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Relationship of Tooth Movement to Measured Force Systems: A Prospective Analysis of the Treatment Effects of Orthodontic Intrusion Arches

Zackary T. Faber

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THE RELATIONSHIP OF TOOTH MOVEMENT TO MEASURED FORCE SYSTEMS: A PROSPECTIVE ANALYSIS OF THE TREATMENT EFFECTS OF ORTHODONTIC INTRUSION ARCHES

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THE RELATIONSHIP OF TOOTH MOVEMENT TO MEASURED FORCE SYSTEMS: A PROSPECTIVE ANALYSIS OF THE TREATMENT EFFECTS OF ORTHODONTIC INTRUSION ARCHES

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University of Connecticut

2001
The application of mechanical engineering principles to orthodontic appliance design has been described in the literature over the last century. Static force systems produced by orthodontic spring and wire activations have been illustrated by applying the principles of statically determinant force systems. The assumption, however, that the force system is the determinant factor in the expected clinical treatment response has not been vigorously tested. A biomechanical emphasis in orthodontic care implies a predictable "stimulus-response" model, i.e. the teeth move in a manner consistent with the forces and moments delivered by wires, springs, elastics, etc. Logically this makes sense, and has been empirically accepted, but it has never been validated by clinical trial.

Cantilevers are the most commonly used biomechanical stimuli utilized by orthodontists during treatment. A clinical trial using an intrusion arch creates a very important arena due to its simplicity and abundant use during treatment. One method for the correction of deep overbite, defined by the excessive overlap of the incisors, is to use an intrusion arch. The force system (Figure 1) is one that has been established and utilized in orthodontics for the last 25 years.

A non-randomized clinical trial was conducted to investigate a force system stimulus and tooth movement response model. Sixteen patients undergoing three months of intrusion therapy served as subjects. Two different force magnitudes were used as the stimulus. A carefully designed cephalometric approach was utilized to assess the response. The findings suggest that the qualitative force system predicts the dental response, while the quantitative forces produced similar outcomes. The physics of the
force system are therefore predictive of the resultant dental displacements despite a biologic environment.

Substantial amounts of inter- and intra-subject variability were documented. Nevertheless, the significance of this investigation is the documentation of a short-term response to a qualitative stimulus without confounding effects of continued treatment. The geometry of the expected result was a significant factor and increases the need for the orthodontist to monitor and re-evaluate each patient throughout treatment. The documentation of responses occurring as a result of relatively discrete stimuli enhances the orthodontists' ability to make reasonably predictable in-course corrections.
ACKNOWLEDGEMENTS

The pursuit of lifelong knowledge begins by first learning what questions should be asked. There are many people who have been instrumental to this investigation by providing the questions that were important to this subject. With the guidance of these special people, this thesis grew from a small idea between faculty members and an inquisitive resident. Many opinions helped to create the manuscript that lies before you.

DR. ANDREW J. KUHLBERG

Without the expert teachings of Dr. Kuhlberg, I would not be the clinician, researcher, or teacher that I am today, or that I will become in the future. His ability to translate the philosophical teachings of biomechanics into innovative and creative orthodontic solutions never ceases to amaze me. Every discussion relative to orthodontics reveals within me an increasing admiration for the breadth and depth of knowledge that Andy possesses and is able to translate into useful clinical ideas. In addition to my orthodontic knowledge base, Andy has become a close friend.

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Dr. Godwin entered this program as faculty member as I began my training. I wish to thank Dr. Godwin for being organized because he is responsible for keeping this project on its strict timeline. His positive support and constructive criticisms on this project and in the clinic have been appreciated greatly.

RESIDENTS

The difficult task of creating a prospective study is confounded by the collection of eligible patients. Drs. Kristen Walters, Brad Jacobs, and Lubna Shafi allowed me to intrude into their clinical learning time to collect the data for this project and for that I am grateful to them. I would like to thank all of my classmates and fellow residents as well as the residents who graduated before me (especially Drs. Chris O’Hea, Anita Bhatt, Jacqueline Sohn and Robert Marzban) for creating a family environment within which to grow and excel.

MY FAMILY

My grandfather is the inspiration to enter orthodontics, his enthusiasm and undying love for orthodontics was contagious. It not only inspired my father, but also was the greatest influence on my career. It is to his memory that I dedicate this project.

My father, my future partner, has provided for me the opportunity of a lifetime. As an orthodontist, he has few equals. His work ethic is amazing, and only my grandfather could rival his enthusiasm for what he does. While I hope that someday I can achieve the level of excellence that he has set forth as the standard, I make only a promise to make his life easier by “holding down the fort” while my mother and he spend quality
time together. His contribution to this thesis was immeasurable with timely and insightful suggestions.

Last, but hardly least, I owe a lot of my success to the love of my life, my wife, Brooke. Since she is my best friend, she has endured the worst of all of the schooling that I have completed, and by doing so, she shares in all of my successes. So to her I dedicate the rest of my life to make her life easier.
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INTRODUCTION and REVIEW OF LITERATURE

The application of mechanical engineering principles to orthodontic appliance design has been described in the literature over the last century. Static force systems produced by orthodontic spring and wire activations have been illustrated by applying the principles of statically determinant force systems. The assumption, however, that the force system is the determinant factor in the expected clinical treatment response has not been vigorously tested. A biomechanical emphasis in orthodontic care implies a predictable "stimulus-response" model, i.e. the teeth move in a manner consistent with the forces and moments delivered by wires, springs, elastics, etc. Logically this makes sense, and has been empirically accepted, but it has never been validated by clinical trial. An important foundation linking biomechanical principles to orthodontics is that tooth movement is not independent of the force system created by the clinician.

The relationship between the appliance-driven stimulus and the biological response necessitates clinical documentation. This present investigation attempts to imitate the dose-response model of contemporary medicine, by creating the stimulus-response model to determine efficacy and efficiency of orthodontic care. By utilizing the intrusion arch as a model for this type of test, the study employs a relatively simple and determinant force system to be evaluated. (Fig. 1) From a clinical perspective, the anterior segment is elevated (intruded) away from the occlusal plane in order to correct the dental deep bite. The posterior segment is rotated distally with a mild extrusive force, which aids the clinician with Class II and deep bite correction. Several authors have discussed the force system applied1-4, but as a part of scientific literature, no force has been tested to provide the "optimal" force for intrusion mechanics. The availability of
newer materials has increased the ability for the orthodontist to deliver accurate, calibrated, and light continuous forces over a large range of deflections.

The opportunity to observe the biological model creates an opportunity for this study to mimic the dose-response model found in medicine. The relatively straightforward mechanics of the intrusion arch lend this project an ideal forum for evaluating whether biomechanics "works the way it's supposed to." It also gives hard evidence to the clinical model utilized by many clinical orthodontists.

**Appliance Design**

Orthodontists have been describing techniques for performing tooth movement since the turn of the century. In the beginning of the twentieth century, orthodontists began attempting to describe the applied force in mechanical engineering terms. A reasonable assumption can be made that mechanical engineering principles were available to orthodontists around the turn of the century, but Calvin Case was the first to describe tooth movement in those terms in 1921. Burstone, who was heavily influenced by Case, reintroduced the principles of mechanical engineering to the "current" literature. The transformation of mechanical engineering principles from conceptual theories of free body diagrams and physics into the force driven appliances that are in current use today had its origins with these men.

Calvin Case, in 1921, described the principles of mechanics in the movement of teeth. Case was the first orthodontist to describe in detail an approach of designing force-driven appliances. "A dental regulating apparatus—however simple or complex—is a machine for the application and transmission of power which is given to it by the operator in the form of potential energy for the movement and correction, primarily, of
malposed teeth; and secondarily for the correction of all forms of malocclusion and
dento-facial imperfections.” Case further described that, “a machine is a contrivance, or
device, or a combination of mechanical elements by means of which a force or forces
may be advantageously applied” to correct malocclusions. “In the contemplation of
applying force to a tooth for its movement, every condition should be considered:

1) its situation in relation to the arch and adjoining teeth;
2) the number, probable length, shape, and inclination of its roots;
3) the probable yielding quality of its alveolar imbedment in relation to the
   required movement;
4) the possibility of attaching appliances to the crown, which will permit the
   proper application of force;
5) finally, the influences of occlusion, dento-facial relations, and the possibilities
   of retention.”

“In the choice or invention of a regulating apparatus, after the several required
movements of the case have been determined, a careful study of the demands will present
opportunities for its application.” Unfortunately, Case was never appreciated for the
biomechanical principles that he presented because Case advocated therapeutic
extractions when necessary for orthodontic treatment, which dissented from the Angle
philosophy. Angle, in a remarkable paper read before the New York State Dental Society
in 1903 proclaimed:

“Extraction is wrong. The full complement of teeth is necessary to the best
results, and each tooth should be made to assume its correct relations with its
fellows. I shall try to impress you from the orthodontist’s standpoint with the full
value of each individual tooth and with the absolute necessity of preserving the full complement of teeth or its equivalent in every case. I shall try to bring conclusive evidence that the sacrifice of teeth for either the intended prevention or correction of malocclusion is not only wrong practice and fallacious teaching, but most baneful in its results. I shall further try to show that the full complement of teeth is necessary to establish the most pleasing harmony of the facial lines.”

With the promotion of the Angle philosophy of non-extraction in every orthodontic case, Case was ostracized from the orthodontic community due to the following committed to Angle. The principles advocated by Case, and his belief in force-driven appliances was relatively forgotten for almost forty years.

In the 1950’s, engineering principles were discussed by Sved and Stoner, to “save us time, without reducing our standards, for it will increase our efficiency and be of benefit to us and to our patients.” Motion cannot take place without the application of a force, and even though the orthodontists’ problems have a biological basis, the therapeutic application is entirely mechanical in nature. Using mechanical engineering principles, Sved analyzed bending moments to show beams (orthodontic wires) to describe the amount of force used in a single “straight” wire. Stoner introduced a new way to think into the orthodontic literature; he talked about force control. “Force control implies control of the degree of force, the distribution of force, the direction of force, and the duration of force—the “four D’s” of force control.” An important concept to be considered is optimum force. A known force that is optimal in one direction can be detrimental or ineffective in another movement. The force levels that had been sought,
the optimal force, were starting to be described. Prior to this, the force levels were derived from clinical observation and animal models.\textsuperscript{2, 7-9}

Burstone, in 1961, continued on this theme and presented an analytical approach to orthodontic tooth movement with a thrust towards the use of physics and engineering principles to predict tooth movements. Rather than through trial and error, which had been the method of clinical science in use since Angle.\textsuperscript{10} The purpose of this new direction was to consider basic biomechanical principles involved in the production of light continuous forces. The forces in orthodontics are useful only insofar as they initiate desirable tissue responses that are distributed throughout the periodontal ligament. The force distribution depends on the root (length, diameter, and contour), nature of the periodontal ligament, site of force application, and the distance over which the force acts.\textsuperscript{10} Burstone, in the early 1960’s, provided the orthodontic community with one of its most important contributions. The ability of the orthodontist to treatment plan the objectives of the case in terms of where the teeth should be placed at the end of therapy and then to design those mechanics which are required to move them to their final position remains the gold standard for treatment planning.

