1981

A Strain Gauge Comparison of Torquing Forces Generated by Orthodontic Archwires

William R. Caryl Jr.
Loyola University Chicago

A STRAIN GAUGE COMPARISON OF TORQUING FORCES GENERATED BY ORTHODONTIC ARCHWIRES

by

William R. Caryl, Jr., D.D.S.

A Thesis Submitted to the Faculty of the Graduate School

of Loyola University in Partial Fulfillment

of the Requirements for the Degree of

Master of Science

April

1981

DEDICATION

To my wife, Debby, for her love, patience, support and understanding through this difficult period and throughout our life together.

ACKNOWLEDGEMENTS

I would like to thank the following people for their assistance in making this thesis:

James L. Sandrik, M.S., Ph.D. for the many hours he spent helping in the development of the thesis and for the intellectual stimulation he provided as my advisor.

Joseph Gowgiel, D.D.S., Ph.D. for his input and for his understanding, which aided in the completion of this thesis.

John Katsis, Jr., D.D.S., M.S. for his experience and advice, which were valuable in completing this investigation.

My parents for instilling the value and importance of education and for their continuing support.

VITA

William R. Caryl, Jr. was born on September 7, 1953 in Syracuse, New York, the son of William R. and Joyce D. Caryl.

His elementary education was received in the West Genesee School District and secondary education at West Genesee Sr. High School in Camillus, New York. He was awarded a Regents diploma and a New York Regents scholarship.

In 1971, he entered the State University of New York at Buffalo and obtained a Bachelor of Arts in Biology in 1975. In 1975 he was married to Deborah Susan Auerbach.

He entered the State University of New York at Buffalo School of Dentistry in August, 1975. The Doctor of Dental Surgery degree was obtained in June, 1979.

He began a residency program in orthodontics in July, 1979, at Loyola University of Chicago. Concurrently, he was accepted into the Oral Biology Department of the graduate school.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

CONTENTS FOR APPENDICES

INTRODUCTION

Torque is an essential aspect of orthodontic treatment to achieve a final result that is stable, functional and esthetic. The advent of pretorqued orthodontic appliances has helped to simplify this goal. A pre-torqued edgewise appliance was used in this study to observe the forces generated by pre-formed rectangular archwires.

A simulated maxillary dental arch was created by placing plastic teeth, with the orthodontic appliance attached to them, in a base of dental stone. The central incisors were positioned as they would be in a patient who required lingual movement of the roots, while all of the remaining teeth were placed so that a flat pre-formed arch would lie passively in the edgewise slot. Strain gauges placed on the lingual apsect of the central incisors' roots were then used to measure the microstrain caused by tying the arch wires into the brackets. The microstrain data were an indication of the forces produced by the different types and sizes of arch wires used.

The microstrain data were then compared for significant differences between each type of wire in a specific size and by each size within a wire type. The stainless steel, blue Elgiloy and yellow Elgiloy arch wires were also heat treated after the initial testing and then tied in again in the heat treated condition. This allowed a comparison to be made of the effects of heat treatment on the strain generated by the wires.

REVIEW OF LITERATURE

The review of literature includes information on the edgewise orthodontic appliance since it was used in the experiments conducted. Background information on similar or related studies was also provided. Some research on torquing force, as well as force in other orthodontic movements was written. To help put these data in proper perspective, research on the biological reactions in response to the forces of orthodontic appliances was presented. Although these experiments were done in vitro, the clinical and biological usefulness were the major considerations.

An introduction of the edgewise orthodontic appliance is important in understanding the appliance used in the experimental apparatus. The edgewise appliance was introduced by Edward H. Angle (1928, 1929 A, 1929 B, 1929 C). This appliance used brackets, soldered to bands, that had a rectangular slot cut in them to receive a rectangular archwire. The rectangular archwire was bent in such a way that when it was ligated into the bracket slot, the desired tooth movement would result. Angle (1929 B) explained that torque was affected by twisting a segment of the rectangular wire on itself to bring about movement of the root.

Ringenberg (1969) stated that the edgewise appliance had a desirable advantage in that dependable torque can be placed and delivered to the anterior teeth to prevent "rabbitting" of these teeth. Torque is considered to be one of the most important forces used in orthodontics according to Rauch (1959). He wrote that torque itself was the twisting of the rectangular edgewise wire and that torque force was the force generated by the wire on the bracket as it tried to untwist. When translation of a tooth was desired a simple force will cause tipping of the tooth about the center of rotation with the crown moving in one direction and the root in the opposite direction. The addition of torque using a rectangular wire moved the center of the rotation toward infinity resulting in a bodily movement of the tooth in one direction.

Sims (1972) concurred that torquing the maxillary central incisors in particular is too often overlooked. This aspect of treatment must be anticipated during the initial treatment planning and carried out faithfully. Long term stability of the finished orthodontic result is dependent on proper torque.

Orthodontic torquing auxiliaries may also be used to deliver torquing forces. They may be attached to a round arch wire (Hitchcock, 1970) or a rectangular arch wire (Perlow, 1973).

A recent concept that has evolved is that of placing the slot in the bracket to cause desired tooth movements when a wire bent only to form a smooth arch is placed in them. Andrews (1976) and Roth (1980) have assisted in promoting this new edgewise appliance. The amount of tip or angulation, torque and horizontal control desired have been decided by working with ideal occlusions. Since this appliance was introduced, other manufacturers have developed similar appliances with their own variations.

The forces involved in tooth movement have been studied by many investigators. Sved (1937) wrote that an orthodontist deflected the wire into the bracket through mechanical work. This resulted in potential energy that was stored in the wire when it was ligated in the bracket and this potential energy performed the work of tooth movement. With a round wire the resistance to bending increased to the third power of the increase in diameter, e.g., doubling the diameter required eight times the work to deflect the wire a given distance.

Sved (1937) used a 0.022 x 0.028 inch gold platinum rectangular arch wire in calculating forces involved with deflection of the wire. The forces were found to reverse direction at each consecutive attachment, moving away from the area of force application.

An apparatus was constructed by Brumfield (1937) to test the values calculated by Sved (1937). The apparatus consisted of knife-edged supports representing the brackets, which could be deflected a known amount. The forces involved could then be determined by hanging weights from the supports. The values of the forces observed experimentally were found to agree very closely with those calculated.

Sved (1952) carried his calculations further using the model of the arch wire as a continuous beam resting on free supports. The torque at any one support was split to each side of the support. A span ratio Q_n, and the transmission coefficient C_n, were calculated and used to find the stiffness index $R_n = Q_n\ (2-C_n)$. Then using the stiffness index the torque split was calculated $T_s = \dfrac{1}{\frac{1}{R_n} + \frac{1}{R_{(n+1)}}}$.

Sved (1952) also found that a deflection of 0.022 inch round wire 0.01 inch could produce a force of over one pound. If other teeth were also out of alignment, the forces produced were additive so that a force of 10 pounds or more could be produced.

Reitan (1957) wrote a paper on forces in orthodontics recommending light forces to avoid hyalinized areas of the periodontal ligament. With torque the greatest force was found at the alveolar margin and the force decreased toward the apex. The following equation determined the force at the apex, Q, when the forces on the bracket, P_1 and P_2, half the diagonal of the wire, D, and the length of the root, A, were known. $Q = \frac{(P_1 + p_2)\ D}{A}$. A Q value of 130 gms. would move the tooth without hyaline development.

A study of the reactive forces to a torquing force on the four maxillary incisors was performed by Schrody (1974). He found that the major force in the buccal segments was that of counter torque followed by intrusive and then lateral forces. The forces involved were large, ranging as high as 180 gms. at the canine with a 0.0215 x 0.028 inch wire. Schrody (1974) recommended using progressive torque to help reduce the force.

An acrylic maxilla and teeth were used in conjunction with strain gauges by Steyn (1977) to measure torquing forces created by a rectangular arch wire. The strain gauges were wired to a bridge box and a self balancing indicator. Pins were placed at 9 and 18 mm from the bracket slot to measure forces at both of these points. The 9 mm pin was to correspond to the alveolar crest, while the 18 mm pin was to represent the apical length. The strain gauges were attached to a second steel pin which would push against a pin on the tooth. The strain in this loading pin would be detected by the strain gauge.

