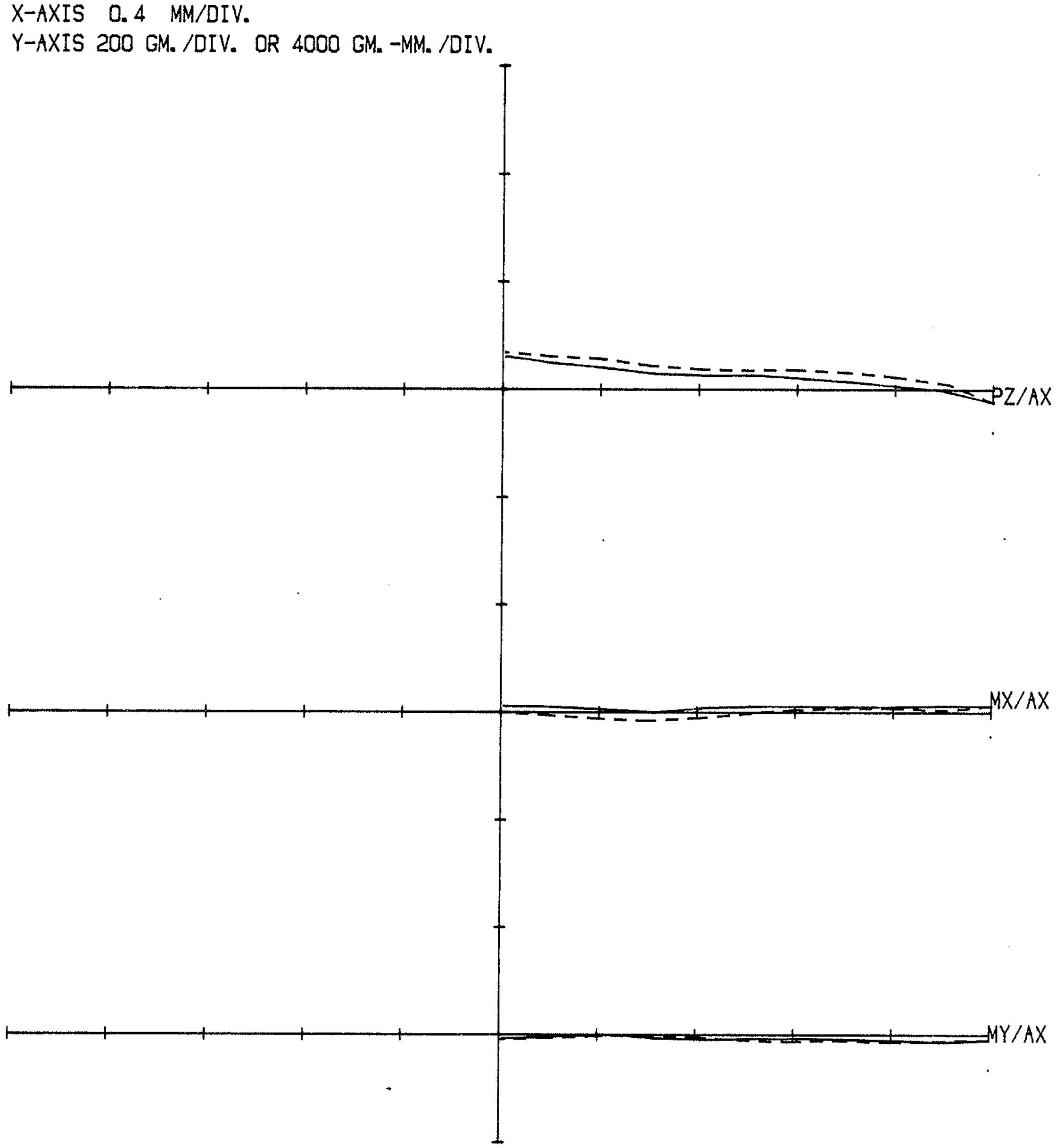


Figure A15: BUCCAL ELASTIC: plots of Pz/Ax, Mx/Ax and My/Ax

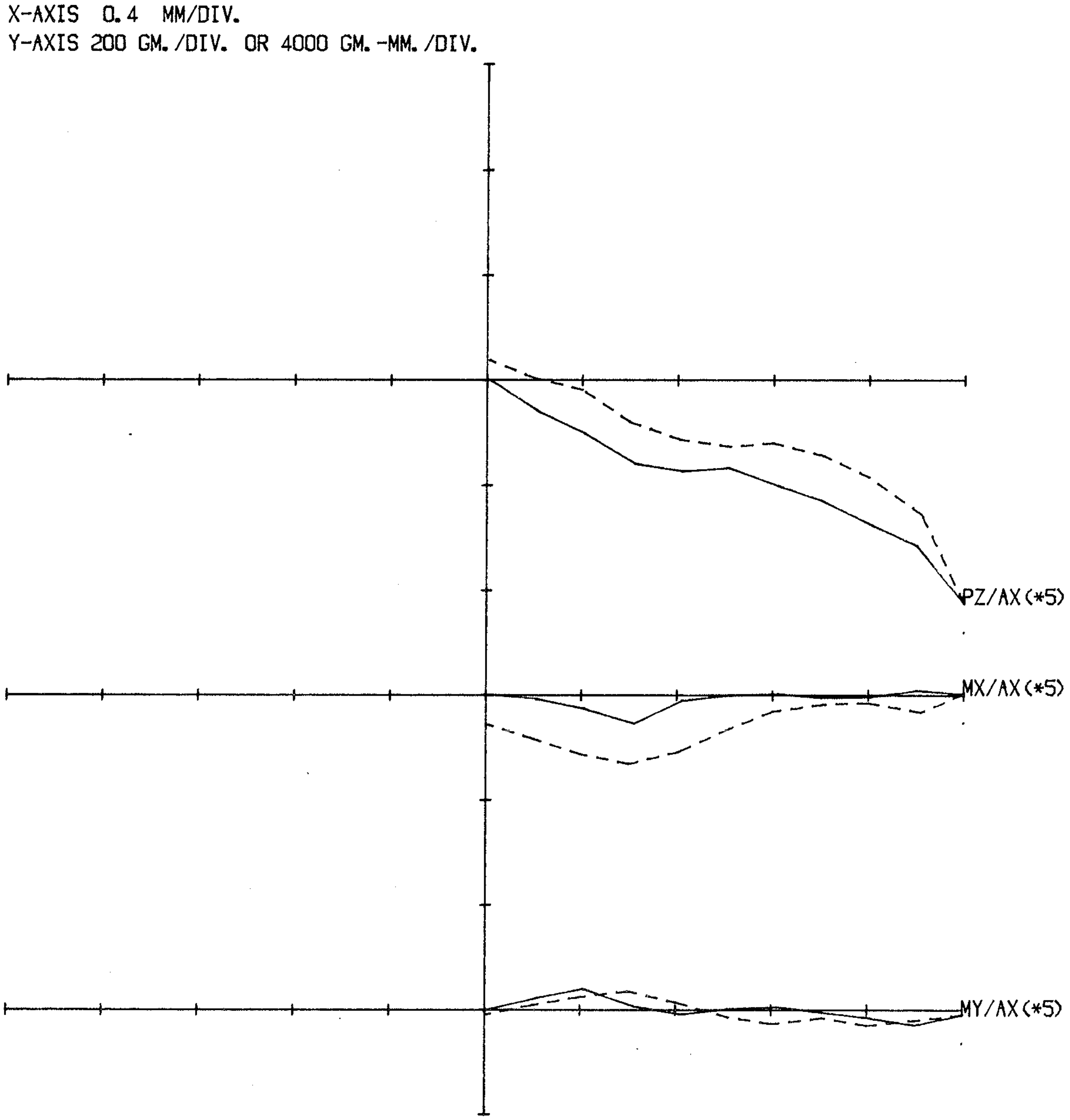


Figure A16: BUCCAL ELASTIC: plots of Pz/Ax, Mx/Ax and My/Ax (with zero shift and multiplication)