**Force Magnitude and Optimum Orthodontic Forces**

"Orthodontists must select for the usage of those forces, which will best sustain normal growth vectors, positions of the teeth, and provide proper function and happy esthetics."\textsuperscript{11} "For many appliances, no attention is paid to specifying those features of the design which determine the value of force applied."\textsuperscript{12} A series of articles in the 1950’s proposed theories of optimal forces, differential forces and anchorage considerations. Storey and Smith from Australia are regarded as the first orthodontists to
test spring designs that were used in clinical practice at that time. "In the designing of an orthodontic appliance to perform a specific function, it is necessary to know the maximum force which may be applied without causing damage to tissues." It is also essential to know whether a force level exists where the surrounding tissues will respond without any bone resorption but tooth movement is maximized, i.e. "a tissue threshold force." Prior to the Storey and Smith articles, the values of forces were not measured because all of the forces were felt to cause damage to teeth; therefore intermittent forces were better to allow rest periods so not to cause increased damage to the teeth.9 A review of the appliances (Edgewise, Twin wire, Begg, and Labiolingual) that were used in the first half of the century by Halderson, states that, "our modern appliances have evolved and survived not so much because of their engineering design, but because they do, indeed, work in the mouth."11 "Most desirable types of tooth movement are produced by a relatively constant force within an optimum range, therefore we want to design the active components of an appliance so that they will have desirable spring effects."14

In the original intrusion literature written by Burstone1, Burstone recommended force levels on the average of 100g for the four incisors for incisor intrusion. These force magnitudes had been derived from Sloan15, in which Sloan and Burstone 1) proved cephalometrically that intrusion was possible and 2) 50-75g is the optimal depressive force for the four maxillary incisors. With this force value, there seemed to be minimal discomfort and maximal tooth movement. However, Gottlieb16 proved that there was no difference between an intrusive force with a force magnitude of 60g or 90g. This study also confirmed the research done by Sloan that proved radiographically that intrusion is possible. Gottlieb found that intrusion of the maxillary incisors with a base arch, i.e. an
Intrusion arch, is possible using forces as low as 60g for four incisors, with as much as 4.5mm of intrusion achievable. Significant posterior occlusal plane steepening occurred in the absence of an occipital headgear. Also, Gottlieb stated that the amount of intrusion that occurs as a function of time during which a base arch is active has no relation to the magnitude of the intrusive force applied, when that force is between 60 and 90g to the four incisors. 16

In terms of force magnitude, Quinn and Yoshikawa17 in a review of the literature described four different biologic responses to the applied forces that have been prevalent in orthodontics. The four graphical representations can be seen in Figure 2. The third hypothesis stems from the Storey and Smith13 belief that there is a biologic maximum after which the rate of movement will decrease as the force increases. This was the basis for belief in anchorage control in some of their cases. Important is the fourth hypothesis. This hypothesizes that the rate of tooth movement is linear until a maximal biological rate is reached above which the rate of tooth movement will not increase. The rate-limiting factor is the cellular response to the force magnitude and remodeling of the periodontium. Further emphasizing that an optimal force level is the maximum force which may be applied without causing damage to tissues, while maintaining a non-pathologic biological response.

**Intrusion and Centers of Rotation and Centers of Resistance**

Since the beginning of the profession, designing methods and appliances for the employment of optimal forces has been a quest for orthodontists. A common mechanical usage of the differential application of forces is for the correction of deep overbite or a closed bite. The amount and percentage of overlap of the lower incisors by the upper
incisors can define a dental deep bite. The overbite can be calculated as a percentage of
the clinical crown height of one of the mandibular central incisors. Extruding molars,
intruding incisors, a combination of both, as well as tipping of incisors and differential
growth of the maxillary and mandibular structures can accomplish deep bite correction.
Individualized treatment planning for the deep bite patient requires that the relative
amount of anterior intrusion and posterior extrusion is determined before treatment and
that differential mechanics are utilized to produce the desired correction. Every patient
with deep overbite requires a comprehensive treatment plan, which establishes how
extrusion of posterior teeth or inhibition and genuine intrusion of anterior teeth should
correct the deep overbite. This decision is based in part on where the clinician desires to
place the occlusal plane, the amount of mandibular growth anticipated, and the vertical
dimension desired at the end of treatment.¹ The intrusion of incisors can be indicated for
several reasons. Gottlieb enumerated those reasons in 1979:

1) If a patient shows an excessive amount of upper incisor and gingiva, due to
   either a short upper lip or supereruption of the upper incisors, intrusion of the
   maxillary incisors can improve the esthetic result of the finished case.

2) If a patient has lip incompetence, hinging the mandible open via posterior
   tooth eruption is contraindicated, making anterior intrusion the treatment of
   choice for correcting the deep overbite.

3) If a patient has a greater than average vertical dimension, with a high ratio of
   lower/upper facial height, posterior eruption could hinge the mandible open
   thus increasing the lower facial height even more.
4) If a patient has a Class II skeletal pattern with a large A-B discrepancy and a high mandibular plane angle, hinging the mandible open via posterior eruption would worsen the antero-posterior relationship of the apical bases.16

How the deep overbite is to be corrected should be determined by proper treatment planning and not by the indiscriminate use of mechanics, without regard for occlusal plane, anterior esthetics, lip competence, or anteroposterior discrepancy.16

“Intrusion may be defined as the process of changing the relation of a tooth to the surrounding by causing retrusion into the alveolus.” Lefkowitz and Waugh, in 1945, proved that intrusion was possible in canines, and that continuous stresses were better tolerated by the periodontium than intermittent stresses.18 Dellinger, in 1967, determined that intrusion by orthodontic procedures can be demonstrated only if certain variables are controlled:

1) The tooth that is said to be depressed must actually show a measurable amount of depression in reference to a stable extraoral site that will not be affected by the ever-changing oral environment.

2) The orthodontic force that is said to produce the intrusion must be of a measured magnitude and direction.

3) Histologic material that indicates intrusion of the root into the alveolus must be presented.19

Prior to the report by Dellinger, apparent incisor intrusion was explained by orthodontists who believed that intrusion was by root resorption and relative intrusion, with posterior extrusion.
In 1977, Burstone defined intrusion as the apical movement of the geometric center of the root (centroid) in respect to the occlusal plane or a plane based on the long axis of the tooth. The center of resistance of a tooth is dependent on the root length and morphology, the number of roots, and the level of alveolar bone support. The exact location of the center of resistance for a tooth is not easily identified. Analytical studies have determined that the center of resistance for single-rooted teeth with normal alveolar bone levels is about one-fourth to one-third the distance from the cementoenamel junction (CEJ) to the root apex. Experimental and analytical studies report the center of resistance for intrusive movements of maxillary anterior teeth can be found distal to the lateral incisors. A recent study by Matsui et al reviewed the previous literature and provided a new anterior segment center of resistance (CR). The CR of the maxillary anterior segment was reported on the mid-sagittal plane, approximately 6mm apical and 4mm posterior to a line perpendicular to the occlusal plane from the labial alveolar crest of the central incisor. This new CR lies approximately mesial to the lateral incisor root, and halfway between the CEJ and the root apex, which is considerably more mesial than the conventional theory. In relation to this “new” CR, the Vanden Bulcke et al CR is slightly more coronal and at the distal of the canine. Pederson et al in a study on human autopsy material found a CR that was close to the Vanden Bulcke et al, but slightly more mesial. The presentation of these three different centers of resistance can be differentiated by technique (Laser holography vs. photoelastic technique) and the preparation of the model used (photoelastic model vs. macerated dry skull vs. human autopsy material). There appears to be a discrepancy between the models that utilized biologic specimens and those based purely on mechanical models. Thus in the
photoelastic and laser holography studies, a major flaw exists because the periodontal ligament is absent in these two techniques. The absence of a periodontal ligament removes the anisotropic nature of the ligament itself and the biology of the tooth-ligament-bone interface. The other factors that alter the position and accuracy of finding the center of resistance are the shape of the surrounding bone, root morphology, position of each tooth, and structure of the periodontal attachment.

By producing forces which do not pass through the center of resistance moments are created and induce flaring or uprighting of the incisors. Labial tipping of an incisor around its centroid produces pseudo-intrusion, or relative intrusion. Although this pseudo-intrusion would help to correct a deep overbite, it should not be confused with genuine or true intrusion. Therefore, incisal edges should not be used to evaluate intrusion, since they are easily affected by tipping movements of the incisor. Ideally, a point should be selected in the center of the root (centroid) and comparison should be based upon the movement of this point.\(^1\) Other investigators (Engel, Castaldo, Barton, Carlyle, Otto et al) have also recognized that tipping changes influence incisor vertical height have not yet devised a method to account for the interaction of these variables.\(^{24}\)

**Clinical Techniques for Intrusion**

Case, Burstone, Ricketts and Begg propose arch leveling with respect to the dental deep bite and soft tissue esthetics during treatment. Calvin Case, in 1921, presented a chapter in his book on the ability to treat closed bites through a new modification to the ribbon arch appliance that was in use in the early part of this century. Case had earlier presented a removable bite plane that seemed to allow posterior extrusion of the teeth, therefore opening the bite. After several years Case introduced the
fixed appliance due to reluctance of patients to cooperate while wearing the removable bite plane. A rigid posterior fixture with crowns that were intentionally above the occlusal plane to open the posterior bite. The wire that was placed had a reverse curve of spee, which intruded the anterior teeth and extruded the premolar teeth into the freeway space that was created by the posterior crowns.2

In 1956, Begg introduced a technique for the application of optimum forces for tooth movement by using a single round (0.016 inch) stainless steel arch wire. A student of Angle, Begg made adjustments to the original ribbon arch which was the appliance of choice prior to the evolution of the edgewise bracket developed by Angle in 1928. Begg incorporated tip-back bends into the continuous archwires that were used in order to progress into the stages of treatment. The light-wire appliance employed by Begg applying intermaxillary elastics to tip teeth into position. One of the principle stages in Begg treatment is to proceed to an edge-to-edge bite (0 OJ and 0 OB). Bite opening is accomplished with the tip-back bends placed mesial to the molars which intrudes the maxillary and mandibular incisors as they are retracted with intermaxillary elastics in a Class II vector. It was believed that light elastic force would insure that anterior six teeth would move back before the posterior teeth move forward by the natural process of mesial migration. The light, tipping forces, which cause rapid apical movement of maxillary and mandibular incisors, causes the reduction of deep anterior open bite.25

Burstone considered the natural plane of occlusion, anterior esthetics, amount of attached gingiva in the mandibular incisors and A-B discrepancy when determining whether to level by intrusion or extrusion.1 The intrusive appliance created by Burstone is an integral part of the segmental arch technique, described by Burstone, in the early
1960's. The basic mechanism for intrusion consists of a posterior anchorage unit, an anterior segment, and an intrusive arch spring. The posterior anchorage unit is joined together with a buccal stabilizing segment, which includes the first and second molars and the premolars. Right and left posterior segments are joined together across the arch by means of a transpalatal lingual arch in the maxilla and a lower lingual arch in the mandible. The anterior alignment arch or anterior segment is placed into the brackets of the central incisors or the four incisors and the intrusive arch is tied either labially, incisally, or gingivally to that wire. The intrusive arch as described consisted of a 0.018 by 0.022 inch or 0.018 by 0.025-inch stainless steel edgewise wire with a 3-mm helix wound two and a one half times placed mesial to the auxiliary tube. Curvature or a tip back bend is placed in the intrusive arch, so that the incisal portion lies gingival to the central incisors. When the arch is tied to the level of the incisors, an intrusive force is developed. (Figure 1) In order that the arch does not increase its length during the activation, a gentle curvature should be placed with the amount of curvature increasing as one approach the helix. In this way the activated arch wire will appear relatively straight, and as it works out during intrusion. This will limit anterior flaring. The intrusion of anterior teeth during treatment as Burstone proposed it should be part of the entire treatment plan for each individual patient. Burstone recommends six principles, which must be considered in incisor or canine intrusion:

1) the use of optimal magnitudes of force and delivery of this force constantly with low load-deflection springs;

2) the use of a single point contact in the anterior region;
3) the careful selection of the point of force application with respect to the center of resistance of the teeth to be intruded;

4) selective intrusion based on anterior tooth geometry;

5) control over the reactive units by formation of a posterior anchorage unit

6) inhibition of eruption of the posterior teeth and avoidance of undesirable eruptive or tip back mechanics.