Steyn (1977) found the following:

1. The force at the alveolar crest (9 mm pin) was twice that found at the apex (18 mm pin).
2. More force was generated at the lateral incisors than the central incisors.
3. The fewer the number of teeth, the greater the force on each individual tooth.

Burstone and Koenig (1974) maintained that very little was known about the forces utilized in orthodontics. They attributed this ignorance to be a cause of undesirable forces and, therefore, undesirable tooth movement. The idea of an ideal arch wire being placed and moving all teeth to an ideal position was valid only with large, stiff arch wires. The small, more resilient wires created a complex system of forces.

The forces produced when an arch wire was ligated into the brackets of the maxillary teeth, when the central incisors were lingually positioned, was studied by Steiner (1932). He wrote that initially the wire was passive in all brackets except the maxillary central incisors. The central incisors were pulled labially using the lateral incisors as fulcra, which then placed a labial force on the canines. As each tooth moved, the force translated distally until all of the stored energy in the arch wire had been dissipated.

The study of histologic reactions of teeth, bone, and soft tissue to orthodontic forces was an important issue.

This response, which was a biological response, was the final determinant for tooth movement. The amount of force necessary to effect tooth movement without causing necrosis or other pathology was the crux of research on this problem. Unfortunately, total agreement has not resulted among the various researchers.

Schwartz (1932) presented the results of Sandstedt (1904) who worked on maxillary incisors in dogs. Sandstedt described the histology of tooth movement and gave three conclusions:

1. On the side of tension, bone deposition occurs on the alveolar wall.
2. Resorption occurs when light pressure is applied against the alveolar wall.
3. When heavy forces are applied to a tooth undermining resorption occurs in the nearby marrow spaces. Schwartz (1932) agreed with the conclusions drawn by Sandstedt in research conducted on moving dog premolars using recurved finger springs. Four degrees of biologic effects were described. The first degree involved a force that was either very light or for a short duration so that no reaction was observed. A force that was sufficient to effect tooth movement, without causing necrosis of the periodontal ligament or alveolar bone or root resorption, was the second degree effect. In the third degree, some hemostasis in the periodontal ligament occurred with resulting necrosis. The liga-

ment returned to normal, but some root resorption, primarily of the cementum, resulted. The fourth degree involved very heavy forces that tore the periodontal ligament, caused periodontal necrosis and even caused the tooth to contact bone. The blood supply to the tooth was sometimes interrupted causing pulpal necrosis. Severe root resorption and ankylosis also resulted in the fourth degree reaction.

The edgewise appliance, utilizing a rectangular wire, generated forces well beyond the limits of physiologic forces, according to Moyers and Bauer (1950). Effective tooth movement was accomplished, but care had to be taken to avoid periodontal hemorrage.

Reitan (1964) conducted force magnitude and tooth movement studies in animals and humans. In the animal experiments some hyalinization of the periodontal ligament was observed along with direct bone resorption, especially in the apical area. Some root resorption also occurred. Bone deposition was seen on the periosteal surface. The above observations were seen with a continuous force of 200 gms. When the force was decreased to 70 gms., bone resorption still resulted, but with much less root resorption. When human premolars were torqued with a 50 gm. force for 30 days, small areas of root resorption repaired with cellular cementum were seen. Extensive direct bone resorption was seen even with this light force. Root resorption was found to be greater with continuous forces than with interrupted forces.

The maxillary central incisors of four monkeys were moved with lingual root torque by Ford (1970). Two of the monkeys had their incisors torqued for 25 days and two for 50 days with a continuous force of about 75-90 gms. Lateral cephalometric rediographs were used to demonstrate root movement. A histologic study showed osteoclastic activity on the lingual side and osteoblastic activity on the labial side. The animals whose incisors were torqued for 25 days showed some resorption of the cementum, while the incisors torqued for 50 days showed resorption of the cementum and dentine. This showed the importance of time as well as force magnitude.

Stoner (1960) talked of the "4 D's" of orthodontic force control: 1) Degree or intensity or magnitude of the force; 2) distribution - the force transmission to the root or alveolar process; 3) direction or plane of tooth movement; and 4) the duration or range of force activity. These four principles can be applied to any tooth movement situation in orthodontics.

Using a non-invasive technique of laser holography, Pryputniewicz and Burstone (1979) measured maxillary incisor movement when a force was applied from lingual to labial. Forces of 300 gms. and 500 gms. were used on three adult patients. A counterclockwise rotation was observed with the velocity of movement decreasing non-linearly with time. The center of rotation was found to be apical to the theoretical center of resistance. As the force applied to the tooth was increased, the center of rotation moved apically, if the moment to force ratio was constant and the same root geometry existed. The longer the root, the further apical the center of rotation was located.

Studies of forces used in canine retraction were done by Storey and Smith (1952) and Smith & Storey (1952). A fixed appliance with retraction springs was used. Light springs were in the range of 175-300 gms. and heavy springs ranged from 400-600 gms. It was found that rapid movement of the canine occurred with forces of 150-250 gms. in 12-15 year old children. This was considered to be the optimal force for canine retraction. Above this range, little movement of the canine was observed, while anchorage loss in the form of mesial movement of the molar was noted. This loss of anchorage was thought to be due to undermining resorption.

There are three biologic systems working with tooth movement, according to Storey (1973). The first system involved bioelastic effects. It consists of the interstitial fluid which acts as a lubricating film, the periodontal ligament fibers which can strangulate the small blood vessels and the viscoelastic properties of the periodontal ligament. The viscoelastic properties resist compression by heavy forces, yet allow compression with light continuous forces.

When force levels exceeded the bioelastic limit, the second system of bioplastic effects and tooth movement resulted. Movement occurred without the disruption of tissue. If forces were increased above the bioplastic range, the biodisruptive system was begun. Characteristics of biodisruption were ischemia, cell death, connective tissue inflammation and rupture. Repair began, however, with the termination of tooth movement.

Storey (1973) found that forces in the heavier range, i.e., over 35 gms./cm^2, caused inflammation of the periodontal tissues and slow tooth movement in experiments on guinea pigs. In addition to periodontal inflammation, bone strain is induced with heavy forces.

It was concluded that all evidence points to an optimum force range for tooth movement. Many variables were involved, including species, age, sex, hormones, diet. The multi-causal complexity of this problem precluded the assignment of a single force as being best. Instead, a range of forces was given for a tooth movement.

Nikolai (1975) also wrote in favor of an optimal force theory. He believed that optimal forces could be determined for a single tooth for tipping in a particular patient. This information could then be expanded to bodily movement of individual teeth and segments using root surface area. Very little has been written concerning the upper limit of the optimal range of tooth movement.

Nikolai (1975) believed that this was another area which needed further study.

A study was done by Andreasen and Johnson (1967) on maxillary molar distalization with eccentric head gear. Sixteen healthy females aged 8-10 years were the subjects of the study. It was observed that, on the average, more tooth movement resulted with a force of 400 gms. than with 200 gms.

Two torquing auxiliaries were compared by Mitchell and Kinder (1973) on a sample of nine patients aged 13-16 years. The forces generated were calculated by lifting the auxiliary off of the tooth surface with a spring tension gauge. The force was recorded just as the spring was observed to leave the tooth. The mean forces were 305 gms. with a wire auxiliary and 326 gms. using an elastic auxiliary. Both methods caused satisfactory torquing movement of the maxillary central incisors.

Integral parts of the orthodontic appliance are the arch wires. Round, rectangular and square wires have all been utilized to treat malocclusions with the edgewise appliance. The properties of the various materials that made up orthodontic wires have been studied. The properties were important to force production and tooth movement.

From basic physics, it is known that a force could start, stop or change the motion of an object.

In orthodontics, elastic wires are used to store and deliver forces. Jacobson (1966) wrote that elasticity was dependent on 1) the stiffness or load-deflection rate of the wire; 2) the allowable load on the wire and 3) the range of the wire.

Orthodontic appliances can store energy and deliver forces that vary in amount, direction, time, range and constancy, according to Steiner (1953). The materials and design of the appliance determine these properties. Ideally, to deliver uniform forces to each tooth, a wire would have to be used that was smaller for smaller teeth and largest at the molars. Instead, a compromise wire of a constant cross-sectional area was used for convenience.