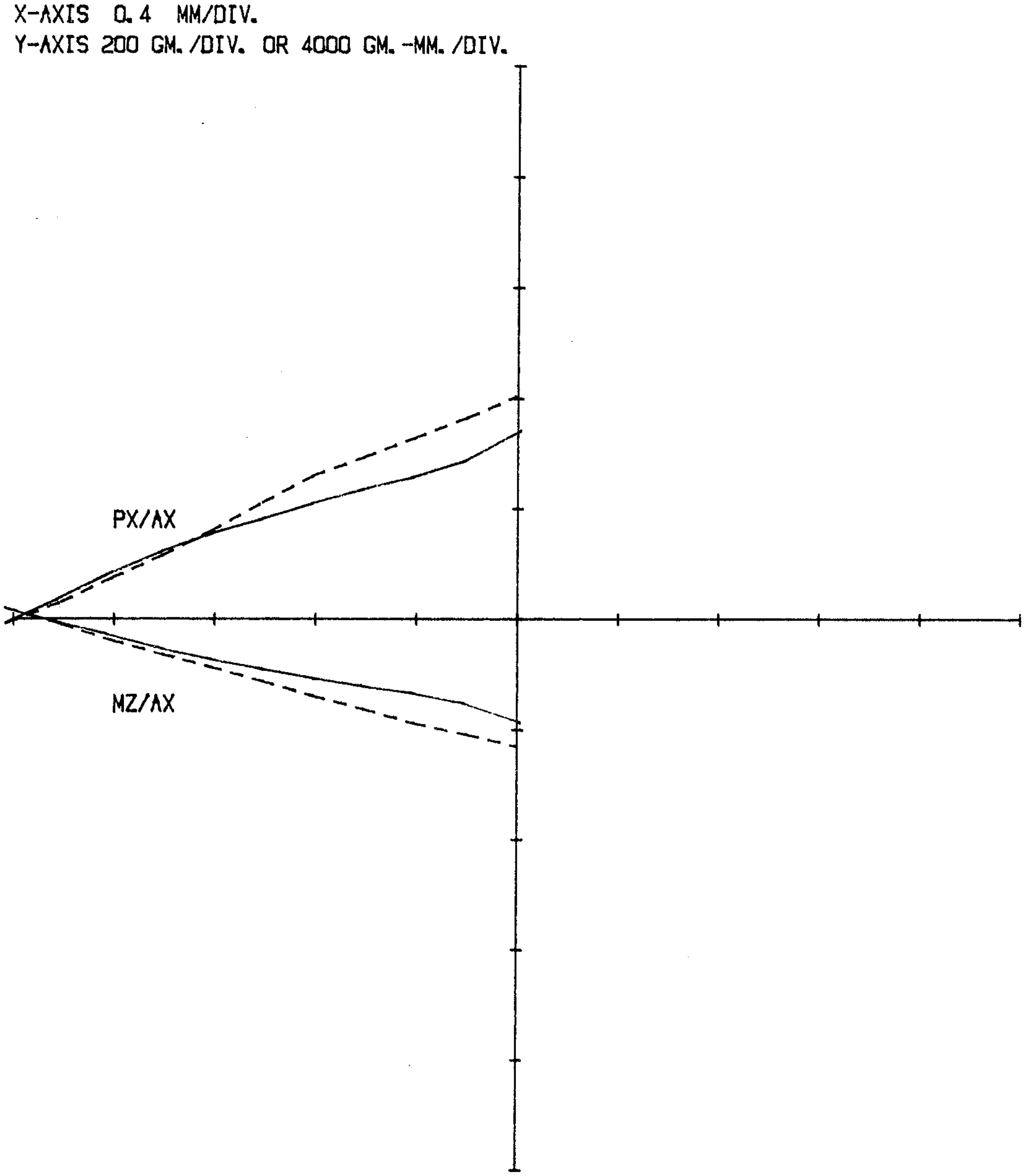


Figure A17: LINGUAL ELASTIC: plots of Px/Ax and Mz/Ax

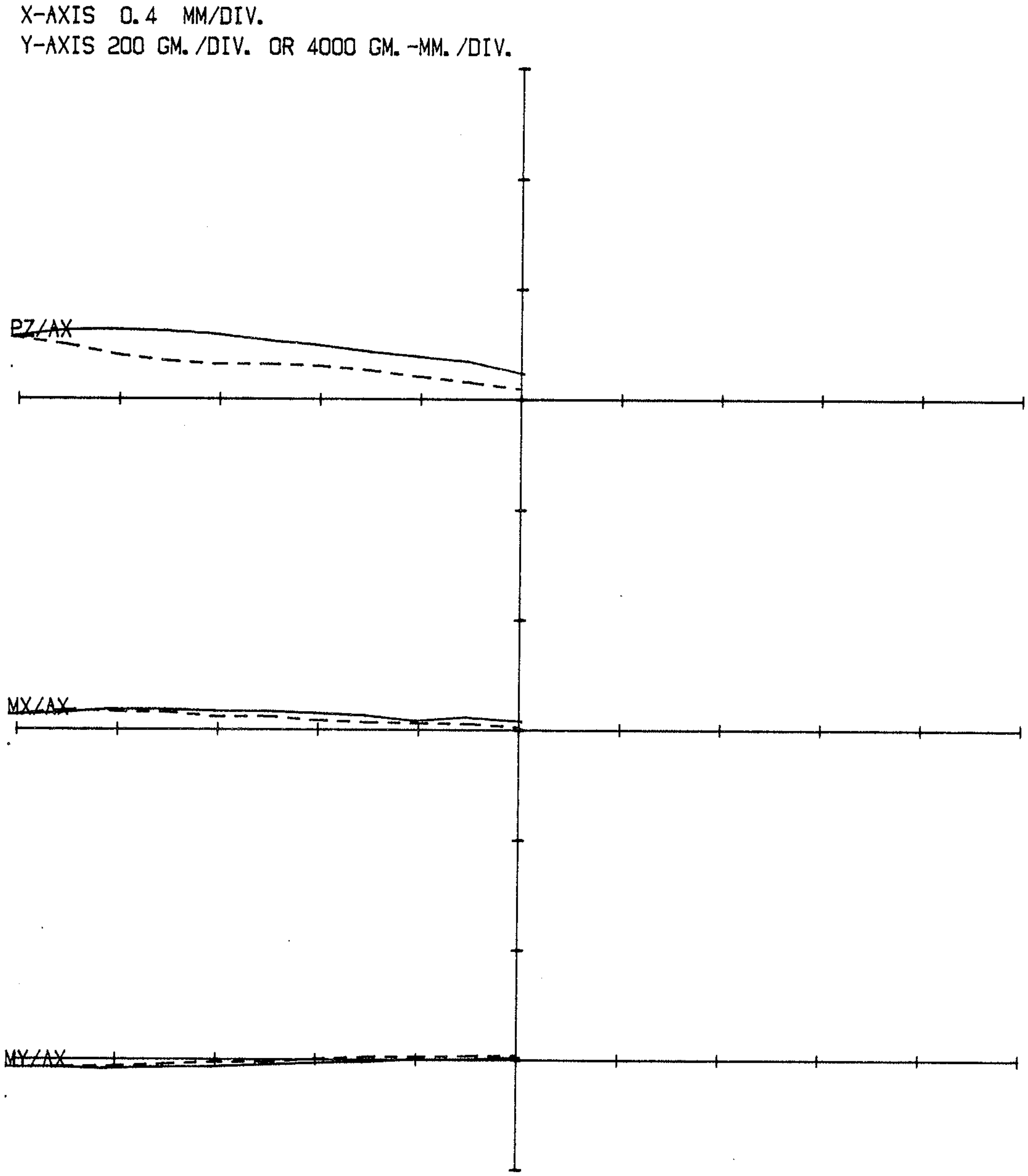


Figure A18: LINGUAL ELASTIC: plots of Pz/Ax, Mx/Ax and My/Ax

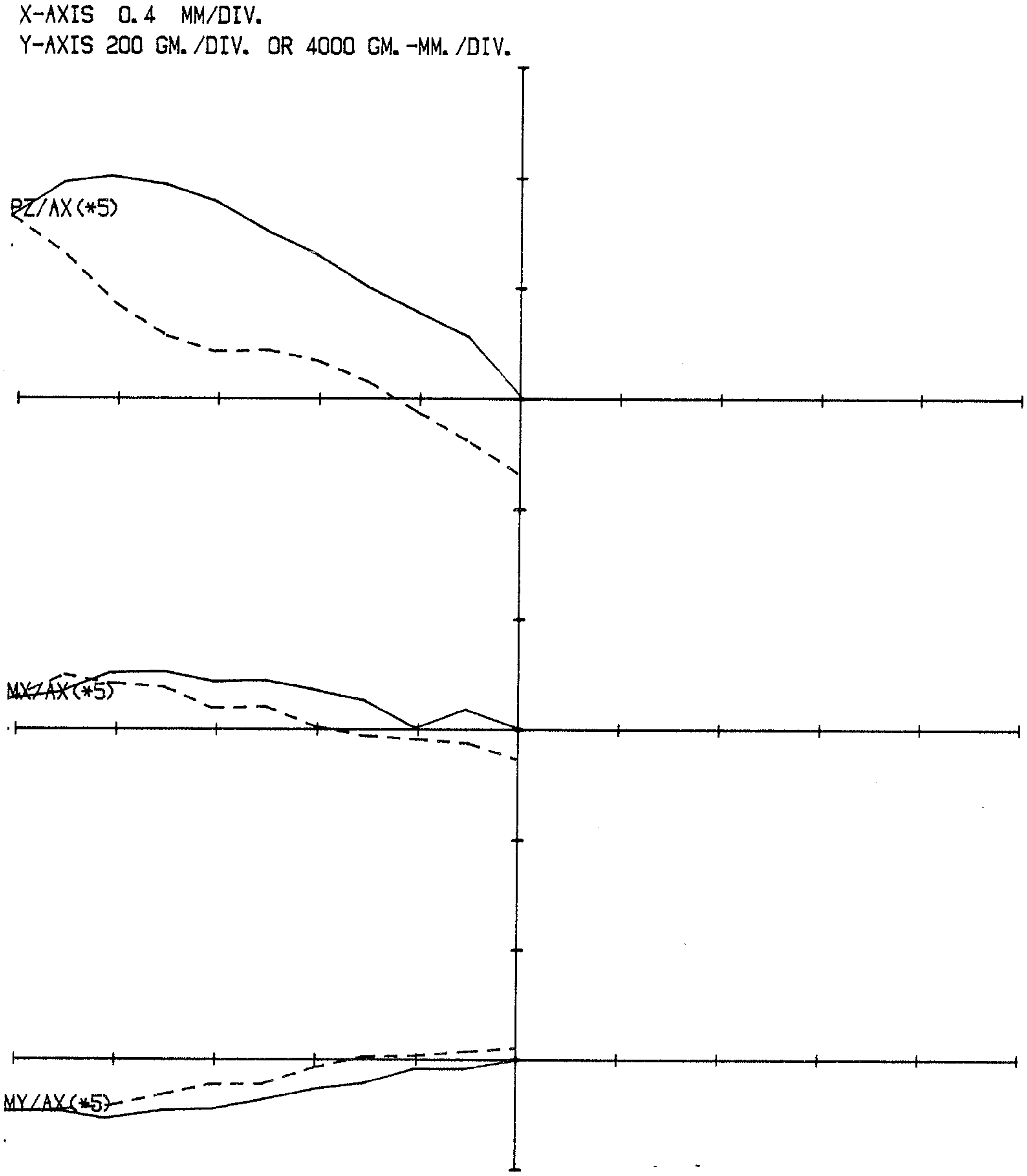


Figure A19: LINGUAL ELASTIC: plots of Pz/Ax, Mx/Ax and My/Ax (with zero shift and multiplication)