As seen in Figure 1 an intrusive force is applied to the anterior teeth, with an extrusive force, which is equal and opposite of the intrusive force, is applied at the molar. As a result of static equilibrium, a moment is created at the molar causing a distal crown tipping and mesial root movement of the posterior segment. Dependent on the reactive unit, the extrusive force can be minimized with a high pull headgear is recommended to counteract the tip-back moment.¹

Ricketts also proposed an arch leveling device around the same time as Burstone with the advent of his Bioprogressive therapy. The utility arch was fabricated out of 0.016 by 0.016 inch blue Elgiloy. It is tied into the incisor brackets while 15-20° of buccal root torque is bent into the anterior segment to move the roots from the lingual cortical plate into medullary bone. Cortical bone is used to brace the posterior teeth because it is denser than medullary bone and has less blood supply. The method of arch leveling is determined by facial height and incisor display. Convergent occlusal planes and deep bite should be corrected by incisor intrusion rather than posterior eruption. The utility arch can be modified with bends for molar rotation, molar tip back, buccal root torque and buccal expansion.⁴, ²⁶
Previous to archwire leveling techniques, bite plates and splints were used to open the bite. In a study of six patients, Carlsson\textsuperscript{27} investigated the effect of a temporary increase in the vertical dimension of occlusion by inserting splints and increasing the vertical dimension beyond the original rest face height. He concluded that a moderate increase in the vertical dimension did not seem to be a hazardous procedure, provided that occlusal stability was established. Hans et al\textsuperscript{24} presented a study to compare the correction of excessive overbite achieved using cervical pull headgear and tandem mechanics to the changes in overbite achieved using a bionator-type appliance. This cephalometric study found that both types of mechanics successfully corrected the pretreatment condition of deep overbite. Fixed appliances, by design, were more efficient in moving teeth and in this study provided twice as much vertical change in overbite than removable functional appliances. Vertical growth inhibition seemed to be the mechanism by which the bionator/orthopedic corrector produced about half of its net effect, while also increasing mandibular skeletal height, with a large increase in the mandibular plane angle.\textsuperscript{24}

While bite planes and splints are currently in use today, fixed appliances are preferred to be a more efficient modality to induce bite opening. A clinical and cephalometric evaluation, which compared a continuous arch wire technique and the segmental arch wire, proposed by Burstone, was published in 1996. With a continuous arch wire technique, overbite reduction will be due mainly to extrusion of molars or premolars and some intrusion and flaring of the incisors. Incisor intrusion with little extrusive movement in the molar area, however, is found with the segmented arch technique as recommended by Burstone. The application of a segmented arch intrusion
technique, rather than using continuous wires, therefore is indicated if correction of deep overbite is indicated due to the treatment goals dictated by the patient problems.\textsuperscript{28}

In 1995, an \textit{ex vivo} study measured the intrusive forces exerted by a variety of standardized archwires and the premolar involvement on these forces. Begg and edgewise (Andrews Straight-Wire\textsuperscript{®}) attachments were placed on "phantom head jaws" representing the upper arch with plastic teeth. Round wire composed of 3 different types of nickel-titanium and seven different types of stainless steel were used to place the intrusive forces on the models. An Instron testing machine was used to measure the intrusive forces for all wire types and sizes. The authors noted that a direct comparison between Begg and Straight-Wire intrusive forces using initial archwires typical of the two techniques is unfair since other factors, such as intermaxillary traction forces complicate the situation in the patient. Increasing the archwire diameter increased the intrusive force, and the Begg archforms produced more force than the edgewise archforms of similar deflection when attached to molars only.\textsuperscript{29}

Clinical adaptations to allow the intrusion arch to reach its full potential have been demonstrated in recent (past 5 years) literature. Kalra\textsuperscript{30} presented a variation on the intrusion arch called the K-SIR (Kalra Simultaneous Intrusion and Retraction). The K-SIR incorporates a vertical closing loop that is placed distal to the center of the interbracket distance of the extraction space, which acts as an off-centered V-bend resulting in the horizontal effects of the closing loop and the vertical effects of an intrusion arch. Greenfield\textsuperscript{31}, in 1993, described a utility-type arch used for the simultaneous torquing and intrusion of the incisors. Greenfield used incisor root springs attached to the incisor brackets and the intrusion auxiliary, in order to cause the incisor
torque. Shroff and Lindauer have described a three-piece intrusion arch to effect simultaneous incisor retraction and intrusion.\textsuperscript{32, 33} Rajcich and Sadowsky\textsuperscript{34} used an intrusion auxiliary arch to increase the molar anchorage by increasing the posterior moment-to-force ratio. Differential moment mechanics nullify the concept of multiple teeth on the anchorage side to form large reactive units, with the belief that it is possible to control anchorage solely with intraarch bends without adjunctive appliances. Anchorage is obtained with off-centered v-bends, the bend closer to the molar on each side.\textsuperscript{34} The usefulness of these intrusion arches has been explained through the use of clinical examples.

**Archwire Selection**

Stainless Steel has been the classic material used in orthodontics since the change from the gold archwires used by Dr. Angle. In the 1980's, Burstone and Goldberg\textsuperscript{35} described beta-titanium archwires for orthodontic use. Stainless steel maintains its popularity due to its balance of environmental stability, stiffness, resilience, formability, and economics. Burstone listed the properties required in an orthodontic wire:

1. First, it should be possible for the wire to be deflected over long distances without permanent deformation; hence, large springback. This assures better control over tooth movement and minimizes adjustment intervals.

2. Second, the wire should have a stiffness that is lower than that of stainless steel, which would allow wires to fill the bracket for control and at the same time produce lighter forces.
Third, the wire should be highly formable, that is, capable of being easily shaped, bent, and formed into complicated configurations, such as loops, without fracture.

All three of these characteristics can be found in elgiloy, a cobalt-chromium-nickel alloy, and austenitic stainless steel. Elgiloy can be heat treated to obtain strength characteristics similar to stainless steel, but possesses excellent formability in its soft condition. Beta titanium, which has 11% molybdenum, 6% zirconium, and 4% tin, demonstrates an increase in deflection of 105% over steel without permanent deformation. Its stiffness makes it ideal in applications where less force than steel is required but where lower modulus materials would be inadequate to develop required force magnitudes. The formability of beta titanium is similar to that of stainless steel; however, the alloy cannot be bent over as sharp a radius as stainless steel. For a given cross-section, TMA can be deflected approximately twice as far as stainless steel without permanent deformation. The forces that are generated are approximately 0.4 times that of steel, producing gentler forces; for example an 0.018 by 0.025 inch wire in beta titanium delivers the same amount of force as an 0.014 by 0.020 inch steel wire. Nitinol is a stoichiometric nickel-titanium alloy with approximately 52 percent nickel, 45 percent titanium, and 3 percent cobalt. High springback characteristics allow nitinol to sustain large elastic deflections while delivering low forces. Heat treatment causes the alloy to have significant changes in mechanical properties and crystallographic arrangement that is responsible for the “memory” effect. Superelastic NiTi wires have shown 1.4 times the springback of nitinol wire and 4.6 times the springback of stainless steel wires. These wires have an unusual
nonlinear unloading curve that describes a constant force mechanism in the middle of deactivation, which allows for lighter forces over large deflections.\textsuperscript{36}

In 1998, Nanda et al\textsuperscript{37} described the Connecticut Intrusion Arch (CTA) which is fabricated from a nickel titanium alloy to provide the advantages of shape memory, springback, and light, continuous force distribution. Nickel titanium alloys are currently the materials of choice for delivering light, continuous forces under large activations.\textsuperscript{38, 39} The nickel-titanium wires were found to exert a lighter force for a given deflection than their stainless steel counterparts. This was due to the lower modulus of elasticity values of nickel-titanium compared to stainless steel.\textsuperscript{29} The CTA, by virtue of its nickel titanium composition, remains active at a constant force level for a long period of time.

\textbf{Periodontal Considerations}

Orthodontics is intimately related to periodontics since tooth movement requires a biological adaptation by the periodontium. The understanding of the periodontal structures (cementum, bone, and periodontal ligament) is essential to orthodontic tooth movement, intrusion included, and orthodontic tooth relapse. It is well known that when a tooth is moved bodily, bone resorption occurs on the pressure side and deposition occurs on the tension side. The tooth moved horizontally pushes against the gingival tissue on the pressure side without passing through it and pulls it on the tension side.\textsuperscript{40, 41} This is somewhat different than intrusive forces. In research on periodontal structures undergoing tooth intrusion in dog incisors, Bunch reported resorption of cementum at the apex of the root, and reorientation of the direction of periodontal fibers consistent with the induced intrusive force.\textsuperscript{42} This could be explained due to vascular differences in the
periodontal ligament at the apex and the coronal portions of the tooth as well as the differences in fibers (elastic (apical) vs. collagen). Zachrisson and Zachrisson measured the gingival pocket depth during treatment and retention in orthodontic patients treated with an edgewise appliance and found that pocket depth increased during treatment. They reported that the increase in pocket depth was caused by edematous swelling in the gingiva and by tissue accumulation during tooth movement, not by deepening of the gingival pocket.\textsuperscript{43} Ericsson and Thilander reported that when dogs' teeth were moved sagitally, junctional epithelium was always located at a more apical level of the test teeth than of the control teeth, contrary to the Zachrisson findings.\textsuperscript{44}

Murakami et al reported that the buccal gingiva, from the gingival margin to a tattoo mark, moved along with tooth intrusion at a rate of approximately 60% of the tooth movement. The gingival sulcus also deepened about 40% of the tooth intrusion. The position of the sulcus bottom moved in the apical direction with the tooth intrusion as much as the tooth was intruded, as long as the orthodontic force is applied vertically within biologic limits with good oral hygiene. The dentogingival and the dentoperiosteal fibers can separate from the cementum when the intrusion exceeds 3mm. This happens because not enough hyperplasia and/or extension of fibers catch up with the tooth intrusion. Thus, as long as the intrusion is less than 2mm, the dentoperiosteal and dentogingival fibers remain attached, but as the intrusion increased past 3mm the fibers were torn and separated from the cementum.\textsuperscript{45}

Melsen studied the reaction of the periodontal and gingival tissues to the intrusion of teeth and the effects of oral hygiene. Marginal bone levels after the intrusion period showed a marked difference between the amounts of resorption on the "hygiene" and the
“nonhygiene” sides. On the nonhygiene side (no tooth brushing) the resorption activity of the alveolar bone had included the marginal ridge, thus reducing the height of the alveolar ridge. On the hygiene side, resorption had involved only the periodontal ligament side of the bone, thereby reducing the height of the alveolus to a minor degree. Clearly, the effect of intrusion of teeth is highly related to the standard of oral hygiene. The distance from the epithelial junction to the gingival margin on the nonhygiene side was increased by two times that of the hygiene side. It was also shown in a continuation study that new connective tissue attachment can be formed during the intrusion of periodontally involved teeth if the gingival infection is eliminated and the root surfaces are scaled to a degree that makes it possible for a new cementum layer to form on the former infected root surface.

There have been studies that delve into the remodeling of the periodontal ligament during intrusive forces. Assumptions of the nature of the periodontal ligament (i.e. isotropic and elastic) limit their validity to general considerations. However, until further biologic models of the periodontal ligament are available the finite element model with these assumptions can be used.