Steiner (1953) tested different shaped wires with equal cross-sectional areas. It was found that a rectangular wire loaded on its narrow side was most resistant to deformation for a given load and least resistant when loaded on its wide aspect. The round wire followed the narrow side of the rectangular wire in resistance to deformation, with the square wire next.

Thurow (1972) defined stiffness as a resistance to bending. Deflection follows Hooke's Law, i.e., deflection was proportional to load, within certain limits, for a given wire. Ideally, a wire with a constant force delivery throughout its working range was desired, but this didn't agree with Hooke's Law and didn't exist.

A compromise was desired where force variation was as small as possible throughout the working range.

Stiffness is affected by the length, the cross-sectional area and the material. In round wires stiffness is inversely proportional to the length to the third power. With square wires, stiffness is directly proportional to an increase in breadth and proportional to the third power of the depth. Stiffness is also directly proportional to Young's modulus.

The range of activation was the area of elastic deformation below the elastic limit. The wire can be deflected this amount without plastic deformation or a permanent set. Any permanent deformation obviously resulted in inefficient tooth movement. The allowable load was that load just below the elastic limit of the wire, i.e., a force that will not cause plastic deformation.

Austenitic stainless steel (18-8) was first used in orthodontics as hard drawn wires around 1929. Stainless steel has three desirable qualities for orthodontic use: 1) High strength; 2) a high modulus of elasticity; 3) a resistance to intraoral corrosion.

The composition of 18-8 austenitic stainless steel is 18% Cr, 8% Ni and 0.2% C with other trace elements, and iron. The stability of 18-8 stainless steel is thought to be due to a film of a hydrous oxide which was stabilized by Cr.

The crystal structures of the wires used in orthodontics are mostly face centered or body centered cubic. Small impurities act as centers of crystallization. The faster the metal is cooled, the greater the number of nuclei and, therefore, the smaller the grain sizes.

Kohl (1964) wrote that the crystal lattice structure was deformed when the wire was stressed. If the stress was high enough, the crystals shifted along a slip plane with permanent deformation as a result. A fine grained wire was more resistant to permanent deformation or was stronger due to a higher number of grain boundaries. Tensile strength and elasticity were also increased.

Austenitic stainless steel, when annealed, had grains which were basically equiaxed according to Wilkinson (1962). Tensile strength, proportional limit and hardness can be improved by cold working (Wilkinson, 1962; Kohl, 1964). Smaller crystal size aids the cold working process. Recrystallization, by heating and then cooling, would increase the number of crystals to further increase these properties.

The proportional limit was the point where elastic deformation ceased and plastic deformation began. Wilkinson (1962) wrote that this was the major property influencing the resilience of a wire. The resilience was a measure of the ability to store energy in a wire. The modulus of resiliency, $R = \frac{P^2}{2E}$, where P = proportional limit, E = the modulus of elasticity.

The composition of Elgiloy wires is Co - 40%, Cr - 20%, Ni - 15%, Mo - 7%, Mn - 2%, C - 0.15%, Be - 0.04%, Fe - 15.81%. Kohl (1964) wrote that most properties were similar to stainless steel, but greater changes in resiliency were reported with heat treatment. Elgiloy was very ductile prior to heat treatment, which was done at 900° F. for ten minutes. Nitinol was developed in the 1960's by William F. Buehler at the Naval Ordnance Laboratory in Maryland. The name comes from Ni for nickel, Ti for titanium and NOL for Naval Ordnance Laboratory. It was an alloy of Ni and Ti which has a "shape memory". The shape memory was a property where the plastically deformed wire returned to its original shape when it was heated through a temperature transition range (Andreasen, 1978).

The main use for Nitinol in orthodontics is based on the very high resiliency of the alloy when compared to either stainless steel or Elgiloy. This allows a greater deformation of the Nitinol wire before a permanent set occurs.

Another wire used in orthodontics is an alloy called TMA. This alloy is an aerospace fastener and spring material (Ekinaka, 1980). The composition is: 77.65% Ti, 11.5% Mo, 6.0% Zr, 4.5% Sr and 0.35% Fe.

Braided rectangular wires are also used for their resilience. These wires are formed by braiding together 18-8 stainless steel wires and then either rolling or machining the braided wires to a rectangular shape. They have a very low modulus of elasticity when compared to a solid arch of 18-8 stainless steel.

The properties of stainless steel and Elgiloy wires can be changed by low temperature heat treatment. Wilkinson (1960) used the equation $R = \frac{P^2}{2E}$, where E = modulus of elasticity, P = elastic limit, and R = the modulus of resilience; to show how heat treatment can change the resilience of the wire. Heat treatment, as well as cold working, increases both the elastic limit and the modulus of elasticity. Resilience will usually increase, however, since the elastic limit value is taken to the second power.

Backofen and Gales (1952) used the term stress relief annealing interchangably with heat treatment. They attributed the increase in elastic strength in stainless steel after heat treatment to the release of residual stresses. They recommended heat treatment at 500° F. for 20 minutes or 750° F. - 820° F. for ten minutes. It was found that more pronounced results occurred at the higher temperature range. Wilkinson (1960) gave a range of 260° C to 460° C for 75 minutes to 30 seconds. At temperatures exceeding 460° C the properties gained by cold working were lost. Funk (1951) reported that the optimum heat treatment was at 850° F. for three minutes. It was suggested that for practical purposes stainless steel wires could be heated until they turned a straw color, indicating the proper amount of treatment. Kemler (1956) wrote that for stainless steel the optimal temperature range was 700° F. to 800° F. for 5 to 15 minutes and 700° F. to 900° F. for 5 to 15 minutes with 80% Ni - 20% Cr wires.

METHODS AND MATERIALS

The experimental apparatus consisted of 12 maxillary teeth arranged in a simple Bonwil-Hawley arch form. The teeth were set in a stone base, embedded so that only the crowns of the teeth protruded above the stone. The central incisors were different in that they were only imbedded at the root apex. (See Figure 1). Strain gauges were attached to the palatal side of the central incisors and then wired to the electronic strain indicator.

The teeth used for this experiment were made of melamine formaldehyde by Columbia Dentoform. They were modified by adding cold-cure acrylic to form a root apex and then were notched to increase their retention in the stone. The central incisors were further modified by flattening the lingual surface to facilitate placement of the strain gauges.

The appliance used was the Twin Torque "straight wire" type of edgewise orthodontic appliance. Finishing torque, angulation and horizontal control were built into the slots and tubes of the appliance. Open brackets were used for the premolars and anterior teeth with tubes for the first molars. All of the brackets and tubes were

Figure 1. Frontal View of Dental Set-up

attached to a mesh base for bonding to the teeth.

The teeth were arranged in soft utility wax with the proper vertical relationships to one another for bracket placement. The brackets were then placed on the teeth in their ideal locations using Eastman 910 adhesive.

An arch form was selected on the basis of convenience. A preformed arch of Nitinol was selected, taped to a manilla folder and photocopied so that all arch wires could be adjusted to this same arch form. Nitinol was chosen as the model since it is the most difficult material to modify.

The lingual aspects of the central incisors' roots were reduced to a flat surface to facilitate placement of the strain gauges. A rubber wheel mounted on a mandrel was used for gross reduction, followed by very fine sandpaper to finish the surface. The strain gauges used for this experiment are Magnaflux #PA-41-060-BG-120-LEN gauges with attached leads. They were oriented with the grid pattern of the foil parallel to the long axis of the tooth, with the lead wires toward the incisal edge. (See Figure 2). Eastman 910 adhesive was used on the strain gauge backing to glue it on the tooth after cleaning the tooth with alcohol.