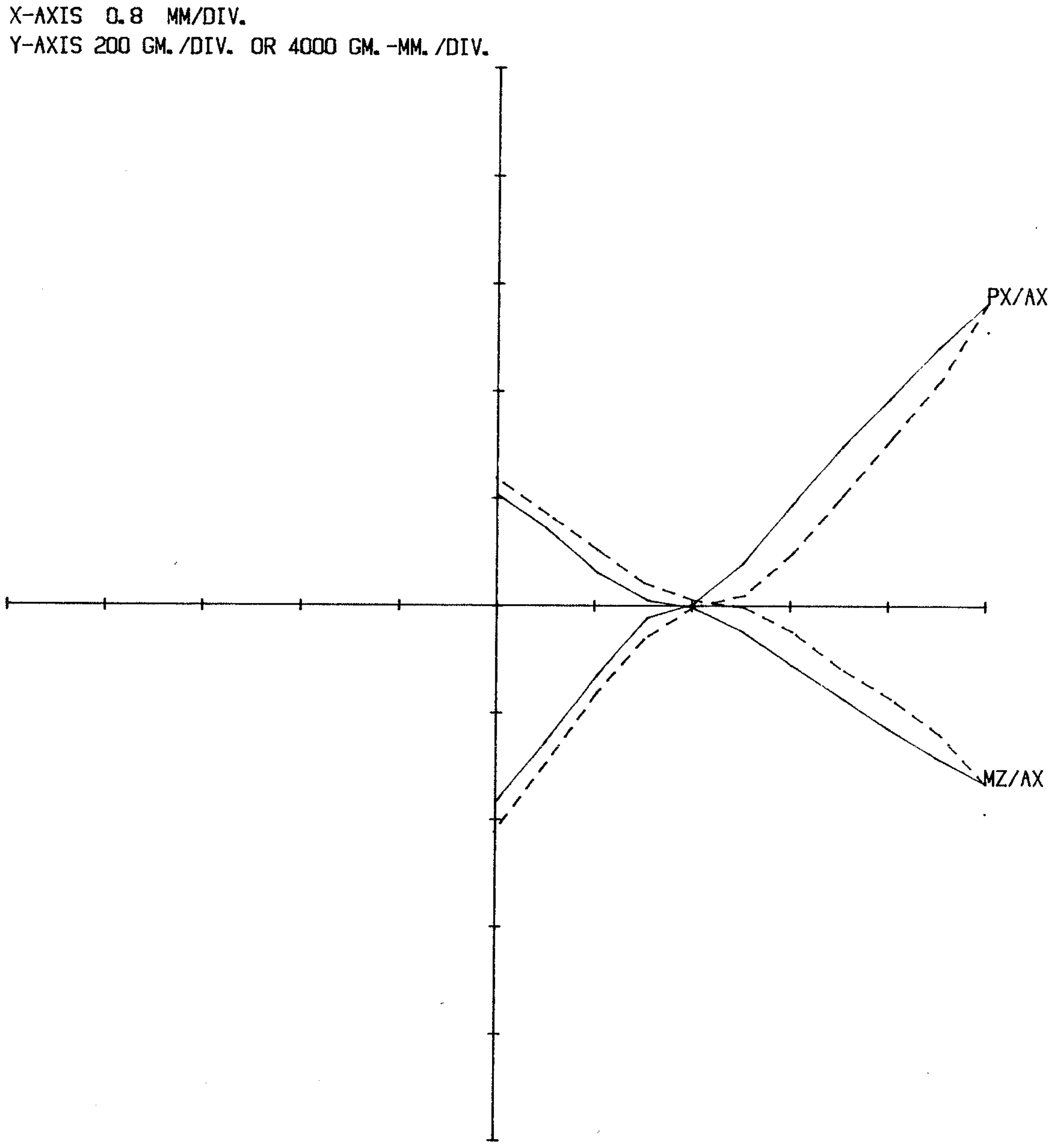


Figure A20: 4 mm. activation of BUCCAL TIGHT: plots of Px/Ax and Mz/Ax

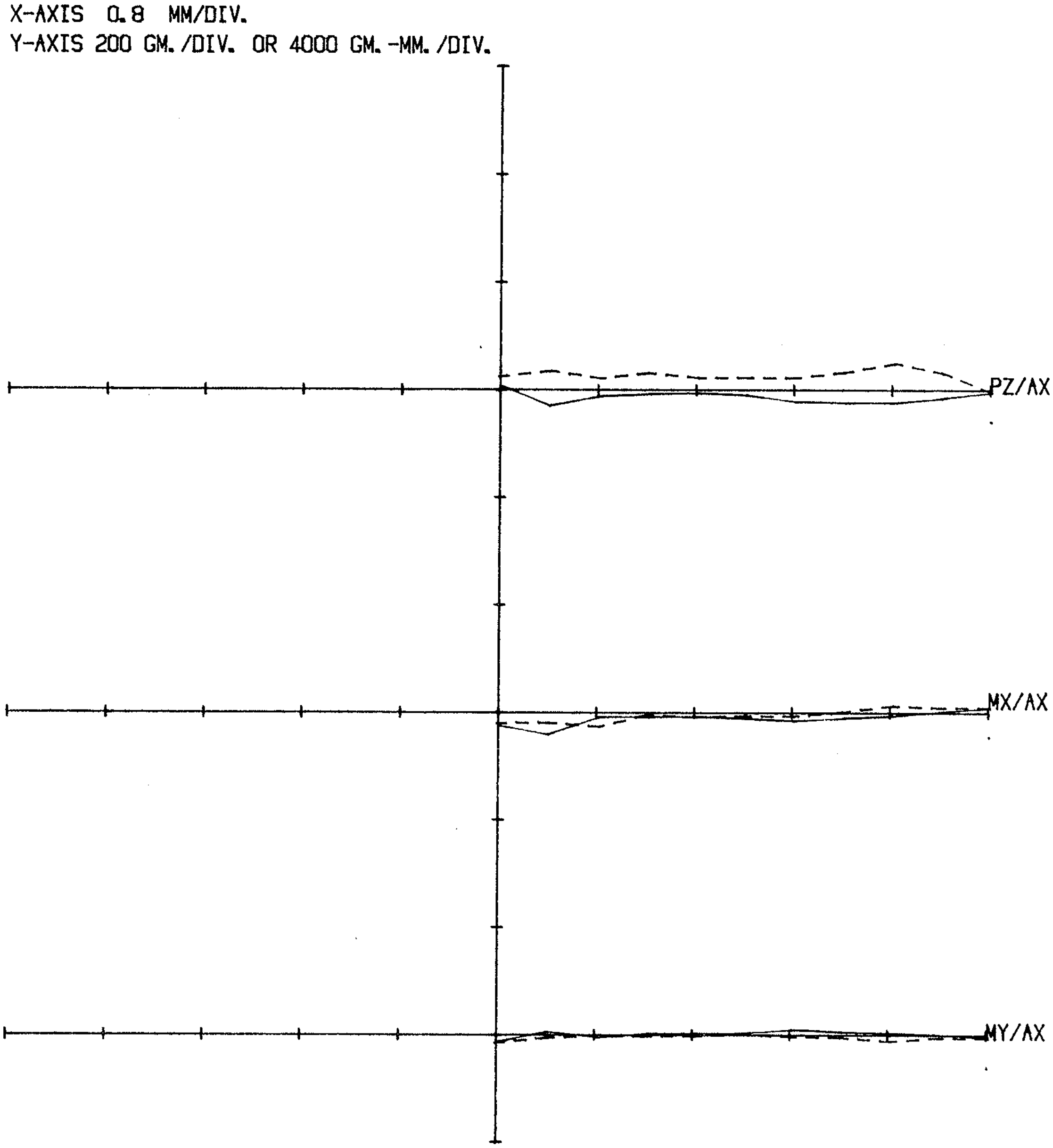


Figure A21: 4 mm. activation of BUCCAL TIGHT: plots of Pz/Ax, Mx/Ax and My/Ax

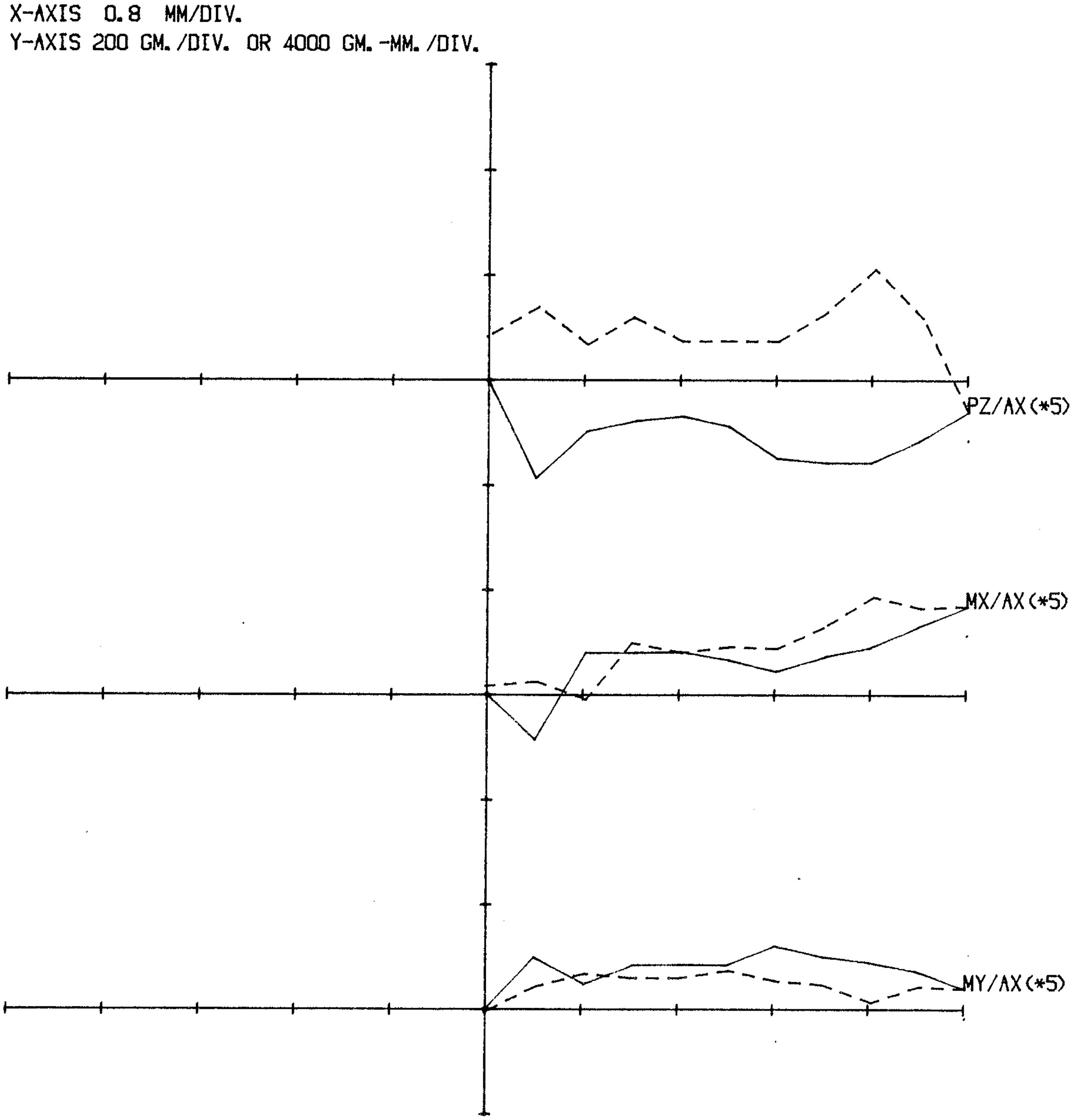


Figure A22: 4 mm. activation of BUCCAL TIGHT: plots of Pz/Ax, Mx/Ax and My/Ax (with zero shift and multiplication)