**External Apical Root Resorption**

External apical root resorption (EARR) is the most commonly associated iatrogenic consequence of orthodontics. Root resorption occurs when the pressure on the cementum exceeds its reparative capacity and dentin is exposed, allowing multinucleated odontoclasts to degrade the root substance. Because cementum normally is more resistant than bone, forces applied to a tooth usually cause bone resorption rather than loss of cementum. However, forces are concentrated at the root apex during intrusion,
placing the narrow periapical region is placed in harm’s way.\textsuperscript{48} Ottolengui first reported a study of apical root loss as a result of orthodontic procedures in 1914.\textsuperscript{49} Early investigators\textsuperscript{50-52} of this phenomenon found maxillary incisors to be the teeth most susceptible to root resorption. It has not been firmly established whether this is because these are the teeth moved the farthest or because of the single-root, spindly cone-shape of the root. Oppenheim postulated that the shape of the roots of the anterior teeth (maxillary in particular) predisposed them to apical root loss.\textsuperscript{8} Additionally, it may be that incisors possess biochemical pathways different from other teeth that place them at risk, but there is no evidence of such a difference.\textsuperscript{48}

Another consideration that has been raised by Rygh\textsuperscript{53}, Sicher and Bhaskar\textsuperscript{54}, and Henry and Weinmann\textsuperscript{55}, is that resorption most often occurs at the apex. This is possibly due to tooth anatomy. The coronal third of a root is covered with acellular cementum, whereas the apical third is cellular and the middle third is intermediate. Cellular cementum forms more rapidly and is more active than acellular cementum, but cellular cementum depends on a patent vasculature; accordingly, periapical cementum is more friable and easily injured in the face of heavy forces and concomitant vascular stasis.\textsuperscript{48}

The intentional movement of teeth that is the backbone of orthodontic treatment typically produces some blunting of the root apices. In general, tooth types that are moved the farthest tend to show the most frequent and most severe EARR.\textsuperscript{56-60} In the study by Parker and Harris, specific directions of movement differentially enhance the extent of EARR, and the amount of EARR is a function of the amount of movement. In combination, intrusive movement and lingual root torque were the strongest predictors of EARR.\textsuperscript{56} Many authors have stated that intrusion is the most common tooth movement
that has been implicated as a possible cause of root resorption.\textsuperscript{56, 58, 61, 62} The tooth apex and associated periodontium can experience relatively high compression stresses when an intrusive force is applied to the crown.\textsuperscript{63} Intrusion damages the root apex because root shape concentrates pressure at the conical root tip.\textsuperscript{64} There is a positive correlation between the amount of resorption and the amount of intrusion.\textsuperscript{51, 59, 65, 66} Stenvik and Mjor found that apart from the size of the apical foramen, the magnitude of force was of utmost importance. Forces above 150 to 200 grams invariably resulted in stasis in the pulp vessels and teeth with completed apices exhibited more severe changes than teeth with incomplete apices.\textsuperscript{64}

Effects of intrusion are also evident on teeth besides the incisors. The extent of EARR on the roots of the maxillary molars used as anchorage has been studied, and the location and degree of resorption depends on the malocclusion.\textsuperscript{67} More resorption occurs on the distal molar root when the bite is opened. Anchorage bends mesial of the maxillary first molar intrude the anterior teeth, but they also compress the distal root of the molar into the socket. Dougherty\textsuperscript{68} and Sjolien and Zachrisson\textsuperscript{69, 70} also showed that where maximum anchorage was prepared, the greatest resorption occurred on the distal (intruded) root of the mandibular molars.

Several investigators have examined the relationship between intrusion of incisors and root resorption. Kaley and Phillips found a correlation of root resorption to maxillary incisor torque; maxillary incisors are 4.5 times more likely to have severe resorption if they undergo root torque. Kaley also stated that a patient is twenty times more likely to undergo severe root resorption of the maxillary incisors when the root apices are forced against the cortical plate. However, Kaley and Philips found that the amounts of
intrusion and extrusion were not significant factors in root resorption, and suggested that it may be beneficial to design tooth movements to avoid lingual plate approximation. 60

DeShields 59 and McFadden 71 looked at retrospective data of thirty-eight patients with deep bite, who were treated with utility arches to intrude incisors, and reported no significant correlation between resorption and the amount of intrusion. Goerigk et al. 72, in a prospective study, looked at thirty-one patients who were treated with an intrusion arch as described by Burstone. Lateral cephalograms and periapical radiographs were taken before and after the intrusion phase of treatment (mean of 4.3 months). The authors described an average intrusion of the maxillary incisors of 2.3mm and average amount of root resorption at the completion of treatment was 1.0mm. Dermaut and De Munck performed another study, which followed the Burstone intrusion regimen. 61 Treatment was followed for an average of 6.7 months and force levels were regulated at 25 g per tooth. Average intrusion was seen as 3.6mm and root resorption was seen as 18%. In the control group of 15 patients, no root resorption was seen. Costopoulos and Nanda 65 in an experimental study to develop a highly accurate technique for quantifying apical root resorption as well as investigate the relationship of intrusive force magnitude and duration and the extent of root resorption. A group of 17 experimental and 17 control patients were selected prospectively for intrusion therapy. The average amounts of root resorption for the experimental and control groups were found to differ by 0.4mm, which was statistically significant. Force levels in this study more closely followed the Gottlieb thesis 16, and remained approximately at 15g per tooth. It is unlikely, as stated in this study, that the small amount of root resorption (<1mm) presumably caused by intrusion has any clinical impact. Finally, O'Hea performed a prospective root resorption
study at the University of Connecticut. Root resorption was followed for the first year of orthodontic treatment with periapical radiographs at three-month intervals. Two groups of individuals are described by O’Hea, the first group is described as average with little or no significant (<2mm) of root resorption in the first six months, and the second group is described as rapid root resorption (>3mm) in the first six months. The rapid resorption group was a smaller subset of the entire experimental group, but the resorption was extreme in this group and treatment was suspended and reinitiated after a rest period.

**Esthetics**

The primary orthodontic treatment goal is to produce maximum stability together with a well-balanced functional occlusion. A second treatment objective is the balanced, esthetic smile. Of all the factors related to a balanced smile, two can be orthodontically controlled. The first factor is the position of the maxillary incisor, and the second factor is arch form. The most important factors relative to the improvement of the position of the maxillary incisor that can be monitored cephalometrically are: (1) reduction of the ANB difference (most important, through posterior movement of A point), (2) improvement of the maxillary incisor angulation, (3) intrusion of the maxillary incisor, (4) improvement of the mandibular incisor angulation, and (5) proper positioning of the maxillary and mandibular incisors to the A-Po plane. Janzen also described the “orthodontic look” which is characterized by a longer nose, a flattened upper lip, and a strong tendency to have excess gum tissue showing when smiling.

Ricketts described a soft tissue analysis that was concerned with lip balance and what he called the law of lip relation. As in Janzen’s paper, Ricketts wrote that lip and tongue function could be read from the cephalometric film. Ricketts acknowledged that
the teeth are influenced by the lips, or conversely, that the teeth influence the lips. The E plane, or esthetic plane, dictates the protrusion of the lips, since orthodontists and lay people object to lip protrusion beyond the E plane. The E plane defines the law of lip relationships: "In the normal caucasian person at maturity, the lips are contained within a line from the nose to the chin (E plane), the outlines of the lips are smooth in contour, the upper lip is slightly posterior to the lower lip when related to that line, and the mouth can be closed with no strain." Proportional lip length is a primary critical consideration in lip imbalances, and the upper incisors may need to be intruded to harmonize with the lip embrasure. Ricketts also presented vertical planes that would extend from the pupils and cheeks, which should contain the lips and nose on the frontal analysis of the patient photographs.

The majority of appraisals of facial esthetics has been limited to the lateral or profile view of the face, especially in the 1950's and 1960's, due to cephalometrics. Webster defines the smile as "a change of facial expression involving a brightening of the eyes, an upward curving of the corners of the mouth with no sound and less muscular distortion of the features than in a laugh that may express amusement, pleasure, tender affection, approval, restrained mirth, irony, derision, or any of various other emotions." Hulsey, in the one of the first studies to look at patients from the front, looked at two questions. The two questions were: (1) Are the smiles of orthodontically treated patients as attractive as those persons with "normal occlusion"? and (2) What relationship between the lips and teeth, if any exists, should the orthodontist consider in positioning the anterior teeth during orthodontic treatment? The answer to the first was that the mean rated smile scores of the orthodontically treated subjects were significantly poorer than
the mean rated smile scores of the subjects with “normal occlusion.” Hulsey suggested that positioning the anterior teeth in harmony with the upper border of the lower lip and careful attention to the midline relationships that exist between the denture and the surrounding soft tissue might enable the orthodontist to give his patients a more attractive smile. Five basic components of each smile were enumerated: (1) the smile line ratio, the congruency of the arc of curvature of the upper border of the lower lip and the arc of curvature of the incisal edges of the upper anterior teeth; (2) the smile symmetry ratio, whether or not the lips on each side of the smile midline were symmetrical with each other; (3) the buccal corridor ratio, the ratio of the width between the canine teeth to the width of the smile; (4) the height of the upper lip, determined by the relationship of the upper lip to the gingival margin of the upper central incisor; and (5) the curvature of the upper lip, whether or not the corners of the smile were above, even with, or below the midline of the upper lip.77

Peck and Peck78 review the evolution of orthodontic standards, which arose from Norman Kingsley, Edward Angle, Calvin Case, and Charles Tweed and into the new millennium. Edward Angle, who inherited the Kingsley ideal, utilized the Apollo Belvedere as the ideal of “beauty, balance, and harmony.” Calvin Case, in his most prominent of arguments with Angle, pleaded that the “standard of beauty should not be confined to a fixed idea of facial outlines of classical art shown in that of Apollo Belvedere, but it should be one which may at times be adjusted...to the different types of physiognomies which present for treatment.”2 As orthodontics moved into the post-World War II era, Charles Tweed, an Angle student, modified Angle’s diagnostic equation by linking facial esthetics to the need for extraction, which changed from the
strict nonextraction dogma of Angle. Tweed’s diagnostic discriminator was cephalometrics, and unfortunately Tweed retained the flat Apollo-like profile and designed his new cephalometric standards to fit this narrow esthetic model. As Tweed, Steiner, Downs, Ricketts, Burstone etc. moved forward with the “new” cephalometric analysis and continued to associate the profile with facial esthetics, and moved away from the frontal view of the patient. 78

Ricketts and Hulsey presented the first collections of facial guidelines for orthodontics in the 1960’s. The expansive growth in scholarly interest is evident in the publication record: 20 years ago, the scientific literature contained approximately five articles annually presenting research on physical attractiveness, including that of the face; now, the annual worldwide output on this subject is approximately 150 scientific publications. 79 Tjan and colleagues 80 described low, average, and high smile lines, attempting to answer some of Dr. Hulsey’s questions. They found that low smile lines (display less than 75% of maxillary incisor crown) were predominately a male characteristic by a two and a half to one ratio, and high smile lines (display a contiguous band of maxillary gingiva) were predominately a female characteristic by a two to one ratio. Peck and Peck found that the upper-lip smile line (or lip position on smiling, relative to the gingival margin of maxillary central incisors) was 1.5 mm higher in female subjects than in male subjects. The female sample averaged nearly a 1 mm gingival smile line, whereas the male group showed a low lip line tendency of nearly a millimeter. 78 Vig and Brundo 81 described a gradual drooping of lip position as an aging phenomenon; therefore, older adult samples in their study displayed progressively less maxillary incisor and more mandibular incisor than young groups. With the esthetic concerns of today,
intrusion of maxillary incisors should be carefully done due to the possible ramifications of "over-intrusion."