A stainless steel 0.018 x 0.022 inch preformed arch

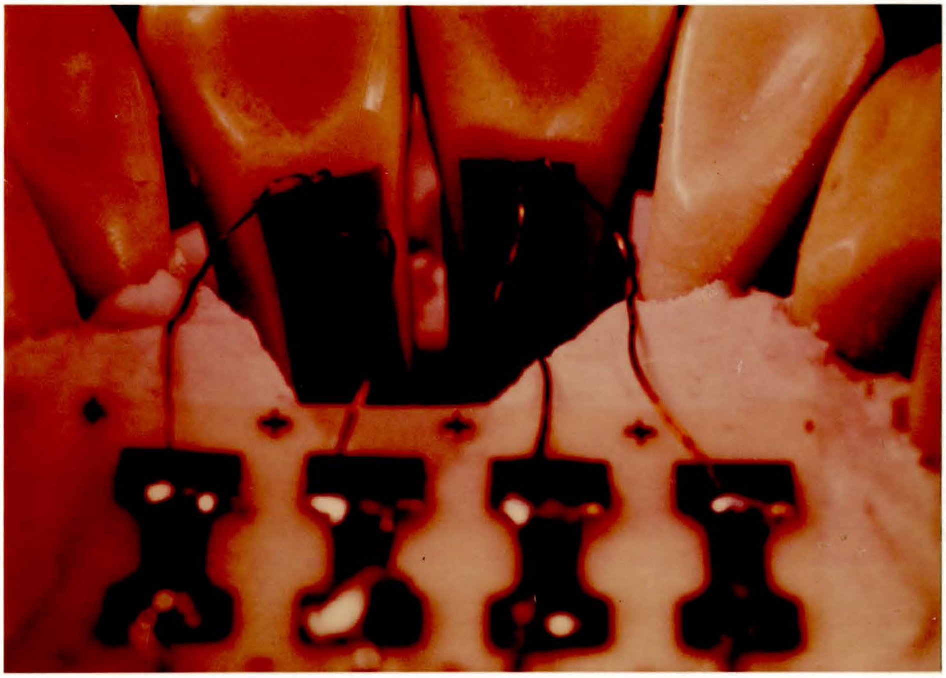

Figure 2. Strain Gauges Mounted on the Lingual Surface of the Maxillary Central Incisors.

wire was adjusted to fit the template and was detorqued, i.e., labial root torque was placed, in the area of the central incisor brackets. The teeth were all ligated to this wire with Unitek Alastik modules. The midline marked on the arch wire was matched with the mesial contacts of the central incisors and all of the other teeth were in contact. Wax was flowed on the wire and tubes of the first molars to hold them in position and prevent any spaces from occurring.

A form was used to hold the stone when it was poured and to prevent stone from covering the strain gauges. The form was made from baseplate wax, fabricating a wall large enough to enable stone to flow on the buccal surfaces of the roots. Two small pieces of baseplate wax were extended from the wall of the form, through the interproximal spaces of the central and laterial incisors, and meeting lingual to the teeth to form a wedge. Whip Mix Silky Rock die stone was vacuum mixed following the manufacturer's specifications. The mixed stone was then poured into the form. Next, the teeth, attached to the arch wire, were placed in the stone, with the central incisors in the divided off "V"-shaped area. A short length of 0.032 inch wire was imbedded in the stone labial to the central incisors and lined up with the dental midline and the marked midline on the arch wire.

After the stone had set, the wax was peeled away from the outer surface and the wedge separating the central incisors from the rest of the teeth was carefully removed. Foil bridges on a plastic backing were attached to the flat area of stone lingual to the teeth with Eastman 910 adhesive. Terminals of wider foil were at each end of the bridges for soldering the strain gauge leads and the lead wires to the switch and balance unit. (See Figure 3). The wires were then soldered to the bridge terminals with a small Weller Model WM 120 12 Watt electric soldering iron.

A flat, multistranded, insulated lead wire (number W-01E01) was used. The wires soldered to the bridges led to the switch and balance unit (Strainsert Model SB10C) using two of the 10 channels available. (See Figure 4). The SB10C was then connected to the strain indicator (Strainsert HW1-D) which was used to measure microstrain in the strain gauge. (See Figure 5).

With the set-up completed (See Figure 6) the wires were selected and placed in the brackets so that the midline on the wire lined up with the dental midline and the 0.032 inch wire placed labial to the teeth. The wire was then ligated to the brackets of the canines and incisors (See Figure 7) with elastic modules. The strain gauge, balanced prior to wire placement was then ready to be read.

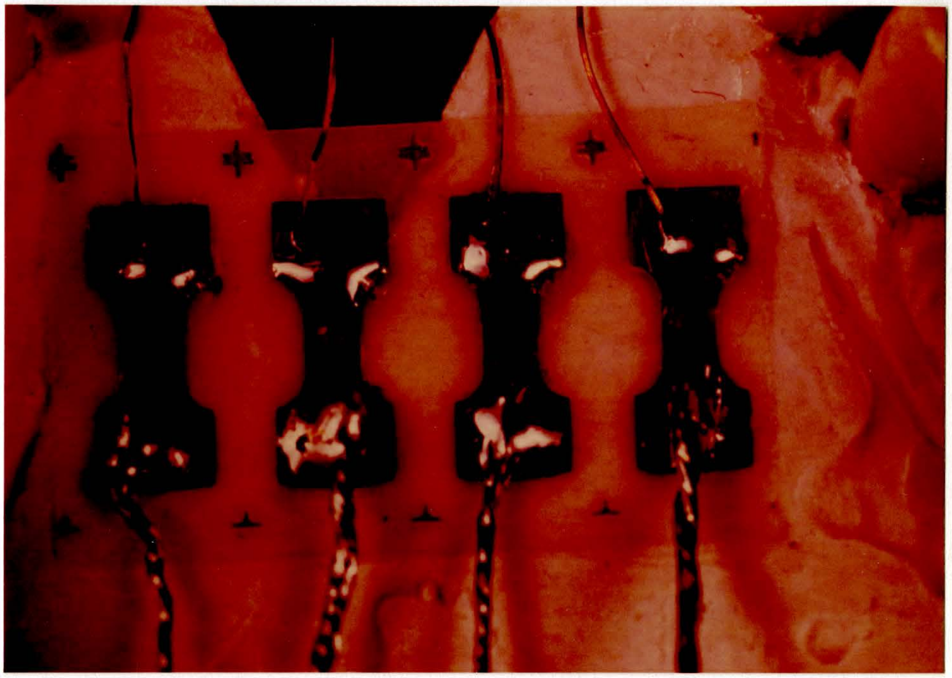

Figure 3. Top View of Foil Bridges.