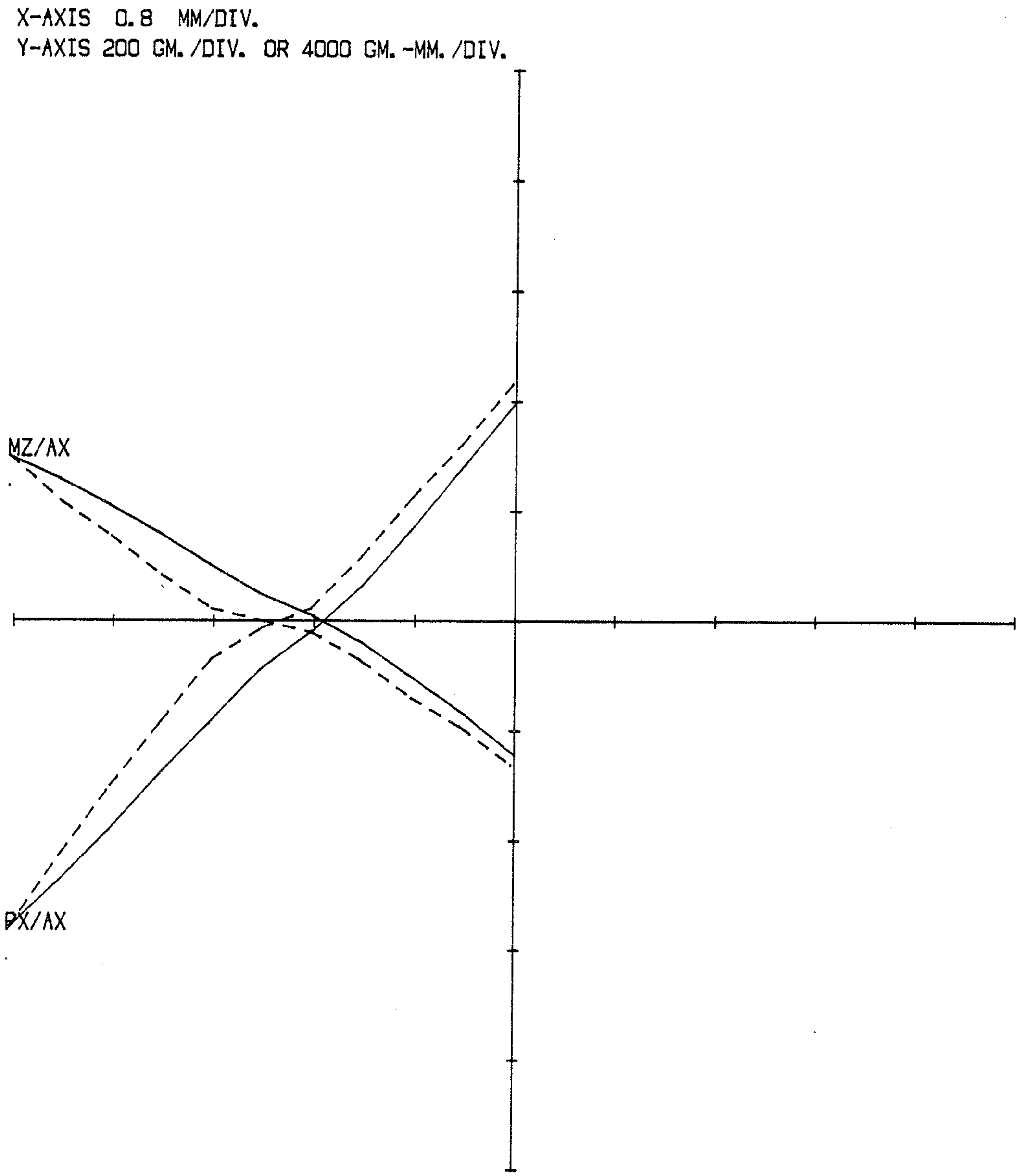


Figure A23: 4 mm. activation of LINGUAL TIGHT: plots of Px/Ax and Mz/Ax

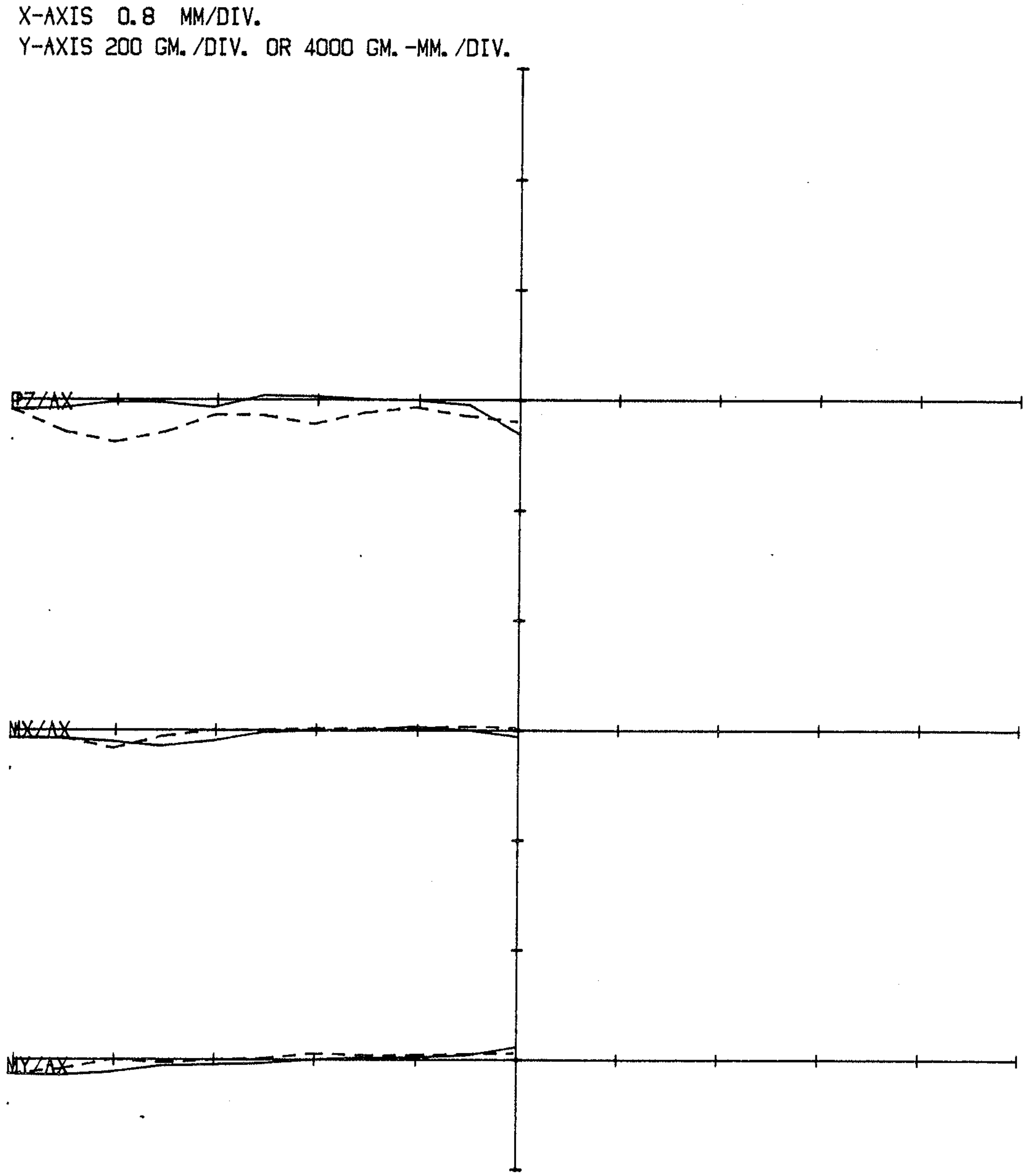


Figure A24: 4 mm. activation of LINGUAL TIGHT: plots of Pz/Ax, Mx/Ax and My/Ax

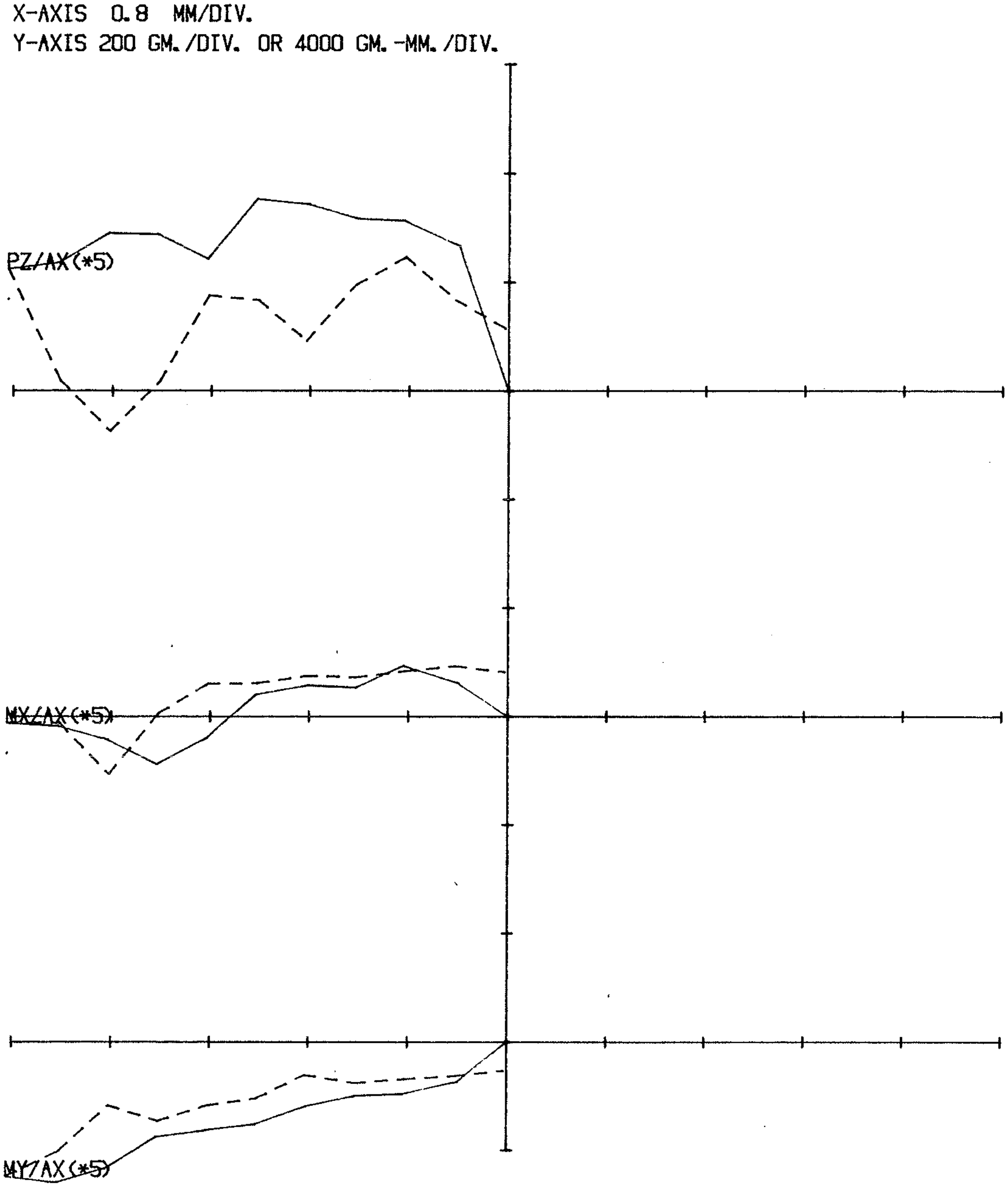


Figure A25: 4 mm. activation of LINGUAL TIGHT: plots of Pz/Ax, Mx/Ax and My/Ax (with zero shift and multiplication)