Clinical crown height and anterior vertical maxillary excess have been identified as factors in gingival smile lines. Peck et al described a moderate correlation ($r=0.38$) between the upper lip line at maximum smile and the incisor clinical crown height. This relation shows possible associations between high smile lines and short clinical crown height and low smile lines with longer clinical crowns. 82 Kokich et al 83 report that fractured, congenitally missing, or avulsed maxillary incisors can often jeopardize the esthetic appearance of the remaining anterior teeth. This unaesthetic appearance is related to the irregular clinical crown lengths of either the fractured teeth or those that have been substituted for the missing teeth. Kokich describes selectively matching the gingival heights of adjacent teeth by utilizing step bends to "intrude" or extrude the appropriate teeth for either restoration or reduction of the incisal edges. An alternative to intrusion and restoration of a fractured and supererupted incisor would be further extrusion, smoothing of the incisal edge, and a gingivectomy to correct the discrepancy in length. If the defect is greater than 2 mm and the tooth has supererupted, a gingivectomy might expose the cementum of the tooth.83

Kokich 83 provides straightwire mechanical solutions to a more difficult problem. To selectively intrude teeth as presented by Kokich an intrusion base arch is needed. By ligating the intrusion arch to the teeth that need intrusion to regain similar gingival margin heights, the individual teeth will be intruded. The biomechanics of the Kokich system suggest extrusion of the surrounding teeth to the level of the extruded tooth because continuous archwires cannot precisely or reliably intrude a tooth with a step-
bend. According to Burstone, a step bend will create the desired forces, but the accompanying countermoments that rotate the adjacent teeth are undesirable. 84

The move into the new millennium has brought forth a renewed focus on facial esthetics. The focus in many fashion magazines and advertising campaigns is the full esthetic smile with a display of 1-2 mm of gingiva in the female smile and a complete maxillary incisor in the male smile. Intrusion of maxillary incisors to control deep overbite is a mildly controversial topic in recent lectures at meetings. While the intrusion of maxillary incisors by utility arches and intrusion arches remains the mainstay of an orthodontist’s armamentarium, the consequent aging of the face and smile is at the heart of the dispute. By changing the lip-to-tooth ratio as identified by Vig and Brundo 81, the increased lip coverage of the maxillary incisors with age can be exaggerated. In patients with a normal to low gingival smile line (display less than a complete incisor on smile) intrusion of the maxillary incisors would amplify the already compromised gingival smile line and create an “aged” smile. When used in the appropriate patient, maxillary incisor intrusion can be helpful in the mild-moderate anterior vertical maxillary excess patient to alleviate the excessively “gummy” smile. The timing of treatment is also important for patients who are considered candidates for maxillary incisor intrusion. If intrusion is initiated prior to the complete eruption of the canines, overbite correction can be achieved and leveling of the canines and premolars will be achieved to the new level of the incisors, preventing separate canine intrusion.

Subtelny astutely commented that: “in many instances evaluations of facial esthetics seem to be singularly influenced by the individual orthodontist’s concept of a pleasing face.” 85 It is important as the profession moves forward that reliance upon the
patient’s smile, chief complaint, and profile be considered in the individualized treatment plan. As the profession moves into the new millennium, the influence of the human smile is very apparent in every day life and the matching of the lips and the smile line is of the utmost importance.

Therefore, in order to study the manner in which teeth move in relation to the applied qualitative force system, this research project was created. By utilizing a statically determinant force system, a cantilever, we can compare the expected tooth movements with actual tooth movements. Along with all of the techniques for the intrusion of teeth, rates and biologic response also can be measured from this study.
OBJECTIVES and RATIONALE

The effectiveness of the intrusion arch in providing bite opening has been well documented. The purpose of this study is to answer a different question: Does the dentition respond in a predictable way reflective of the mechanical stimulus? In other words, does the static force system exerted by the activation of the intrusion arch, manifest itself in a specific dental response? Or, are there some mitigating biological factors that promote one type of tooth displacement over another?

Burstone¹ has reported that the intrusion arch can be broken into two components: (1) An intrusive force on the anterior segment with a reciprocal extrusive force on the posterior segments and (2) A counterclockwise moment active on the posterior segments. The purpose of this experiment is to determine the response of the dentition to a qualitatively determinant force system under a single activation of an intrusion arch. A single activation allows the description of the horizontal, vertical, and angular responses to the stimulus while eliminating confounding treatment variables occurring from subsequent treatment. (Figure 1)

The question is whether the dental changes occurring under the stimulus of the intrusion arch represent the static response of the force system in equilibrium? By determining the movement along horizontal and vertical axes to known force levels for incisor and molar teeth, rates of movement can be determined. By utilizing two different force levels, root resorption as compared to force levels can be watched.

For the purposes of statistical analysis, our null hypothesis is:

\[ H_0: \text{The rate of tooth movement is independent of force magnitude.} \]
EXPERIMENTAL METHOD

Sample

Sixteen subjects meeting the inclusion criteria were recruited from the patient pool available to the University of Connecticut graduate orthodontic program. The mean age of the subjects at the start of observation was 13.1 years with a range of 10.7 to 25.8 years. Seven of the sixteen patients were female. To be included in the study, each subject needed to present with a deep overbite requiring maxillary incisor intrusion, no medical or dental contra-indications to orthodontic treatment and needed to be between 10 and 25 years of age. All patients had permanent maxillary incisors and first molars with adequate periodontal support. Subjects were excluded from participation, however, for the following reasons: (1) Estimated periodontal attachment loss exceeded 25% of root length; (2) Estimated root resorption or remaining root formation exceeded three millimeters; (3) Diagnosis of any systemic endocrine disorders, and: (4) Failure to provide oral and written consent to participation.

Appliance Therapy

All teeth were bonded with 0.022” by 0.028” pre-adjusted brackets (Roth or Nanda prescription). If necessary initial aligning of the four incisors was done, otherwise, a rectangular stainless steel or braided wire of minimum thickness 0.016” by 0.022” was placed in the four incisor brackets. Patients were randomly assigned to the light force or normal force groups in an alternating fashion.

For the normal force group, a one-piece intrusion base arch constructed of 0.017” by 0.025” β-titanium (CNA, Ortho-Organizers, San Marcos, CA) was fabricated. For the
light force group, 0.017” by 0.025” Nickel Titanium Connecticut Intrusion Arches (CTA, Ortho-Organizers, San Marcos, CA) was then ligated to the anterior segment and inserted into the molar tubes of the patients.

The \( \beta \)-titanium intrusion arches were fabricated by hand at chairside for each individual patient. They were all matched and measured to approximate between 60g and 80g of force at the incisors. The NiTi intrusion arches were measured to produce about 40g of force to the incisor segment. The observation period of 3 months was designed to allow the expression of the force system in a clinical situation.

**Recording Technique**

Immediately prior to, and after each observation period, standard lateral cephalograms were obtained. All radiographs were taken with the same cephalostat (B.F. Wehmer) which produces a 12% image magnification. In order to reduce error associated with landmark detection\(^{86}\), tooth positional locating devices (TPLDs), fabricated from sections of stainless steel wire (Ormco, Glendora, CA), were attached to the maxillary first molars and a single central incisor prior to film exposure. The TPLDs served the purpose of precisely locating the pre- and post-treatment cephalometric positions of the teeth. (Figure 3)

The TPLDs attached to the maxillary first molars were fashioned from three sections of wire. For each molar TPLD, two sections of 0.045” round wire were notched and welded to form a “t” configuration. The longer leg of the “t” extended 11 mm apically, as measured from the headgear tube. The cross of the “t” was inserted into the full dimension of the headgear tube of the molar attachment. The horizontal sections were designed to extend six millimeters mesial of the headgear tube. The mesial
extensions allowed for the welded attachment of “L” shaped sections of 0.0215” by 0.028” archwire. “Upside-down” and “right-side-up Ls” were attached to the right and left TPLDs, respectively, to form rectangular shapes when viewed from the buccal aspect. The “L” additions served two functions. First, they acted to support the integrity of the weld between the 0.045” round sections. Second, by welding asymmetric sections to the left and right molar TPLDs, the left and right molars were easily differentiated on the radiographs.

The incisor TPLDs were fashioned from a single section of 0.0215” by 0.028” wire to roughly represent an “L” shape. The short occlusal leg of the “L” engaged the bracket slot. Additionally, a small coronally oriented bend was placed at one end so that the TPLD could not be displaced mesiodistally through the bracket slot. The longer leg incorporated a two-millimeter helix at its apical terminus and extended 12 mm gingivally from the bracket slot. The plane of the helix was configured at a right angle to the bracket slot for the incisors. The rounded contours of the helices had the additional effect of providing more comfortable contours than a cut section. The anterior TPLDs were fixed to the brackets using conventional elastomeric o-rings. The molar TPLDs were fixed to the molar attachments with elastomeric chain extending from the attachment hook to the mesial extension of the TPLD.

In addition to using the anterior TPLD for positional identification of the incisor during intrusion, a periapical (PA) radiograph was taken of the central incisors to monitor root resorption. Following the findings of Costopoulos65, a TPLD with known length can be used as a reference to measure apical root resorption.
**Superimposition Method**

Once the time-point one and two radiograph records were collected at the end of the observation period the maxillary and cranial base structures were traced on acetate using 0.5 mm drafting pencils. All bilateral landmarks were bisected to average the images to the midsagittal plane. Functional occlusal planes as described by Johnston\(^87\) were traced from each film. The structures of the maxillae were then superimposed with the effort of ignoring dental changes. The superimposition technique was modeled after the structural method proposed by Bjork\(^88\) who reported on the suitability of superimposing serial tracing on the contours of the anterior surfaces of the zygomatic processes. While not as accurate as superimposing on implant reference markers, Nielsen\(^89\) suggests that Bjork's structural method is superior to a "best-fit" method which tends to underestimate normal vertical dental development by 30\% to 50\%. When the identification of anterior surface of the zygomatic process proved to be difficult, common endosteal trabecular details of the maxillae were included as proposed by Johnston.\(^87\) Additionally, since Bjork and Skieller have shown that the majority of maxillae rotate down and forward,\(^88\) the cranial base tracing was included to help eliminate gross rotational error. After superimposition, a mean functional occlusal plane (MFOP), as described by Johnston\(^87\), was chosen as a horizontal reference plane. At 90° to the MFOP, a vertical reference plane that intersected common posterior borders of the tracings of the two maxillae was drawn. From this coordinate system, dental changes were assessed. (Figure 3)
**Measurement Technique**

All tooth positions were represented by the traced image of the TPLDs. The occlusal termini of the TPLDs at the bracket slot were extended 90° to the MFOP. The resulting line segments (MFOP-perp, hereafter) were used to assess anteroposterior and vertical changes. Anteroposterior changes were measured as the positional differences between time-point one and two, MFOP-perps to the posterior vertical plane. Vertical changes were measured as the change in length of MFOP-perp between T1 and T2 films. Both anteroposterior and vertical change dimensions were measured as the change in inclination of the TPLD relative to the MFOP. A protractor graduated in 1° increments was used for angular changes.

**Data Handling**

All data was entered onto a spreadsheet (Microsoft Excel 98, Microsoft Corp., Redmond, WA) for recording and analysis. Descriptive statistics of means, standard deviations and ranges were computed for horizontal, vertical, and angular dental changes. Paired one-tail t-tests were used to test mean differences between intra-subject molar and incisor horizontal, vertical, and angular displacements. Alpha levels were set at 0.05; mean differences were considered significant at p<0.05.

**Measurement Error Method**

The error standard deviation between original and repeat measures of five randomly selected film series was determined using Dahlberg’s formula:

\[
SD_{\text{Error}} = \sqrt{\frac{\sum D^2}{2n}}
\]
RESULTS

Observation Period

On average, the subjects underwent observed maxillary incisor intrusion for an average of 103.2 days (S.D. = 43 days). Due to the clinical nature of the study the range was 77 to 258 days. The one patient with a 258 day time period disappeared from treatment and only had one adjustment in the time period assessed by the study. Most patients were held to a standard 3-month schedule with 2 visits between the T1 and T2 visits.