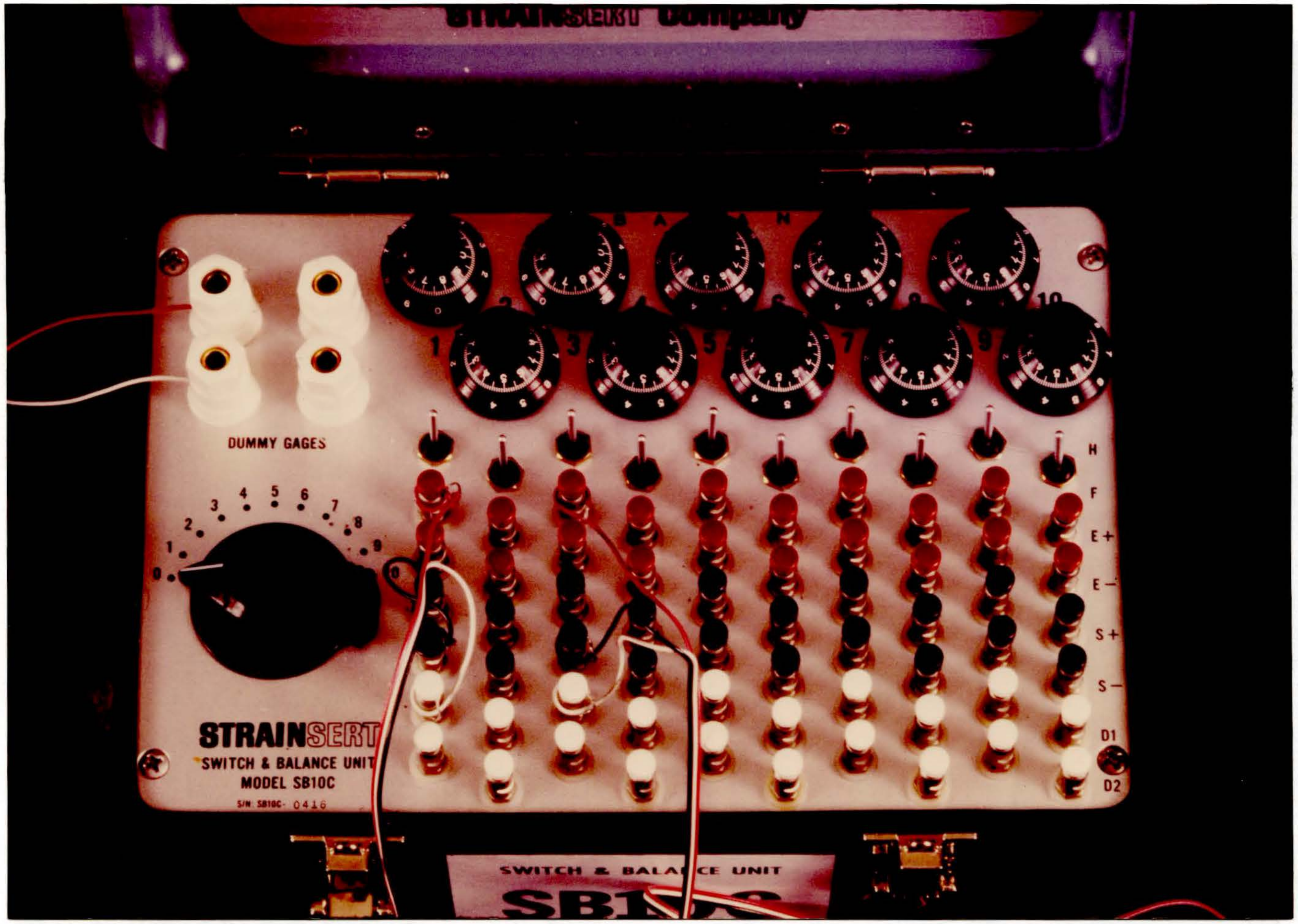

Figure 4. Panel of the Strainsert Switch and Balance Unit SB10C

Figure 5. Panel of the Strainsert Strain Indicator Model HW1-D

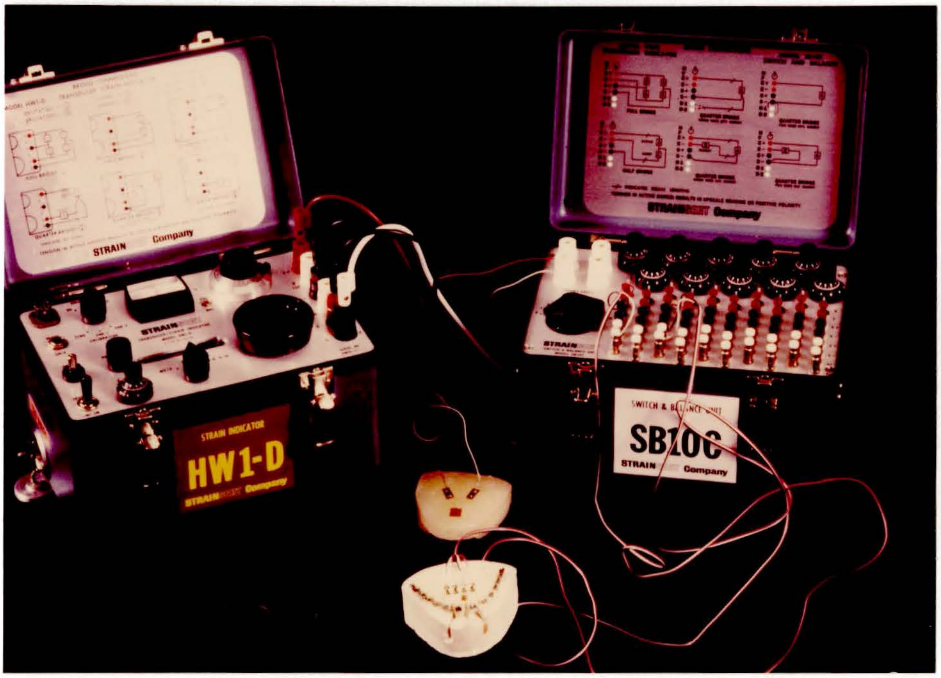

Figure 6. The Complete Experimental Apparatus.

Figure 7. Dental Set-up with an Archwire Ligated in the Brackets.

Six arch wires were tested for each size and type of wire. They were selected at random from a box of ten arch wires received from the orthodontic supply companies. The strain indicator was balanced to zero between each wire to assure accuracy of the readings. The following wires were used: 0.016 X 0.022 inch, 0.017 x 0.025 inch and 0.018 x 0.025 inch stainless steel (Ormco); 0.016 x 0.022 inch and 0.017 x 0.025 inch blue Elgiloy (Rocky Mountain); 0.016 x 0.022 inch and 0.017 x 0.025 inch and 0.018 x 0.025 inch D-Rect (Ormco); 0.016 x 0.022 inch, 0.017 x 0.025 inch and 0.018 x 0.025 inch Force-9 (Ormco); 0.017 x 0.025 inch TMA (Ormco); 0.016 x 0.022 inch, 0.017 x 0.025 inch and 0.018 x 0.025 inch Nitinol (Unitek). The D-Rect and Force-9 wires were made of braided stainless steel. All of the other samples were solid rectangular wires. All of the wires were supplied as blank preformed arches. Some physical properties of the wires are presented in Table 1.

After the stainless steel and Elgiloy wires were tested, they were heat treated in a Jelenko Model 440-TP burnout oven. The stainless steel wires were heat treated at 700° F. for 10 minutes. The Elgiloy wires were heat treated at 900° F. for 10 minutes. The heat treated wires were tied in and tested in the same manner as the previous wires.

TABLE I

MECHANICAL PROPERTIES OF ORTHODONTIC ARCHWIRES

	MODULUS OF ELASTICITY 10^6 PSI	YIELD STRENGTH 10^3 PSI	TENSILE STRENGTH 10^3 PSI
STAINLESS STEEL[a]	28.5	240	320
TMA[a]	10-12	190	220
FORCE-9	3-5	95	*
D-RECT[a]	2-3.5	80	*
BLUE ELGILOY[b]	28.5	310	340
YELLOW ELGILOY[b]	28.5	310	340
NITINOL[c]	4.8	- -	230-250

[a]American Ormco, 1332 South Lone Hill Avenue, Glendora, California 91740

[b]Rocky Mountain Orthodontics, P.O. Box 17085, Denver, Colorado 80217

[c]Andreasen and Morrow (1978)
* Data not available because of inconsistant breaking points of these braided wires.

RESULTS

The microstrain data recorded in this experiment were measured with strain gauges on the lingual aspect of the maxillary central incisors when the archwires were ligated into the brackets. Table II was used as the data from all of the archwires tested from which Figures 8, 9 and 10 and Tables III, IV, V and VI were made. (See Figures 8, 9 and 10). Although averages were presented in Table II, all six measurements of microstrain for each wire group tested were included in the Newman-Keul's multiple range analysis of variance. The averages and standard deviations of microstrain data, when they are correlated with the statistical analysis of the data, impart a more thorough understanding of the forces generated by the archwires tested. All of the data for these tables were measured by strain gauge number one.

The data were used to compare the arch wires for differences from one type to another of the same size, for differences between sizes within the same type and for the effects of heat treating on stainless steel and Elgiloy, wires.