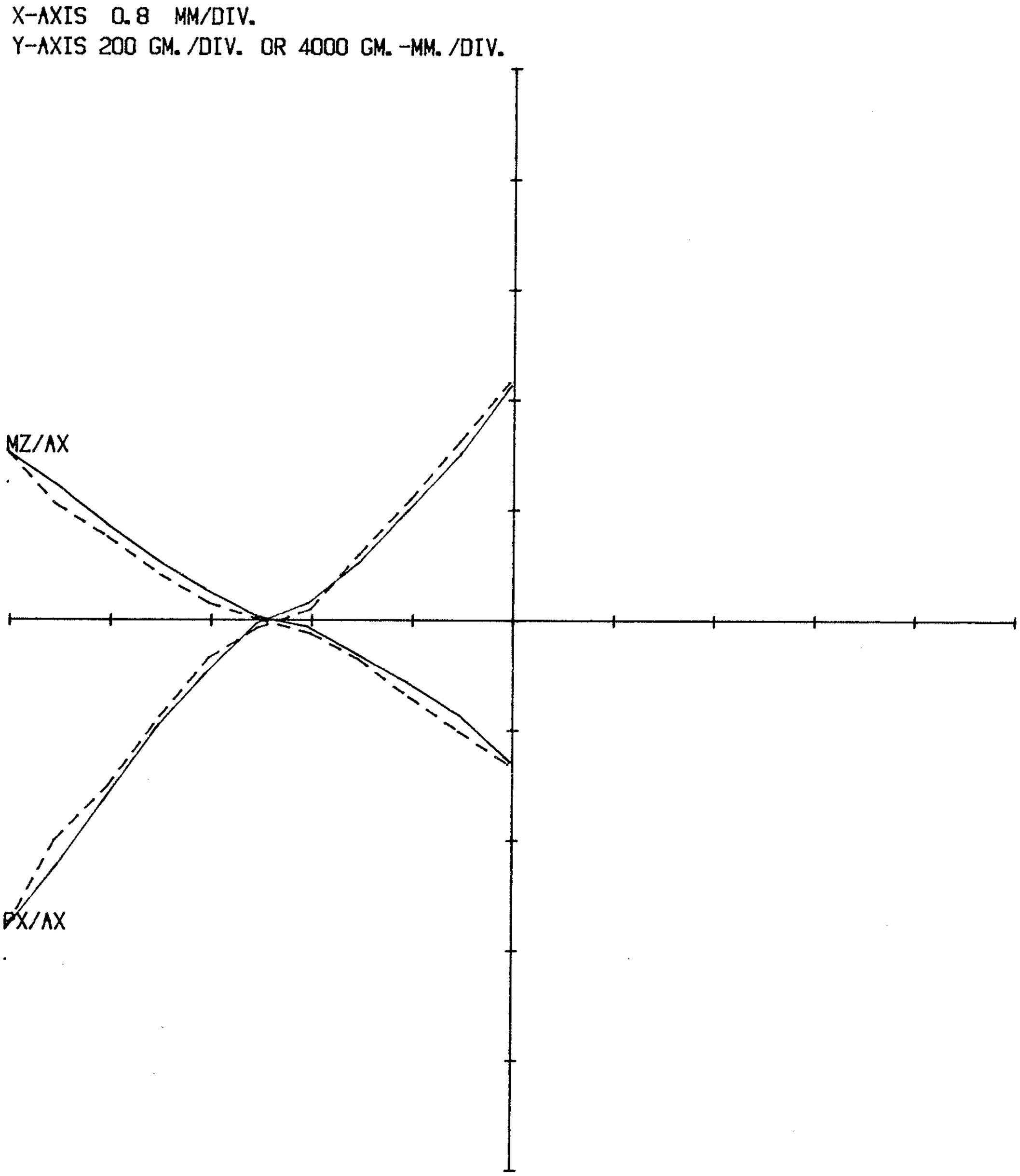


Figure A26: 4 mm. activation of LINGUAL TIGHT: plots of Px/Ax and Mz/Ax (2nd activation)

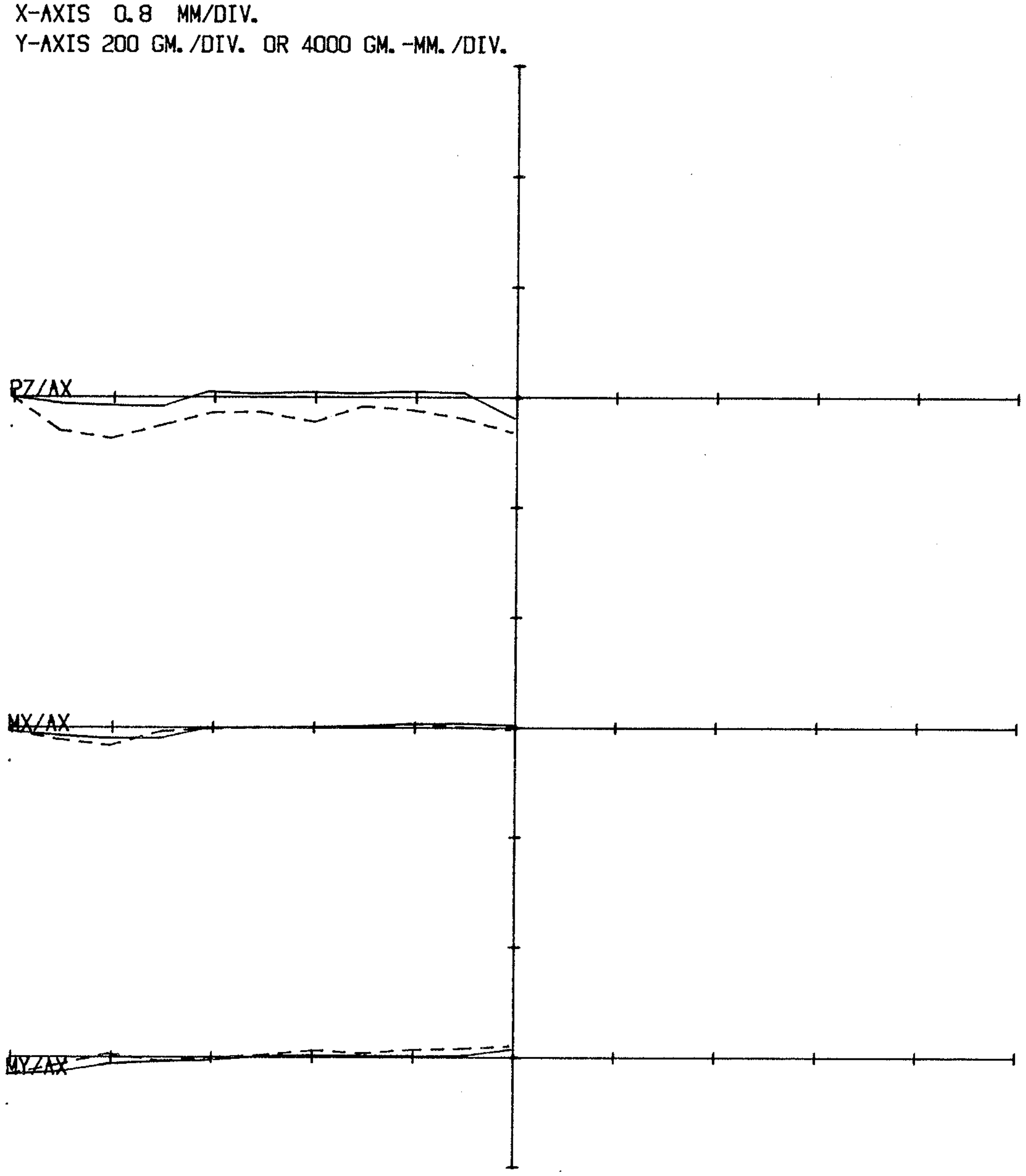


Figure A27: 4 mm. activation of LINGUAL TIGHT: plots of Pz/Ax, Mx/Ax and My/Ax (2nd activation)

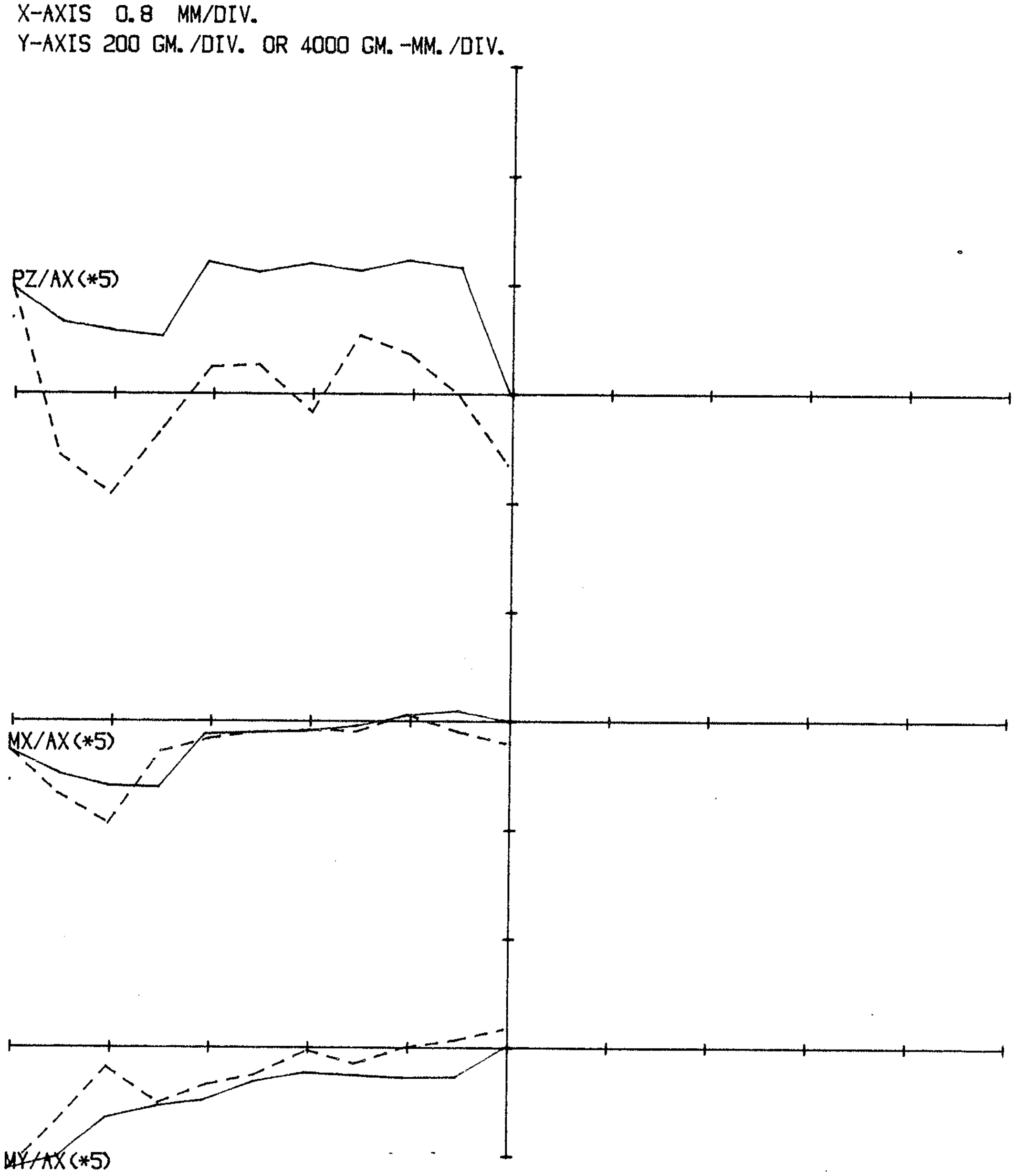


Figure A28: 4 mm. activation of LINGUAL TIGHT: plots of Pz/Ax, Mx/Ax and My/Ax (2nd activation) (with zero shift and multiplication)