Measurement Error

The error standard deviations for the six repeated measurements from five randomly selected two-film series are represented in Table VI. These values approximate the precision of the measuring instruments in which the linear and angular measurements were calculated to the nearest 0.25-mm and 0.5°, respectively.

Incisor Movement

There were three different movements that were measured during this study. All measurements were normalized to a 103.2-day observational period in order to maintain consistency. On average, the incisors intruded 1.27 mm (S.D. = 0.86) with the normal force and 1.10 mm (S.D. = 1.05) with the light force. The patients treated with the β-titanium archwires experienced a range of intrusion of between 0 and 2.25 mm of intrusion, while the NiTi intrusion arches were responsible for 0 to 2.68 mm of intrusion.
during the observation period. The rate of intrusion for the normal force was 0.37 mm/month (S.D. = 0.25) and 0.32 mm/month (S.D. = 0.31). The range of intrusion per month for the normal force was between 0 mm and 0.73 mm per month and 0 mm and 0.78 mm per month with the NiTi arches.

The β-titanium intrusion arches produced −0.99 mm (S.D. = 2.04) of anteroposterior change, with the negative representing posterior movement. The NiTi arches created −1.10 mm (S.D. = 0.73) of incisal movement. Almost all of the patients involved in the study with both intrusion arches experienced retraction of the incisors. Only one individual in the light force system had anterior movement (0.28 mm), while three of the β-titanium intrusion arches caused between 0.43 mm and 1.68 mm of anterior movement. The range of anteroposterior movement for the β-titanium archwires was −4.30 mm to 1.84 mm, while the CTA arches created −1.97 mm to 0.28 mm. The rate of horizontal movement for the incisors was seen as −0.29 mm per month (S.D. = 0.59) for the β-titanium intrusion arches and −0.32 mm per month (S.D. = 0.21) with the CTA. As much as −1.28 mm per month of posterior movement was seen in one patient with the β-titanium arch, 0.54 mm per month of anterior movement was also seen. The CTA created a range of −0.57 to 0.08 mm per month of anteroposterior movement.

Incisor flaring was seen in both intrusion arches; 1.56° (S.D. = 7.03) was seen with the β-titanium intrusion arches and 3.26° (S.D. = 6.39) with the NiTi arches. The range of incisor proclination for the normal force system was −5.64° to 15.36°, while the CTA created between −5.36° to 12.28°. More than half (5 out of 9) patients had uprighting of the incisors during the observation period with the β-titanium intrusion
arch, while only two subjects with the CTA had incisor uprighting. The rate of proclination for the \( \beta \)-titanium was 0.45° (S.D. = 2.04) per month, while the CTA had 0.95° (S.D. = 1.86) per month. There was a wide distribution for the rates of proclination for each of the intrusion arches: -1.64° to 4.46° with the \( \beta \)-titanium archwires and -1.56° to 3.57° with the CTA.

**Molar Movement**

A similar amount of molar extrusion was seen under both test designs: -1.11 mm (S.D. = 2.22) with the \( \beta \)-titanium intrusion arches and -1.10 mm (S.D. = 1.42). This also was seen in the rate of vertical movement with the \( \beta \)-titanium intrusion arch moving the molar at -0.32 mm (S.D. = 0.65) per month and the CTA at -0.32 mm (S.D. = 0.41). A wide range of variation was seen with the \( \beta \)-titanium intrusion arches in terms of molar extrusion (-5.36 mm to 1.58mm); one-third of the patients (3 out of 9) had slight molar intrusion. Similar to the \( \beta \)-titanium, results the CTA had one patient that moved in a superior direction (1.20 mm), but six out of the seven patients had molar extrusion or no movement at all.

The horizontal movement of the molars is slightly more consistent than the vertical movement results. Only one patient with either intrusion arch had anterior movement of the molar (2.11-mm), while all others had distalization of the maxillary molars: -1.67 mm (S.D. = 1.66) with the \( \beta \)-titanium and -0.55 mm (S.D. = 0.50) with the NiTi. There was a range of -0.87 mm to -3.38-mm of posterior molar movement with the \( \beta \)-titanium wire excluding the one patient with 2.11 mm of anterior movement and between 0 mm and -1.38 mm with the NiTi archwire. The rate of distal movement for
the β-titanium wire was –0.49 mm (S.D. = 0.48) per month, while NiTi had a rate of –0.16 mm (S.D. = 0.14) per month.

The axial inclination of the molars was also fairly consistent, with one patient in each group showing an uprighting of the molar. The β-titanium intrusion arches provided 9.09° (S.D. = 9.79) of distal crown tipping, while the CTA created 4.77° (S.D. = 5.30) of distal crown tip. Other than the one patient that had mesial crown tipping (-5.05°) with the β-titanium wire, 1.58° to 25.46° of distal crown tip was observed. In the same respect, 0° to 10.40° of distal crown tip was seen with the CTA, except for the one patient that had –3.16° of mesial crown tip. Also, the rate of distal crown tipping was almost double for the β-titanium intrusion arches than that of the CTAs: 2.64° (S.D. = 2.85) vs. 1.39° (S.D. = 1.54).

**Root Resorption**

Root resorption of the central incisors was measured using a ratio between the actual length of the TPLD and the radiographic length of the TPLD and comparing it to the entire length of the tooth. This allowed a negation of the radiographic magnification that occurred with the periapical radiographs. The T₁ and T₂ total tooth lengths were compared utilizing this comparative ratio with the TPLD acting as our standard. Only 12 of the 16 patients were accepted for this segment of the research protocol due to communication and radiographic errors. 3 patients had panoramic radiographs, while the fourth patient did not have a periapical taken at T₁ effectively limiting our already small sample.
An average of $-0.29$ mm ($\pm 1.35$ mm) of root resorption was noted. This negative number indicates an increase in root length along the average. The range of root resorption that was discovered by our methods was: $-2.79$ mm to $1.93$ mm.
DISCUSSION

Biologic Response and Optimum Forces

The purpose of this study was to examine the response of tooth movement to two different stimuli. Following the work of Quinn and Yoshikawa, this study attempted to mimic the dose (stimulus)-response model that is the standard of the medical literature. Quinn and Yoshikawa outlined four different possibilities for tooth movement. According to their review of the literature, the prevailing opinion is that the relationship of the rate of movement and stress magnitude is linear until the stress level is maximized. At this maximal stress level, increasing stress no longer alters the rate of tooth movement. This hypothesis is relevant especially when coupled with the biological system that governs tooth movement. The removal of tissue from areas of compression is cell-mediated and it is reasonable to suppose that the resorptive process has a maximum rate dependent on the number of cells participating as well as their resorptive capacity. As a tooth undergoes a tipping movement, the stress pattern varies along the length of the root. High compressive stresses are generated near the cervical region and at the apex on the opposite side of the root, while stresses become zero near the middle of the root. This stress pattern correlates well with the observed movement of the tooth. In other words, a simple force applied to the crown of a tooth produces a gradation of stress in the periodontal ligament. It is this difference in stress magnitude along the length of the root that allows the tooth to move greater distances at the cervix and apex than at midroot. The biologic response in tooth movement is dependent on the magnitude of the
mechanical stimulus (stress). As was seen in this study, the rate of movement was not different from the two force levels, except for the tipping movements.

**Biomechanics of Force Magnitude**

Along with the study by Gottlieb\(^{16}\), the range of force for the intrusion of four incisors can be interpreted as a range from 38-90 grams of force, since Gottlieb found no difference between 60g and 90g of force. This study deviates from the Gottlieb study in the manner of control of the force system. A comparison of the rates of movement bears this out. Gottlieb reports a 0.68 mm/month intrusion for his sample of ten patients with no headgear. Our study shows a 0.37 mm/month intrusion rate. There are some important differences in these two studies with regards to force control. Gottlieb had two groups of individuals in his 15 patient sample; one that was assigned a headgear (5 patients) and the second that wore no headgear. In order to control the angulation of the molar, Gottlieb et al used a combination of 0.036 passive trans-palatal arches (TPA), buccal segments (which included at least the premolars and sometime the canines), and headgear. These auxiliaries allowed for the control of the molar angulation and maintained the force levels transmitted to the incisors. The headgear group only saw a 0.41° change in the axial inclination of the molar, while the non-headgear group displayed a 6.13° mean change in the molars. In this study an average change of 9.09°, was seen in the molar axial inclination with a similar amount of force, while only 4.77° was seen with the light force level. Our study did not include the buccal segments, the TPA's, and/or headgears to evaluate the total changes in the molars and incisors over the length of the study design.
By allowing the molars to tip uncontrolled, a geometry problem develops that can affect the amounts of movement of the teeth. Since the angle of the intrusion arch is stable, as the molar tips distally, the level of force on the incisors is lessened (i.e. if the original activation was 10 millimeters above the incisal bracket molar tips back 5°, the activation will decrease to about 6 millimeters) (see Figure 4). This is very important especially when the level of force might dip below the threshold force to intrude the incisor. A moderate to high level of force, or control of the molar inclination, seems to be necessary especially as the force levels are decreased. Burstone 1 originally proposed a force level of 100g in order to intrude all four of the incisors. While this might seem excessive, if control over the axial inclination is not maintained, this force theoretically should stay above the threshold for intrusion of the incisors. Even this force level with a 5° distal crown tip of the molar, decreases the force level by 35% or 35g making the effective force 65g. Therefore, by not controlling the axial inclination, control over the force level is not maintained. The most dramatic effect of this can be seen when the total amounts of intrusion between the two studies are compared, Gottlieb saw an average intrusion of 2.3 mm while our study only produced 1.27 mm of intrusion with similar force levels and 1.10 mm with a lighter force. If the geometry is applied to the CTA, the 38g force coupled with the average 5° of distal crown tip decreases the force level to 25g of force (about 65% of the original level). The β-titanium force levels were measured at 70g and the average tipback was 9°, creating a force level of 31.5g (about 45% of the original force level). This change in the force levels is significant and can be monitored and maintained with the use of any or all of the auxiliaries listed above. 16 Gottlieb 16 describes adjusting the force levels to the prescribed level at intervening appointments,
presumably by altering the angle of the tip activation bend, thereby increasing the force level. This will also maintain the active intrusive force during the treatment period, but this clinical adjustment confounds the interpretation of the treatment response to the original stimulus.

The incisors are also affected by the changes in geometry and force levels. One major issue for the clinician is applying the force close enough to the center of resistance for the anterior segment to control the force levels. Vanden Bulcke et al determined that the center of resistance for intrusive movements of the maxillary anterior teeth could be found distal to the lateral incisors. All intrusive forces directed against the anterior teeth causes flaring of the incisors. Gottlieb used a stainless steel base arch with a helix at the molar tube. This helix performed a dual function. The first purpose of the helix was to decrease the load deflection rate of the wire by increasing its length. The second and more important role of the helix was to allow the clinician to tie back the intrusion arch to fix the length of the cantilever. This is similar to cinching back a wire to fix the arch length when leveling. Gottlieb found a 3.68° change in the axial inclination of the incisors, while our study found a 1.06° with similar force levels and cinched back arches. The CTA produced 4.57° with a lighter force, however these wires were not cinched back. This was done due to the material nature of NiTi. In order to form NiTi a phase transformation must be made in the wire. The most common way to create a phase transformation is to heat the archwire. The force levels might have been affected if the archwire is heated too close to the bend that was placed in the archwire during the manufacturing process. If a phase transformation occurs at the bend in the CTA, the force level will most likely be diminished, but this is an unknown hypothesis at this time.
In order to maintain a constant level, the CTA were untouched other than being shortened for patient comfort.