Using the data from strain gauge number one, all of the 0.016 x 0.022 inch archwire types were compared to each other (Table III). Heat treatment of the blue Elgiloy,

TABLE II

MICROSTRAIN GENERATED BY VARIOUS TYPES AND SIZES
OF
ORTHODONTIC ARCHWIRES

	$\bar{x} \pm s$		
TYPE	ARCHWIRE SIZE (INCHES) 0.016 x 0.022	0.017 x 0.025	0.018 x 0.025
SS	26.7 ± 3.0	51.8 ± 14.2	128.0 ± 33.8
SSHT	81.8 ± 8.8	125.8 ± 19.3	182.0 ± 23.0
BE	41.7 ± 7.1	81.8 ± 10.9	- - - - -
BEHT	100.3 ± 6.9	145.0 ± 30.3	- - - - -
YE	60.8 ± 4.6	110.0 ± 20.7	- - - - -
YEHT	90.0 ± 13.	- - - - -	- - - - -
D-RECT	22.3 ± 5.1	25.8 ± 3.1	44.8 ± 4.9
FORCE-9	28.0 ± 5.0	37.0 ± 1.9	32.8 ± 4.3
NITINOL	35.8 ± 9.2	- - - - -	63.7 ± 16.3
TMA	- - - - -	69.5 ± 11.4	- - - - -

(SS = Stainless Steel, BE = Blue Elgiloy, YE = Yellow Elgiloy, HT = Heat Treated)

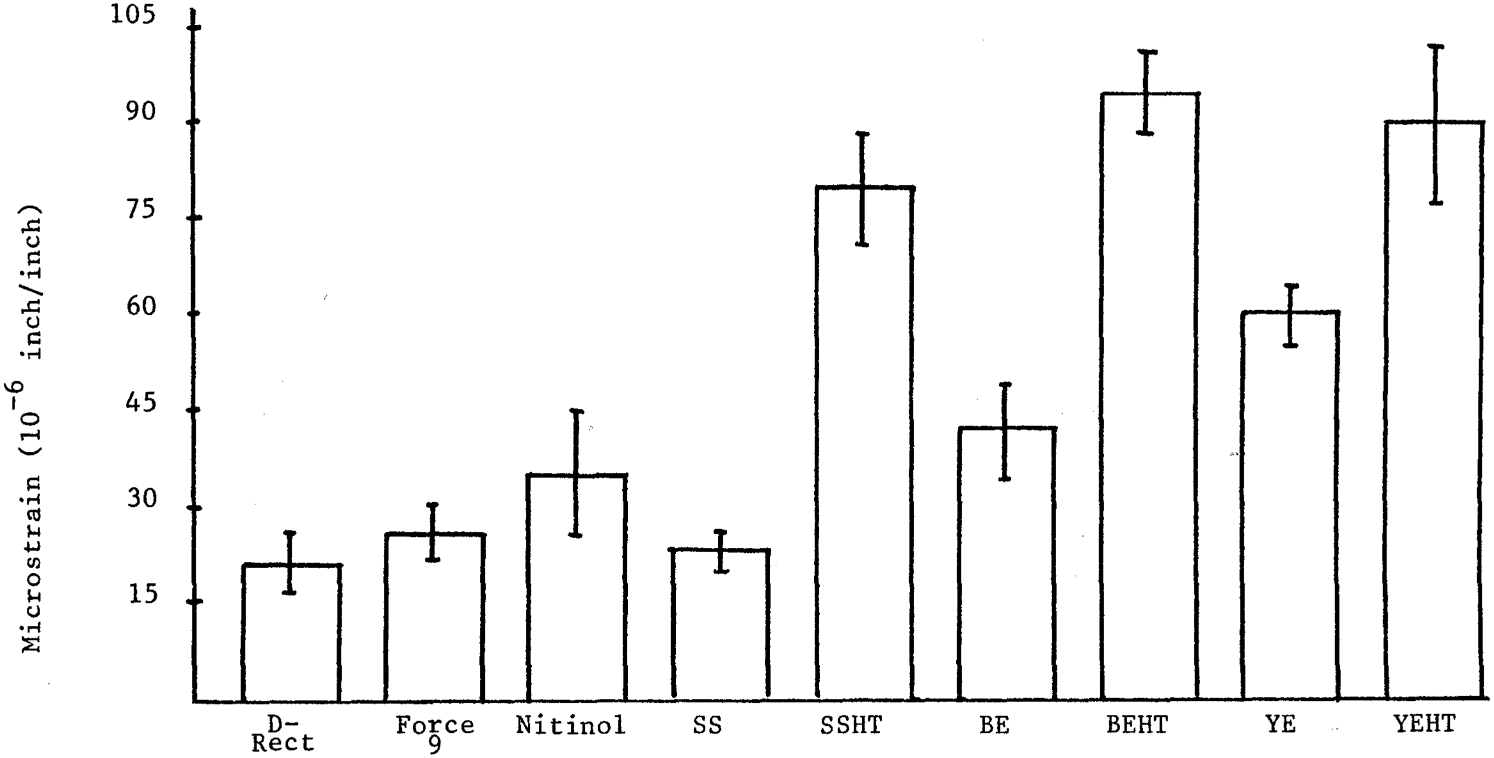

Figure 8. Comparison of Microstrain Generated by 0.016 x 0.022 inch Orthodontic Archwires (SS = Stainless Steel, BE = Blue Elgiloy, YE = Yellow Elgiloy, HT = Heat Treated).

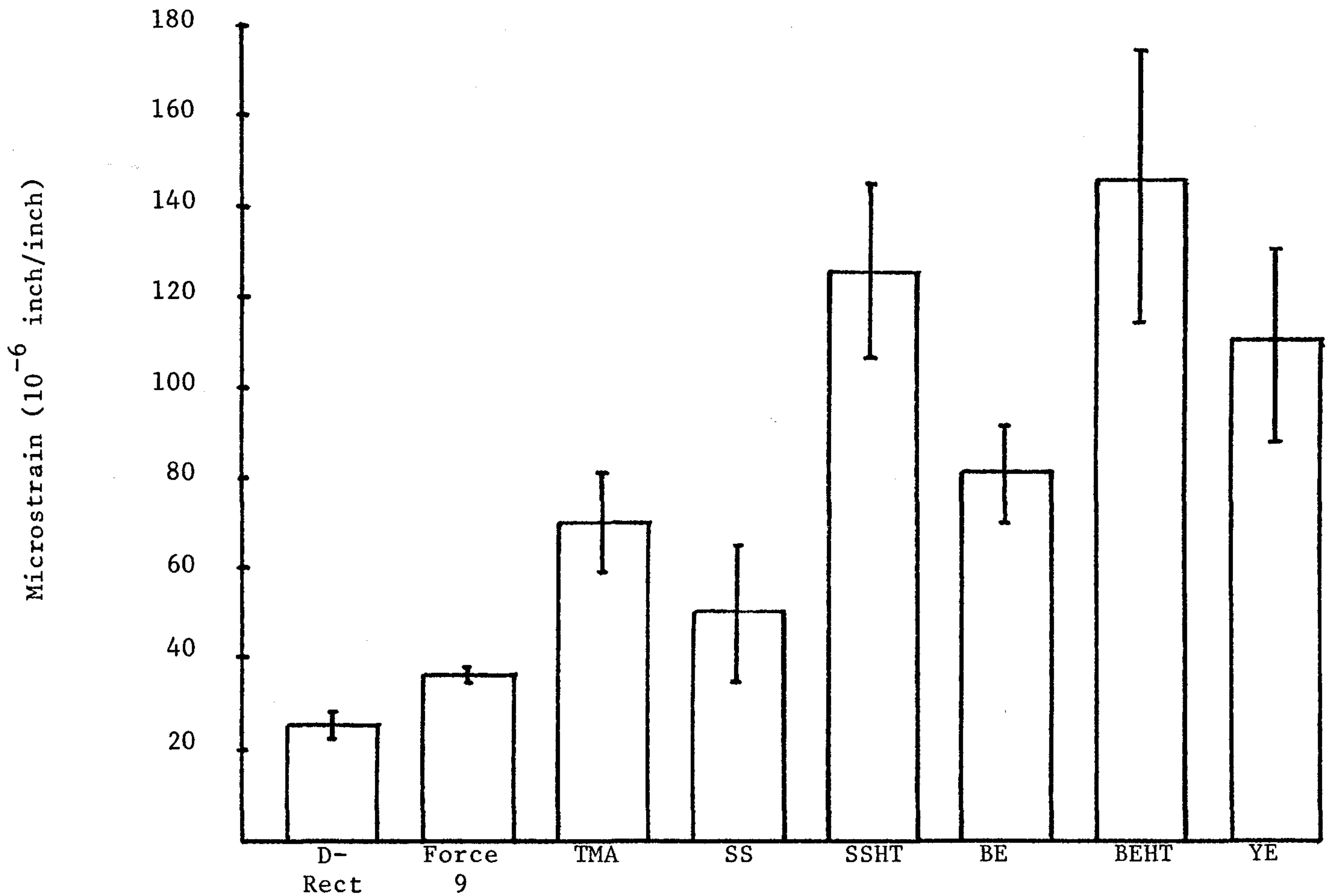

Figure 9. Comparison of Microstrain Generated by 0.017 x 0.025 inch Orthodontic Archwires (SS - Stainless Steel, BE - Blue Elgiloy, YE - Yellow Elgiloy, HT - Heat Treated).