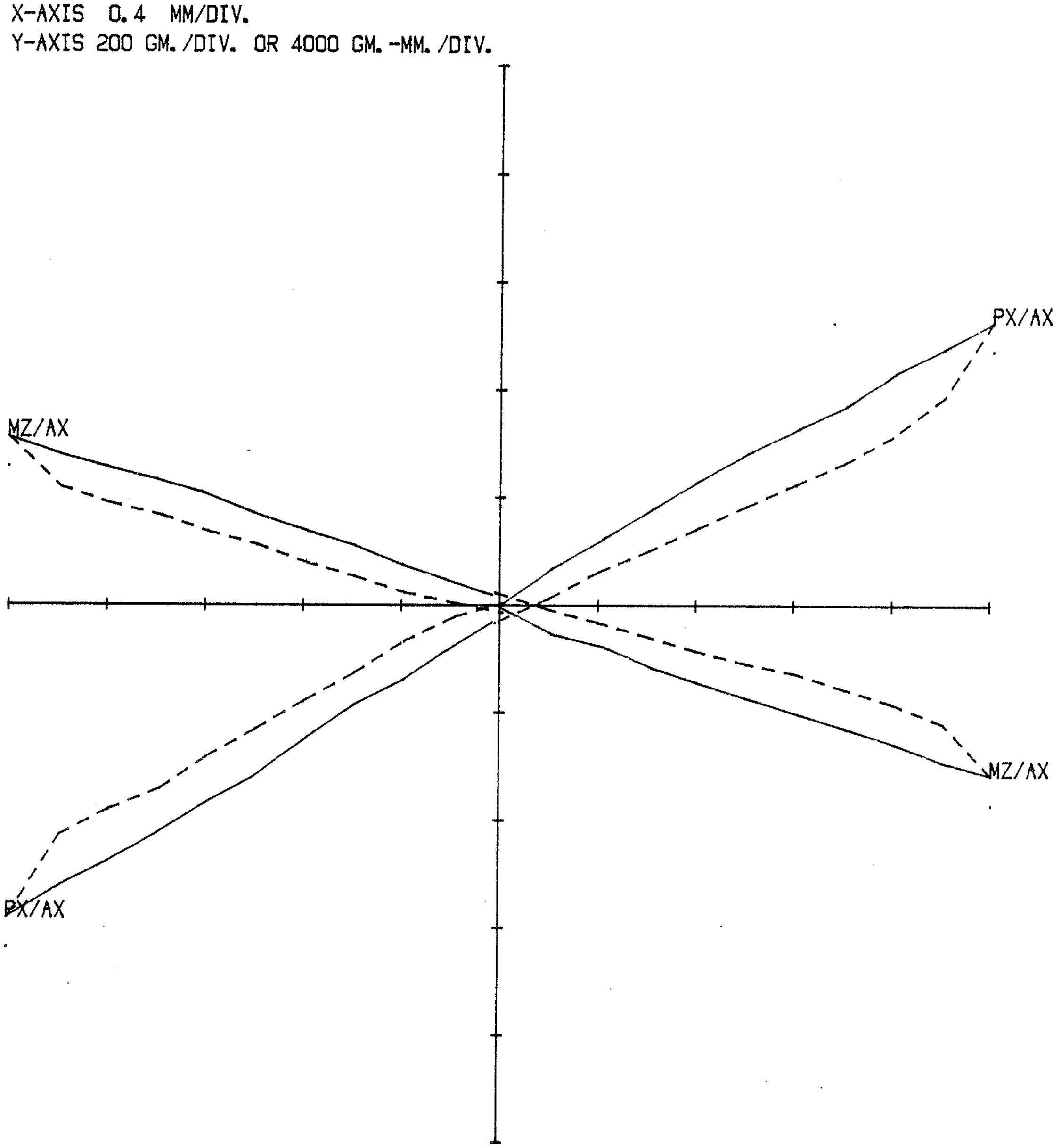


Figure A29: ALIGNED teeth activated 2 mm. Buccally and Lingually: plots of Px/Ax and Mz/Ax

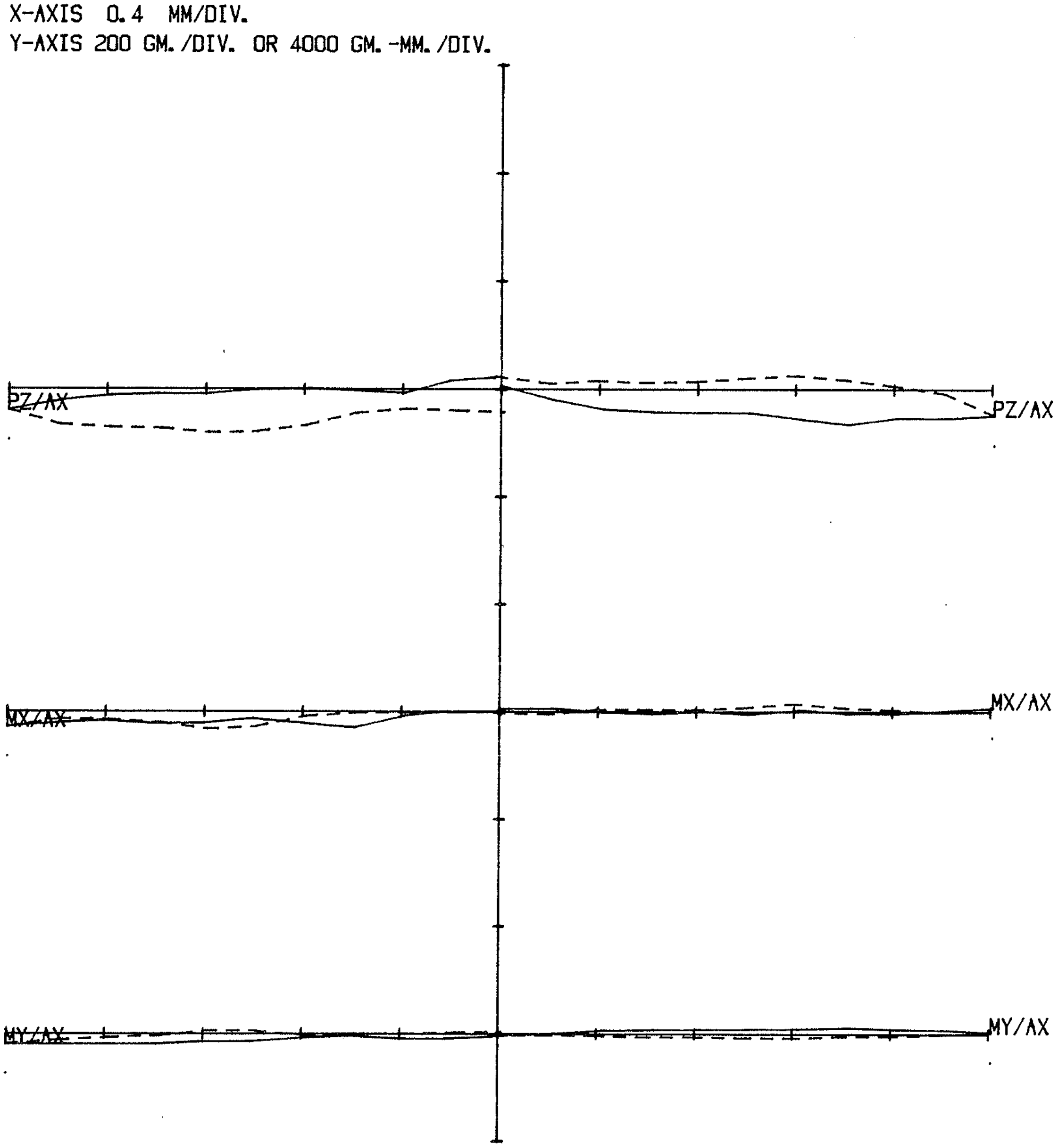


Figure A30: ALIGNED teeth activated 2 mm. Buccally and Lingually: plots of Pz/Ax, Mx/Ax and My/Ax