Another side effect of incisor intrusion is the equal and opposite vertical force that creates molar extrusion. Molar extrusion is also affected by the tipback moment on the molars. Gottlieb controlled for the extrusion with headgear (in some patients), buccal segments, and TPA’s and thus only saw 0.2 mm of extrusion. Our study did not have any secondary wires attached to the molar for either force level, and 0.86 mm for the β-titanium force system and 0.75 mm for the CTA force system. The extrusion of the maxillary molar can assist the clinician in bite opening, although this can be a negative side effect especially in a patient who needs vertical control. Pearson discussed the use of a vertical-pull chin cup to control the vertical extrusive forces caused by appliance therapy, especially in patients with backward rotational tendencies as defined by Bjork. Schudy stated that the maxilla is responsible for about 70% of total growth and therefore has an important effect on the “tilt” of the mandible. He reported that in the treated cases that were included in his study, the amount and distribution of vertical growth was different from that of the untreated cases. The growth of the anterior vertical height was found to have a correlation coefficient of 0.92 with the growth of total vertical height in the molar region. Levin concluded that the resolution of a deep bite in growing individuals would appear to be a biomechanical problem requiring not only an emphasis on incisor intrusion or molar eruption, but also the evaluation and management of rotational facial growth and resulting differential tooth eruption.

Arch leveling techniques are a major staple of orthodontic treatment. Each major treatment sequence has a different regimen for leveling the mandibular arch, and
reconciling overbite and anterior tooth-lip display. The description of the biomechanics of intrusion by Burstone\textsuperscript{1} allows the clinician to interpret the different force systems and their effects on the dentition. Weiland et al\textsuperscript{28} compared the arch leveling techniques between segmental treatment and continuous archwire treatment. The continuous arch group displayed increased molar extrusion (+1.63 mm vs. –0.14 mm) and decreased incisor intrusion (0.26 mm vs. 1.50 mm). These results compare to our results of 0.86 mm of extrusion for the β-titanium wire and 1.17 mm of incisor intrusion for the three month time period. Weiland et al\textsuperscript{28} followed the patients throughout treatment and evaluated the outcome of treatment, but not directly after the conclusion of anterior intrusion, which dilutes the outcomes due to leveling, and mid-treatment corrections to enhance the occlusion and esthetics of the case. The biomechanical approach to treatment planning should be utilized to determine what combination of incisor intrusion and molar extrusion would be most effective.

Root Resorption

The introduction of a complete analysis of the biologic response to orthodontic forces would be irresponsible if apical changes were not discussed. According to the results of this study, -0.29 mm of root resorption, or 0.29 mm of root elongation was observed. A major factor in this variation is that most patients were between the age of 10.7 to 14.6, with one patient over 25 years old. This is relevant because most of these subjects still had one to three years of root development remaining. By virtue of a “negative” average, one might assume that the intrusive forces during treatment did not hinder root development. Only four of the patients in this subsection actually
experienced some root blunting, three were in the β-Titanium group and only one was in the Nickel Titanium group. Two of these patients had more than 1.5 mm of root blunting (#4β-Ti and #7β-Ti). Unfortunately, our sample size was small for this type of correlation to make a useful contribution to the predictability of root resorption. Another shortcoming is that the standard error that is inherent in this method for our sample was tested and it is 1.22 mm which is almost larger than the standard deviation (1.35-mm) of our sample. Therefore, any meaningful correlations could not be discerned from these subjects, only that our measurements might not be accurate enough.

**Individual Variation**

Inherent in this study is the individual biological and biomechanical responses to similar stimuli. As Quinn and Yoshikawa describe, there is a linear force relationship (i.e. the heavier the force, the bigger the movement), until the biologic system reaches an equilibrium or maximal rate. Above this maximal rate, there will be no increase in rate of movement, no matter how high the force level becomes. There are three patients that had interesting individual variations that might be explained biomechanically, or biologically.

In the β-titanium group, there were two subjects that experienced no measurable intrusion, however they accounted for two of the largest recorded molar tipback changes. Large amounts of distal crown tipping and extrusion of the molar were seen with patient #5β-Ti. Uprighting of the incisor also occurred with this patient, leading to a belief that the entire system rotated in a clockwise fashion. Another possibility is that due to the geometry and rotation, the force level might pass below the threshold thereby decreasing the effectiveness of the intrusive force on the incisors. Trigonometric calculations suggest that a 17° axial change in the molar would negate the intrusive force felt by the
incisors. Therefore as the molar passes the 17° mark, an extrusive force system is placed on the anterior teeth. A 25° molar axial inclination would negate the intrusive gains made during the early phases of intrusion, and creating no change in the incisal position of this patient. Patient #9β-Ti had similar results except that an exaggerated amount of incisal flare occurred in this patient. This patient broke one side of the intrusion arch during treatment, and the incisal flare is likely a result of this uncontrolled situation during the observation period.

In the CTA (NiTi) intrusion group, there were two patients that experienced no measurable intrusion. Patient #2CTA experienced mild tipback, excessive flaring of the incisors and molar extrusion. As was noted previously, this group was highly affected by the combined geometric and biologic reactions to the force levels. With the lower force level, any decrease inherited by the geometry of the treatment, might move the force level below the threshold. Currently reported in the literature, 10-15g per tooth is commonly accepted for intrusion.94 Since the CTA only generates about 38g of force it is slightly below this recommendation initially, and will diminish subsequent to any distal crown tip. Patient #5CTA experienced mild molar tipping (4°) with no incisor intrusion, but incisal flaring was excessive (12°). The intrusion arch for this patient was most likely ligated anterior to the center of resistance for the anterior segment, exaggerating the incisal proclination. The patient with the most intrusion of the CTA group (#6CTA) had minimal molar movement. This is not easy to define in terms of geometry or biology, except for possible heavy occlusal forces to maintain molar position. This patient also had the most incisal uprighting (-5.36°) of all of the CTA patients. These individual variations in the sample are quite typical of a larger population in which certain aspects
of the intended treatment work as planned, and some do not. These patients will be observed over the course of the treatment and it is the job of the orthodontist to correctly make any adjustments to the treatment in order to produce the desired results.

**Sources of Error**

Clinical orthodontic outcome studies have inherent limitations. It is clear that cephalometric measurement has inherent errors due to magnification, projection, landmark identification\(^8^6\), and superimposition.\(^9^5\) The use of TPLDs is an attempt to enhance the precision and accuracy of identifying tooth position relative to treatment. Any changes in head orientation during radiograph exposure at the two time points, however, may have adversely effected the comparability of the two head films and acted as confounding error. Rotations in the coronal plane may reflect the range of horizontal changes (i.e. the one patient with mesial movement of his molars). A closer look might reveal a rotational error, especially due to the inconsistency of the movement of the molars with respect to the fifteen other subjects. A short time frame (100 days) should negate a significant growth variation that is seen in many long-term cephalometric studies. Magnification and projection errors were minimized because one cephalometer was used during this clinical trial.

Another limitation with a prospective clinical study is sample size. It would seem that when beginning a prospective study, a large number of patients would be relatively easy to locate, especially in a large university setting that starts about 300 patients per academic year. Unfortunately, recruiting patients for a prospective study is a difficult challenge. The variety of individual treatment needs and the multitude of technical
options offered in an academic setting combine to restrict the eligible patient pool. Small samples are a common occurrence in prospective clinical trials.

**Archwire Selection**

The comparisons that this study provides are relatively clear. With respects to archwire selection, this study describes similar, non-significant results, except with regards to force magnitude. The NiTi intrusion arches were calibrated at a lower force level than the β-titanium arch wires. The rates of tooth movements with respect to the incisors are comparable to the conventional biomechanical approach to treatment as proposed by Burstone in 1977. Molar movements are approximately the same, except for molar axial inclinations. The CTA produced half of the molar tipback during the observation period.

An interesting finding was patient #4CTA who disappeared for 258 days (8.6 months) between T₁ and T₂. This patient had twice the amount of tipback of any other CTA patient, and more total tipback than any patient with the β-titanium arch wire. The normalized data also shows that patient #4CTA had the highest molar tipback but minimal intrusion and increased incisor proclination. The increased time frame allowed the full expression of the force system. One would expect the intrusive forces for this patient to be increased due to the increased amount of time of continuous force levels. There are two reasons that this might not be true, geometry and material. The geometry side of the problem was discussed previously, but it is appropriate to continue the discussion at this time. As the molar tips back in this situation, the archwire exerts less force on the incisors due to the fixed nature of the angle of the bend. In this situation, the
molar had tipped back 26° total in 8.6 months, decreases the activation by about one-third the original activation force level. If the force level is 38g, as we have reported, the force level theoretically will be about 12.67g, probably well below the threshold to intrude four incisors. Now, these results by Gottlieb\textsuperscript{16} are extremely important, because these effects can be counteracted through the use of headgear, TPA, and/or buccal segments, to maintain continuous force levels.

The material side of this problem is whether or not the NiTi intrusion arch (CTA) is a truly superelastic nickel titanium alloy or a nitinol with a force decay rate. If under stress the CTA undergoes a phase transformation allowing a deformation of the bends placed into the wires during the manufacturing process, then the CTA could produce sub-threshold force systems. If the CTA is nitinol or martensitic NiTi it will have a decay rate that over time may decrease the force level to a sub-optimal level. If this decay rate were compounded with the geometry that was discussed previously, a light force that is well below any optimal threshold would be produced. β-Titanium intrusion arches have a load-deflection rate that is about half (0.4) that of steel\textsuperscript{35}, which allows a relatively constant delivery of force without helices. Nitinol has a stiffness that is about 25% that of stainless steel.\textsuperscript{96} The NiTi intrusion arches caused variable results, but material properties alone do not explain this; geometry is a major consideration.

**Clinical Significance**

“Once orthodontic treatment has begun, the orthodontist optimizes the chance for ultimate success by continuously making in-course corrections aimed at correcting the deviations between what was expected and what is, in fact, observed.”\textsuperscript{97} This study
allows the clinician to observe and interpret the results from many different angles. A number of different clinical decisions can be inferred from the results of this study. Some of them have been discussed previously in this section, but further amplification of these ideas and others are relevant to the clinical orthodontist.

In 1960, Stoner commented that "regardless of what appliance is being used, it is the application of the mechanics to move teeth without losing this control that permits the operator to obtain results." The maintenance of control over the observed effects of our appliances and force systems is an on-going process. As we have seen in this study, molar tipback and extrusion are effects that occur due to the qualitative force system applied to the teeth. One of the most interesting findings was associated with the geometric problem of delivering a constant force level. As described earlier, a 5° tipback rotation of the maxillary molar, with no change in the incisor position will create a 35% reduction in the original force level. If this distal tipping is associated with the 1 mm of intrusion that was seen on average with our subjects we now have more than a 50% reduction in the force levels. This is a significant reduction in original force levels.

There are several options for the clinician to choose from in order to counteract these effects. An occipital headgear with an outer bow above the center of resistance to the maxillary molar can counteract both the extrusion and tipback forces of the intrusion arch. As was seen in the individuals with the least amount of molar changes, the greatest amount of intrusion was also observed. Therefore, maintenance of the original configuration is paramount and an occipital headgear would be one option. A patient could wear the headgear in conjunction with the intrusion arch mechanics to further increase the possibility of Class II correction as well as the added benefit of maintaining
the axial inclination of the molars to facilitate intrusion. If the patient is in the late mixed
dentition or adult dentition, buccal segments may be utilized to increase the root surface
area. In either group of patients, adolescents or adults, a TPA might be constructed to
reinforce the molar position. All of these auxiliaries would also allow the orthodontist to
control the vertical forces created by this particular force system, therefore limiting
extrusive mechanics and its potential harmful effects.