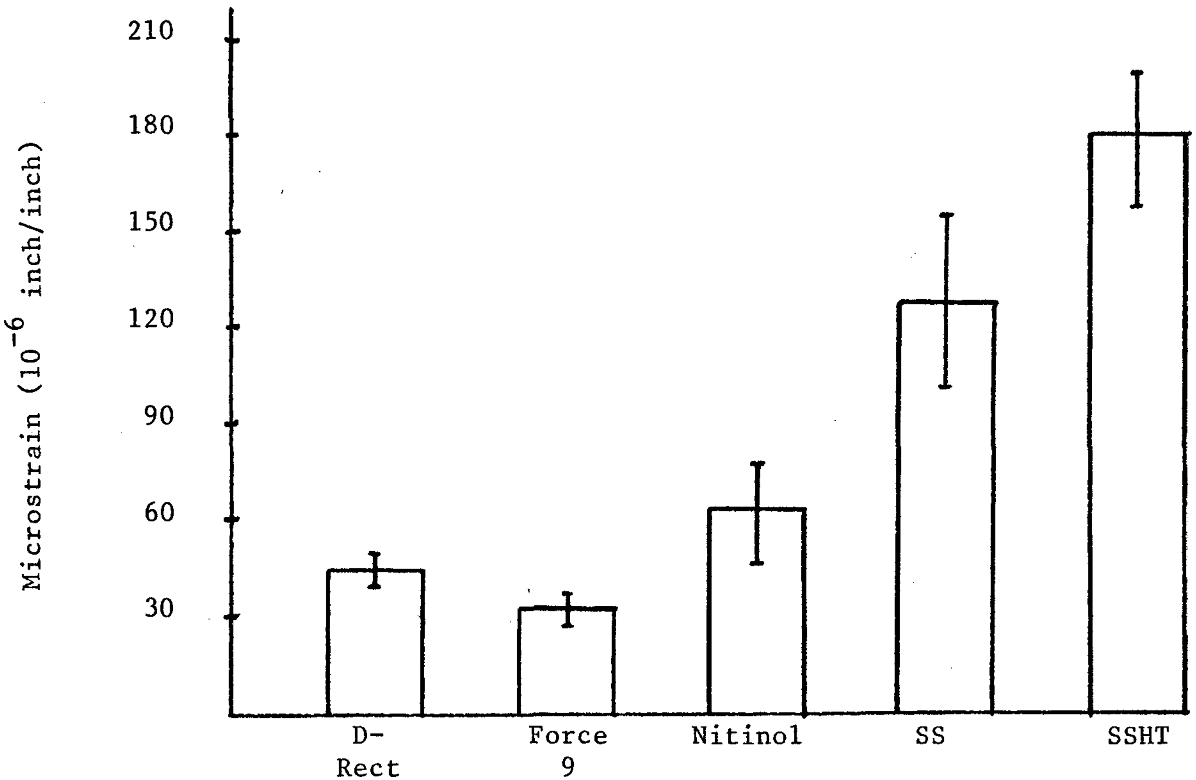

Figure 10. Comparison of Microstrain Generated by 0.018 x 0.025 inch Orthodontic Archwires (SS = Stainless Steel, HT = Heat Treated).

TABLE III

STATISTICAL SUMMARY OF MICROSTRAIN GENERATED BY 0.016 x 0.022 INCH ARCHWIRES
USING NEWMAN-KEUL'S MULTIPLE RANGE ANALYSIS OF VARIANCE
SIGNIFICANT DIFFERENCES AT LEVELS INDICATED

	D-RECT	SS	FORCE-9	NITINOL	BE	YE	SSHT	YEHT	BEHT
D-RECT	- -	$p>.05$	$p>.05$	$p<.05$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$
SS	$p>.05$	- -	$p>.05$	$p>.05$	$p<.05$	$p<.01$	$p<.01$	$p<.01$	$p<.01$
FORCE-9	$p>.05$	$p>.05$	- -	$p>.05$	$p<.05$	$p<.01$	$p<.01$	$p<.01$	$p<.01$
NITINOL	$p<.05$	$p>.05$	$p>.05$	- -	$p>.05$	$p<.01$	$p<.01$	$p<.01$	$p<.01$
BE	$p<.01$	$p<.05$	$p<.05$	$p>.05$	- -	$p<.01$	$p<.01$	$p<.01$	$p<.01$
YE	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	- -	$p<.01$	$p<.01$	$p<.01$
SSHT	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	- -	$p<.05$	$p<.01$

- continued -

	D-RECT	SS	FORCE-9	NITINOL	BE	YE	SSHT	YEHT	BEHT
YEHT	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p>.05$	- -	$p<.05$
BEHT	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.05$	- -

(SS = Stainless Steel, BE = Blue Elgiloy, YE = Yellow Elgiloy, HT = Heat Treated)

yellow Elgiloy and stainless steel archwires caused an increase in microstrain that was significant at the $p<.01$ level.

Data from the 0.017 x 0.025 inch archwires with strain gauge number one showed a significant increase in force in the stainless steel and blue Elgiloy wires after heat treatment (see Table IV).

The 0.018 x 0.025 inch archwire data from strain gauge number one is shown in Table V.

The strain produced by the different sizes of archwires of each type were compared (see Table VI). Generally, an increase in wire size created a significant difference in the microstrain produced on the central incisors.

TABLE IV

STATISTICAL SUMMARY OF MICROSTRAIN GENERATED BY 0.017 x 0.025 INCH ARCHWIRES
USING NEWMAN-KEUL'S MULTIPLE RANGE ANALYSIS OF VARIANCE
SIGNIFICANT DIFFERENCES AT LEVELS INDICATED

	D-RECT	FORCE-9	SS	TMA	BE	YE	SSHT	BEHT
D-RECT	- -	$p<.01$	$p<.05$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$
FORCE-9	$p<.01$	- -	$p>.05$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$
SS	$p<.05$	$p>.05$	- -	$p>.05$	$p<.05$	$p<.01$	$p<.01$	$p<.01$
TMA	$p<.01$	$p<.01$	$p>.05$	- -	$p>.05$	$p<.01$	$p<.01$	$p<.01$
BE	$p<.01$	$p<.01$	$p<.05$	$p>.05$	- -	$p<.05$	$p<.01$	$p<.01$
YE	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.05$	- -	$p>.05$	$p<.01$
SSHT	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p>.05$	- -	$p>.05$
BEHT	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p<.01$	$p>.05$	- -

(SS = Stainless Steel, BE - Blue Elgiloy, YE - Yellow Elgiloy, HT - Heat Treated)

TABLE V

STATISTICAL SUMMARY OF MICROSTRAIN GENERATED BY 0.018 x 0.025 INCH ARCHWIRES
USING NEWMAN-KEUL'S MULTIPLE RANGE ANALYSIS OF VARIANCE
SIGNIFICANT DIFFERENCES AT LEVELS INDICATED

	FORCE-9	D-RECT	NITINOL	SS	SSHT
FORCE-9	- - -	$p > .05$	$p > .05$	$p < .01$	$p < .01$
D-RECT	$p > .05$	- - -	$p > .05$	$p < .01$	$p < .01$
NITINOL	$p > .05$	$p > .05$	- - -	$p < .01$	$p < .01$
SS	$p < .01$	$p < .01$	$p < .01$	- - -	$p < .01$
SSHT	$p < .01$	$p < .01$	$p < .01$	$p < .01$	- - -

(SS = Stainless Steel, HT = Heat Treated)