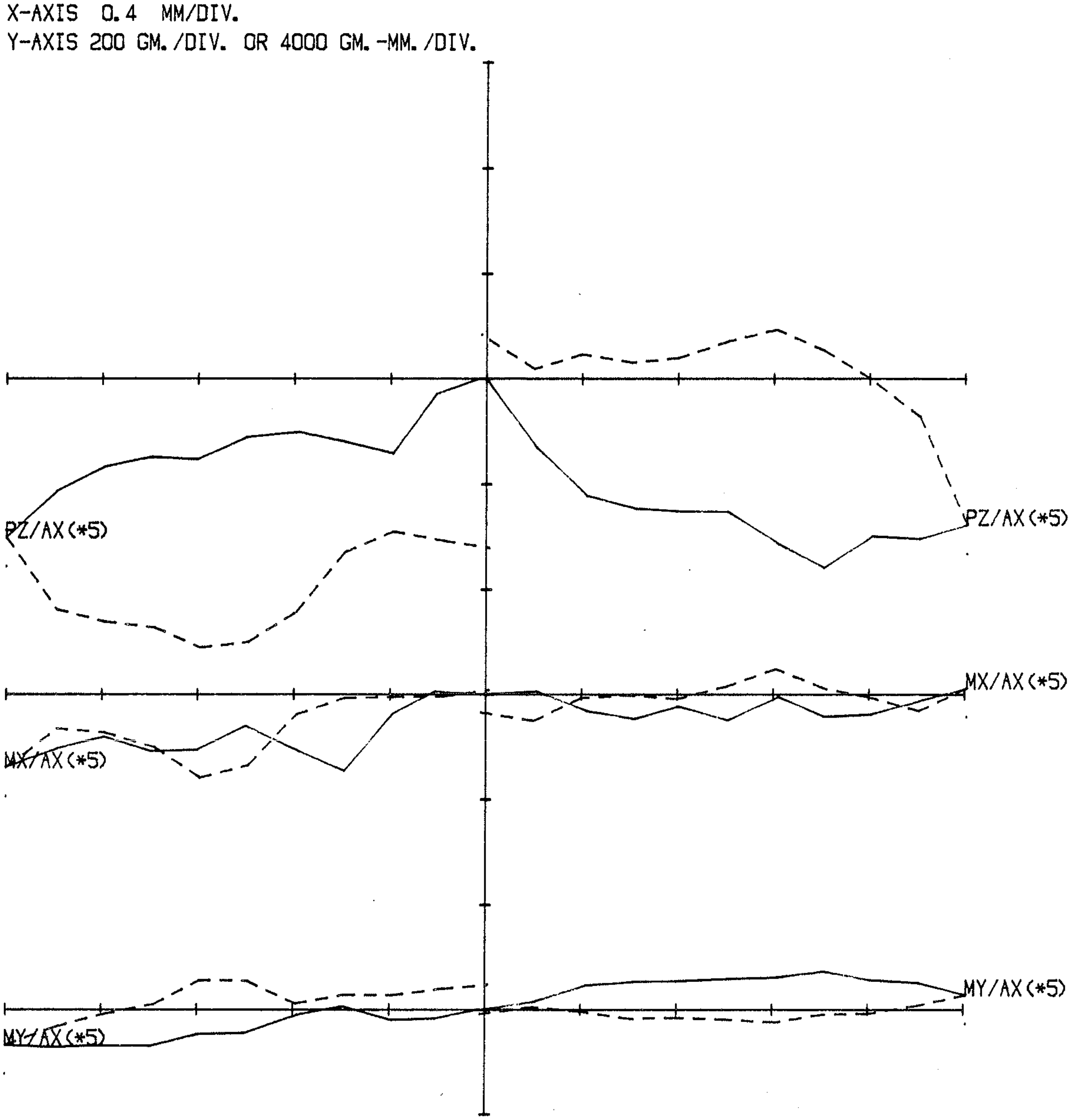


Figure A31: ALIGNED teeth activated 2 mm. Buccally and Lingually: plots of Pz/Ax, Mx/Ax and My/Ax (with zero shift and multiplication)

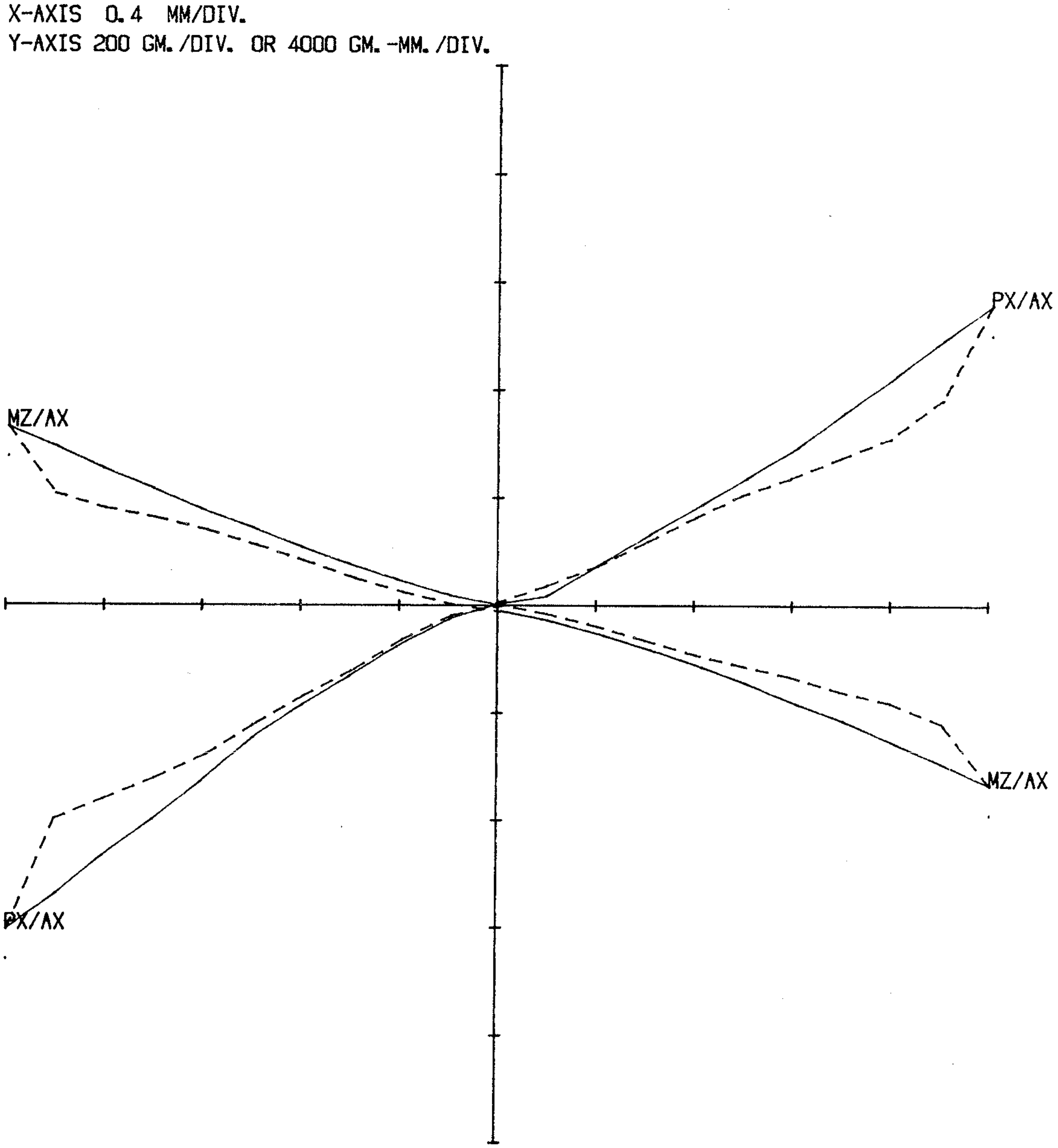


Figure A32: ALIGNED teeth activated 2 mm. Buccally and Lingually: plots of Px/Ax and Mz/Ax (2nd activation)

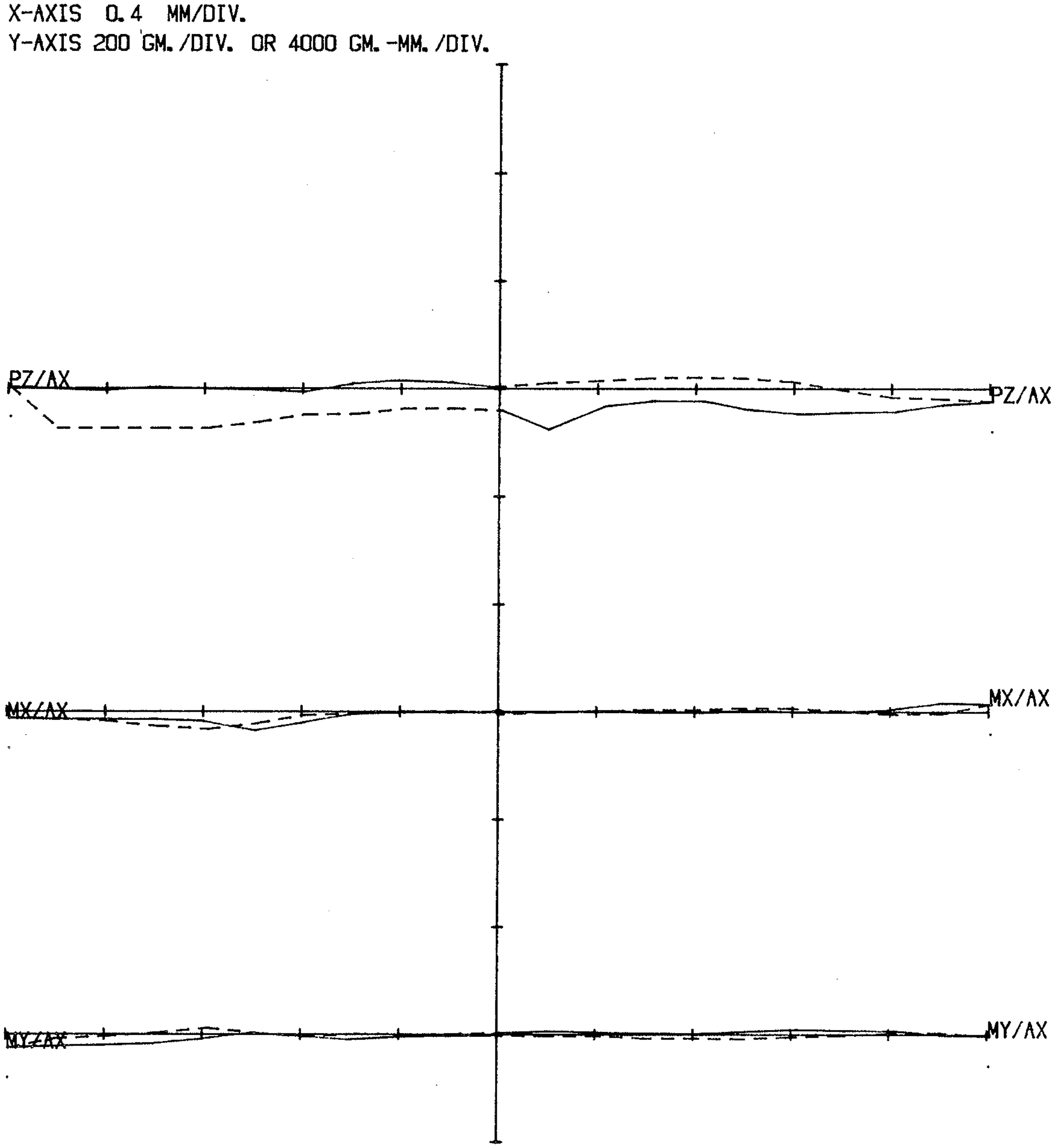


Figure A33: ALIGNED teeth activated 2 mm. Buccally and Lingually: plots of Pz/Ax, Mx/Ax and My/Ax (2nd activation)