The axial inclination of the incisors is a very important consideration for the
orthodontist during treatment planning. The CTA was found to induce almost twice the
flaring of the maxillary incisors. The main reason for this observation can be attributed
to our research plan. The β-titanium intrusion arches were cinched distal to the molar
tubes. In order to prevent mesial movement of the NiTi intrusion arches through the
molar tube, there are several methods:

(1) the Bendistal™ pliers created by Dr. Khouri create sharp bends in nickel
titanium archwires,

(2) creating a phase transformation by heating the wire with a flame,

(3) utilizing a crimpable hook mesial to the molar tube for a ligature tieback.

Due to the nature of our research variables, the area to be bent distal to the molar tube is
close to the intrusive bend in the NiTi archwire, and heat might create a change in the
original force levels. Although the other methods were available they were not utilized
during our clinical trial in order to simulate a situation similar to a private practice
scenario. Therefore, the NiTi intrusion arches were removed from the packaging, sized
to fit, and placed into the patient’s mouth.
An anterior segment was placed in every patient’s four incisors and ligated with either steel or elastic ligatures. The clinician can also control the amount of flaring by changing several variables in the anterior segment. The first variable is the point of force application. According to the literature, the center of resistance for the four incisors is approximately mesial to the lateral incisor root, and halfway between the CEJ and the root apex. The intrusion arch can be ligated in at least three different locations: the lateral incisor brackets (over the anterior segment), and at the midline. The midline ligation point can be included if the incisors are upright, but might be omitted if further incisor proclination is undesired. The second variable is the size and material of the anterior segmental wire. A round or undersized wire will allow an increase in flaring due to the point of force application. Furthermore, in a patient with severely upright incisors the orthodontist could choose to ligate directly into the anterior brackets to increase the flaring of the incisors. However, one should be careful because this does not only tip the anterior teeth, but will create lingual root torque as the intrusion force is expressed. This side effect is minimized through the use of the segment. A full sized wire (0.018” by 0.25” or bigger) will allow the orthodontist to control for this effect by allowing the pre-torqued bracket to express itself.
CONCLUSIONS

1.) The biomechanical force system as described by Burstone\textsuperscript{1} does produce the predicted tooth movement. However, individual patient variability inherent in each patient might actually be too large to accurately predict all of the tooth movements intentional, and otherwise. Individual patient difference is an integral part of the orthodontist’s treatment planning when initiating maxillary incisor intrusion.

2.) Geometry of the force description is a very important factor in the control of intrusive forces.

3.) Initial intrusive force levels should be at least 38g for the four incisors (9.5g per tooth), with no difference in the rate and gross movements at forces up to 70g of initial force (17.5g per tooth).

4.) Generally there is a steady rate of intrusion of 0.37 mm per month with no auxiliary appliances (headgear, TPA, and/or buccal segments).

5.) Distal crown tipping was almost twice the magnitude and rate for the higher force level produced by the $\beta$-titanium intrusion arches.

6.) No root resorption was detected at either force level.
Figure 1: Illustrative example of the biomechanics of an intrusion arch. Vertical force exhibited at the incisors is coupled with an extrusive force at the molars. For static equilibrium a clockwise (tipback) moment is generated in the posterior.
Figure #2: Force magnitude theories reviewed and proposed in Quinn and Yoshikawa. Hypothesis #1 represents a simple on/off switch. Hypothesis #2 represents a linear relationship that implies that the higher the force, the faster the tooth movement. Hypothesis #3 shows the research done by Storey and Smith, where they described a force threshold above which the rate of tooth movement would slow down. This was a basis for the differential force theory of anchorage control. Hypothesis #4 displays the current philosophy, a biological limit to the rate of tooth movement after an initial linear response.
Figure #3: Example of Measurement Method. The lighter occlusal plane was used as the horizontal (A-P) axis, while the dark vertical line near the Pterygomaxillary Fissure was used as the vertical axis. Axial changes were measured using the occlusal plane to marker angle. The lighter color shows the pre-treatment tooth position, while the darker color represents the post-treatment tooth movement.
Figure #4: Graphical representation of the geometric changes involved with intrusion arch treatment. The second figure shows a molar rotation of 5° and the resulting loss of activation for the incisor. Without any incisor movement approximately 40% of the original activation force is lost. 5° was the average rotation for the Nickel Titanium intrusion arch patients. If incisor intrusion had taken place, even 1 mm, the average for the study that would further reduce the force level by approximately 50% of the original force level.
Figure #5: Individual Intrusion of Incisors and Tipping of Molars for the $\beta$-Titanium group of subjects.
Figure #6: Individual Intrusion of Incisors and Tipping of Molars for the Nickel Titanium group of subjects.
Figure #7: Comparison of the Horizontal (A-P), Vertical, and Angular Measurements for the Incisors of the two groups of patients. None of these measurements was statistically significant.
Figure #8: Comparison of the Horizontal (A-P), Vertical, and Angular Measurements for the Incisors of the two groups of patients. The A-P movement was the only statistically significant (p<0.05) measurement. The angular change in the molar was nearly statistically significant. (p=0.14)
**Table I:** Data Summary for the Horizontal, Vertical and Angular changes for the β-
Titanium group.

<table>
<thead>
<tr>
<th>Patient #</th>
<th>(\Delta l_{\text{vert}}) (mm)</th>
<th>(\Delta l_{\text{horiz}}) (mm)</th>
<th>(\Delta l_{\angle}) (°)</th>
<th>(\Delta M_{\text{vert}}) (mm)</th>
<th>(\Delta M_{\text{horiz}}) (mm)</th>
<th>(\Delta M_{\angle}) (°)</th>
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</thead>
<tbody>
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<tr>
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<td>11</td>
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<tr>
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<tr>
<td>Std. Dev</td>
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<td>6.02</td>
<td>1.76</td>
<td>1.42</td>
<td>7.73</td>
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</table>
**Table I:** Data Summary for the Horizontal, Vertical and Angular changes for the Nickel Titanium group.

<table>
<thead>
<tr>
<th>Patient #</th>
<th>Δvert (mm)</th>
<th>Δhoriz (mm)</th>
<th>Δangle (°)</th>
<th>ΔMvert (mm)</th>
<th>ΔMhoriz (mm)</th>
<th>ΔMangle (°)</th>
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<td>2.5</td>
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</table>

Mean: 1.04 -1.25 4.57 -0.75 -0.71 6.93
Std. Dev.: 0.88 0.95 7.80 1.88 0.77 9.64
Table III: Data Summary for the time-averaged horizontal, vertical, and angular changes for the β-Titanium group. The average observation period was 103.2 days (± 43 days). By removing one patient whose treatment duration was 258 days (8.6 months), the average duration is 92 days. 92 days was thus used to calculate these figures.

<table>
<thead>
<tr>
<th>Patient #</th>
<th>Δvert (mm)</th>
<th>Δhoriz (mm)</th>
<th>Δangle (°)</th>
<th>ΔMvert (mm)</th>
<th>ΔMhoriz (mm)</th>
<th>ΔMangle (°)</th>
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<td>-1.07</td>
<td>-1.61</td>
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<td>0.00</td>
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<td>12.32</td>
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<tr>
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<td>-0.97</td>
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<td>7.93</td>
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<td>1.78</td>
<td>6.13</td>
<td>1.94</td>
<td>1.45</td>
<td>8.54</td>
</tr>
</tbody>
</table>
**Table III:** Data Summary for the time-averaged horizontal, vertical, and angular changes for the Nickel Titanium group. The average observation period was 103.2 days (± 43 days). By removing one patient whose treatment duration was 258 days (8.6 months), the average duration is 92 days. 92 days was thus used to calculate these figures.

<table>
<thead>
<tr>
<th>Patient #</th>
<th>ΔIvert (mm)</th>
<th>ΔIhoriz (mm)</th>
<th>ΔIangle (°)</th>
<th>ΔMvert (mm)</th>
<th>ΔMhoriz (mm)</th>
<th>ΔMangle (°)</th>
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<tr>
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<td>0.26</td>
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<td>5.49</td>
<td>1.05</td>
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<td>10.71</td>
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<td>-1.34</td>
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<td>2.68</td>
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<tr>
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<td>2.85</td>
<td>-0.96</td>
<td>-0.48</td>
<td>4.16</td>
</tr>
<tr>
<td>Std. Dev.</td>
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<td>0.64</td>
<td>5.58</td>
<td>1.24</td>
<td>0.43</td>
<td>4.62</td>
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</table>
Table V: Comparison of the monthly rate of tooth movement for the two groups.

<table>
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<tr>
<th></th>
<th>Δvert (mm)</th>
<th>Δhoriz (mm)</th>
<th>Δangle (°)</th>
<th>ΔMvert (mm)</th>
<th>ΔMhoriz (mm)</th>
<th>ΔMangle (°)</th>
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</thead>
<tbody>
<tr>
<td>β-Titanium</td>
<td>mean</td>
<td>0.37</td>
<td>-0.29</td>
<td>0.45</td>
<td>-0.32</td>
<td>-0.49*</td>
</tr>
<tr>
<td></td>
<td>std dev</td>
<td>0.25</td>
<td>0.59</td>
<td>2.04</td>
<td>0.65</td>
<td>0.48</td>
</tr>
<tr>
<td>NiTi</td>
<td>mean</td>
<td>0.32</td>
<td>-0.32</td>
<td>0.95</td>
<td>-0.32</td>
<td>-0.16*</td>
</tr>
<tr>
<td></td>
<td>std. Dev</td>
<td>0.31</td>
<td>0.21</td>
<td>1.86</td>
<td>0.41</td>
<td>0.14</td>
</tr>
</tbody>
</table>

* Denotes p<0.10
Table VI: Error standard deviation of repeated measurements. D = difference between original and repeat measurements made of randomly selected film series (n=5).

\[ SD_{\text{Error}} = \sqrt{\frac{\sum D^2}{2n}} \]

<table>
<thead>
<tr>
<th>( \Delta \text{vert (mm)} )</th>
<th>( \Delta \text{horiz (mm)} )</th>
<th>( \Delta \text{angle (°)} )</th>
<th>( \Delta \text{Mvert (mm)} )</th>
<th>( \Delta \text{Mhoriz (mm)} )</th>
<th>( \Delta \text{Mangle (°)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.31</td>
<td>0.47</td>
<td>1.67</td>
<td>0.39</td>
<td>0.34</td>
<td>1.70</td>
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</table>
Table VII: Calculations of Root Resorption during the observed time period and standard error deviations according to formula:

$$SD_{Error} = \sqrt{\frac{\sum D^2}{2n}}$$

<table>
<thead>
<tr>
<th>Patient #</th>
<th>TPLD Actual</th>
<th>Tooth Actual at T1</th>
<th>Tooth Actual at T2</th>
<th>Root Resorption</th>
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</thead>
<tbody>
<tr>
<td>6Beta-Ti</td>
<td>10.25</td>
<td>29.61</td>
<td>32.40</td>
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</tr>
<tr>
<td>2Beta-Ti</td>
<td>12.50</td>
<td>27.83</td>
<td>29.50</td>
<td>-1.67</td>
</tr>
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<td>4NiTi</td>
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<td>25.92</td>
<td>-1.00</td>
</tr>
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<td>25.00</td>
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<td>-0.93</td>
</tr>
<tr>
<td>2NiTi</td>
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<td>27.00</td>
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<tr>
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<tr>
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<tr>
<td>3Beta-Ti</td>
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</tr>
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<td>25.73</td>
<td>23.79</td>
<td>1.93</td>
</tr>
</tbody>
</table>

| Mean       | -0.29       |
| Std. Dev.  | 1.35        |
| Standard Error | 1.22        |
REFERENCES