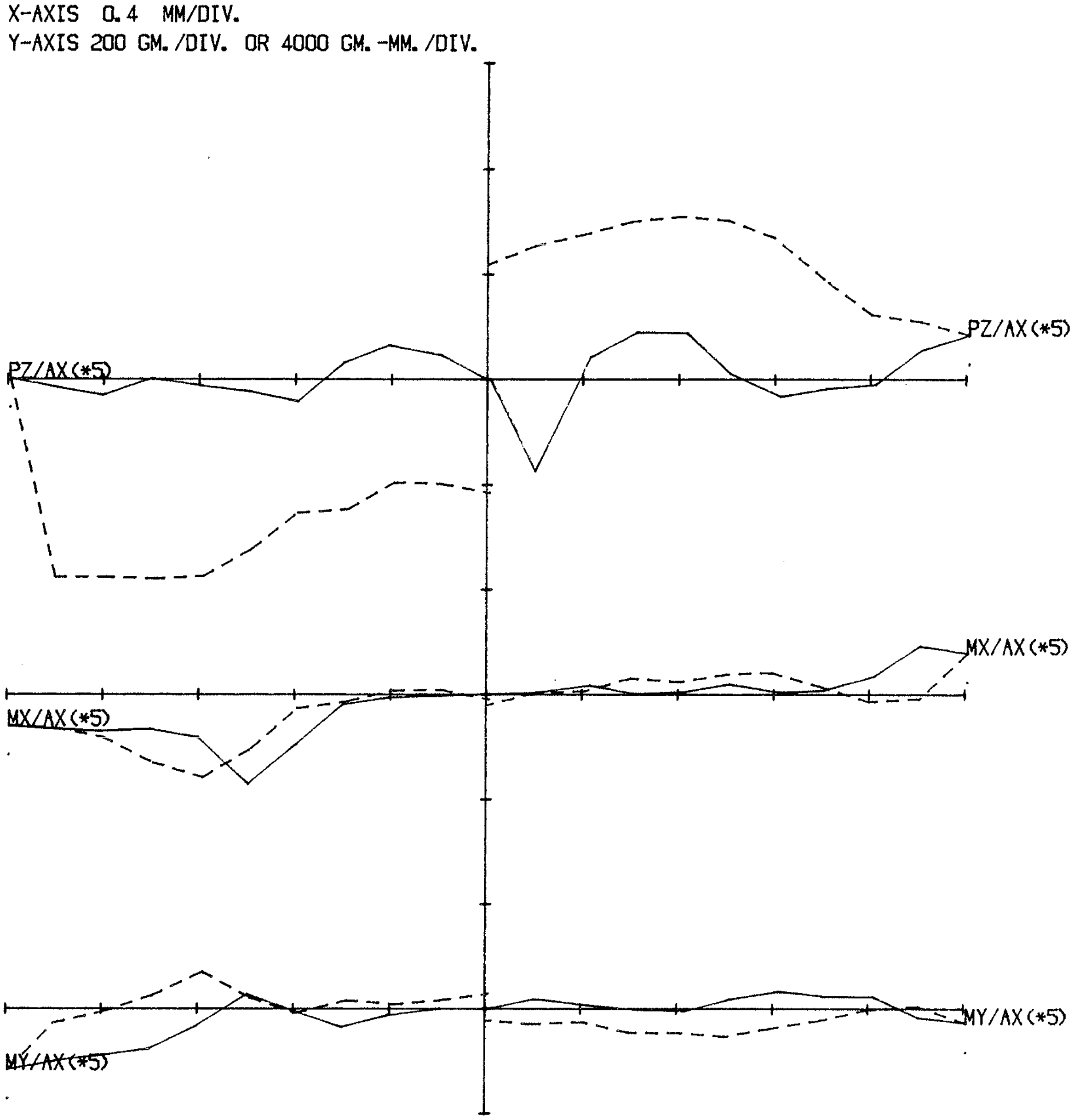


Figure A34: ALIGNED teeth activated 2 mm. Buccally and Lingually: plots of Pz/Ax, Mx/Ax and My/Ax (2nd activation) (with zero shift and multiplication)

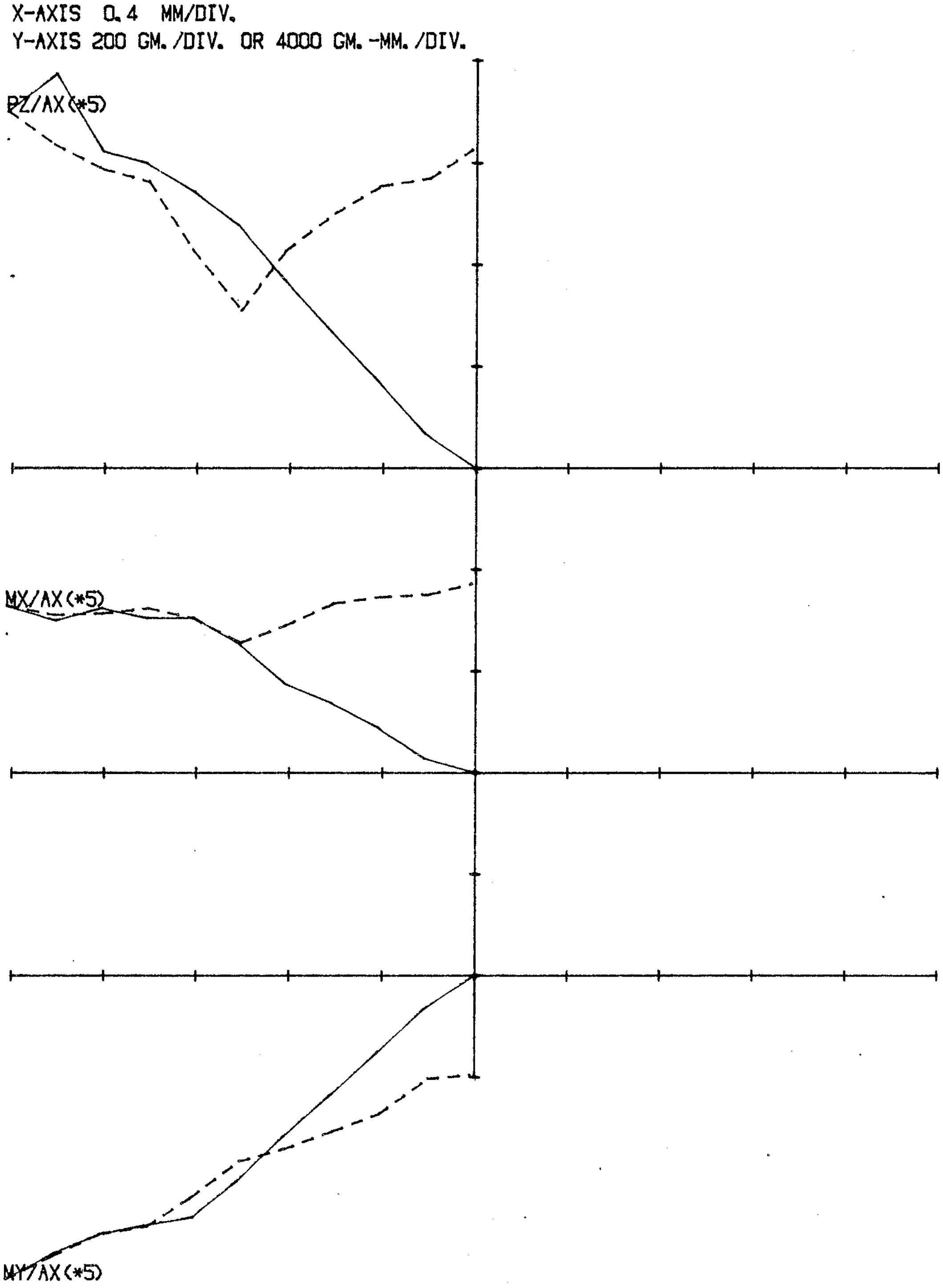


Figure A35: Two-tooth trial (left tooth and center tooth): plots of Pz/Ax, Mx/Ax and My/Ax (with zero shift and multiplication)

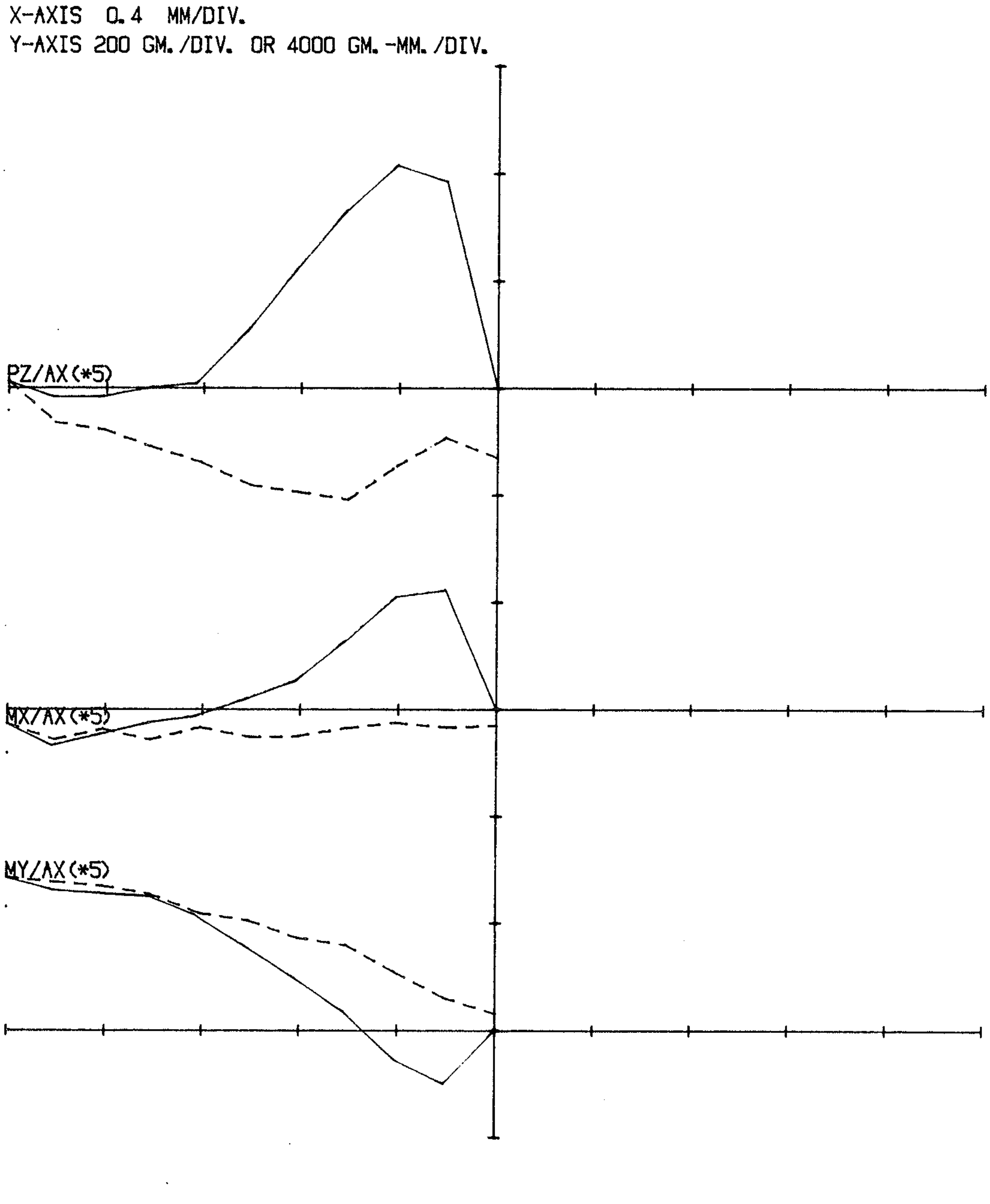


Figure A36: Two-tooth trial (center tooth and right tooth): plots of Pz/Ax, Mx/Ax and My/Ax (with zero shift and multiplication)