TABLE VI

STATISTICAL SUMMARY OF MICROSTRAIN GENERATED BY DIFFERENT SIZES OF ORTHODONTIC ARCHWIRES
USING NEWMAN-KEULS'S MULTIPLE RANGE ANALYSIS OF VARIANCE
SIGNIFICANT DIFFERENCES AT LEVELS INDICATED

	0.016 x 0.022 vs. 0.017 x 0.025	0.017 x 0.025 vs. 0.018 x 0.025	0.016 x 0.022 vs. 0.018 x 0.025
D-RECT	$p > .05$	$p < .01$	$p < .01$
FORCE-9	$p < .01$	$p > .05$	$p > .05$
NITINOL	- -	- -	$p < .01$
SS	$p > .05$	$p < .01$	$p < .01$
BE	$p < .01$	- -	- -
YE	$p < .01$	- -	- -
SSHT	$p < .01$	$p < .01$	$p < .01$
BEHT	$p < .01$	- -	- -

(SS - Stainless Steel, BE = Blue Elgiloy, YE = Yellow Elgiloy, HT = Heat Treated)

DISCUSSION

The lack of experimental evidence found in the review of the literature on forces generated by different arch wires showed the need for more research in this area. In a related investigation, Katsis (1979) measured torquing forces using strain gauges attached to acrylic incisor crowns mounted on 0.045 inch round stainless steel wires with rigid canines and posterior teeth. The strain gauges were mounted on the labial and lingual aspects of the wires. The deviations of the data were very high, which indicated that reproduction of results was difficult to obtain.

In the present investigation, an effort was made to eliminate the variability in strain gauge data by using a more rigid structure on which to mount the strain gauges. It was felt that the 0.045 inch wires used by Katsis were too flexible, causing rotation and extraneous movement. Plastic teeth were chosen as being more rigid, practical and readily obtainable. A trial experimental set-up was made by placing strain gauges on the lingual surfaces of the maxillary central incisors on a Columbia Dentoform typodont. Twin Torque open, bonded brackets were secured to the central incisors and bands were cemented on the first molars.

Surplus strain gauges were used for this first trial set-up. The wires connecting the strain gauge to the strain indicator were soldered to small terminals on the strain gauge. The physical difficulty involved in this soldering prompted the decision to use strain gauges with leads attached for future set-ups.

The trial strain gauges were connected to the strain indicator as shown on the inside cover of the instrument using 22 gauge insulated copper wires. (See Figure 11, two wire internal dummy). Another wire completed the circuit through an internal standard resistor in the strain indicator. This wiring scheme did not produce a microstrain reading on the instrument because of an error in the diagram. By connecting the wire from the standard internal resistor directly to the strain gauge terminal, along with the other wire already soldered there, the circuit was correctly completed and the system functioned properly. (See Figure 11, three wire internal dummy).

An arch wire was then placed into the molar tubes and tied into the incisor brackets. The deflection of the needle on the strain indicator showed that the tooth was being strained to a sufficient degree to enable measurement.

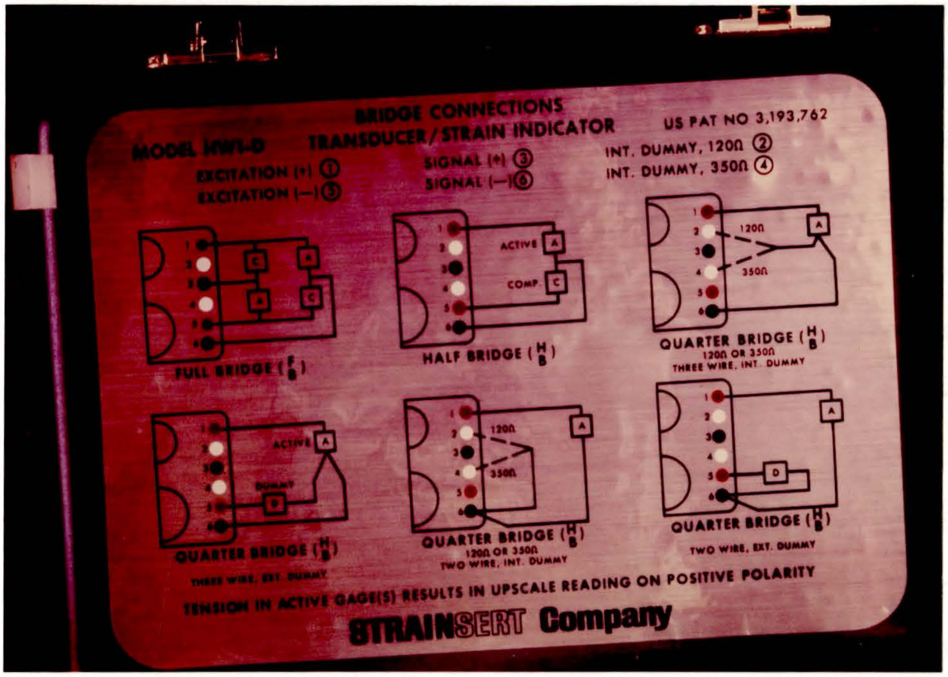

Figure 11. Inside Cover of Strain Indicator Showing Bridge Connections.

The next problem was to find a base material that would be appropriate to hold the teeth. Another trial set-up was chosen as the method to ascertain that the base material would function correctly.

Cold cure acrylic was selected as the base material since it was readily available and easy to use. The central incisors and molars, with their orthodontic appliances still in place, were removed from the typodont and ligated to a round stainless steel arch wire. A U-shaped wax form was made to hold the acrylic after the powder and liquid were mixed. The teeth were then placed into the soft acrylic and supported while the acrylic cured. Only the crowns of the teeth remained above the acrylic, the strain gauges and solder joints were completely imbedded.

When the acrylic had completely set, the round wire was removed and the connections were completed to the strain indicator. The instrument could not be balanced, which indicated that the circuit was not complete. It was thought that one or both of the solder joints on the strain gauge might have broken free during the process of imbedding the teeth in the acrylic. Later, when the teeth were being removed from the acrylic, this was found to be the case. The metal foil of the strain gauge tore away from the plastic backing and fractured, breaking the circuit.

The same procedure was followed for another trial set-up, but this time the teeth were successfully imbedded in the acrylic without any damage to the strain gauges or solder joints. When the strain gauges were wired to the strain indicator and the arch wire was tied into the brackets, an interesting phenomenon was observed. The needle on the instrument, which indicates microstrain, was deflected an initial amount and then continued to drift slowly with time, showing an apparent increase in strain of the tooth. The drift was thought to be caused by a flow or creep of the acrylic as the central incisor was loaded. It might also have been deformation of the entire "horseshoe" of acrylic. It was thought that this problem could be overcome with a more rigid base.

Ths next idea was to place the teeth in a solid block of cold cure acrylic to eliminate the possibility of expansion or contraction of the U-shaped acrylic arch. The new strain gauges with attached leads were also available at this time and were incorporated into the experimental apparatus. These strain gauges were more convenient to work with, enabling the attached leads to be soldered away from the gauge itself. The drift phenomenon of the needle on the strain indicator was still present, though this result lent credence to the theory that the acrylic flowed under pressure. At this point it was decided that a more rigid base material than cold cure acrylic would be necessary.

It was decided that dental stone would be used as the base material, since no creep was expected. A wax form was used again as a container for the mixed stone during setting. The molars were imbedded so only the crowns were above the stone and the central incisors had only the root apices in the stone. This allowed more of the tooth to flex when loaded by the arch wire in the bracket and allowed the strain gauge to remain visible above the stone. When the wiring was completed and the arch wire was tied into the brackets, readings were obtained without the drift phenomenon. It was decided that the stone base should be used for the final experimental apparatus with all of the teeth from the right maxillary first molar to the left maxillary first molar included. (See Figure 12).

This was the genesis of the experimental apparatus as explained in the methods and materials section. The rationale behind the decisions of what materials were used and how, was arrived at through a trial and error process. It was hoped that this process resulted in a better final product than would be obtained without the use of trial set-ups.

Problems with the other components of this experimental apparatus became evident after the dental and strain gauge problems had been solved. The switch and balance unit was not functioning when it was wired to the

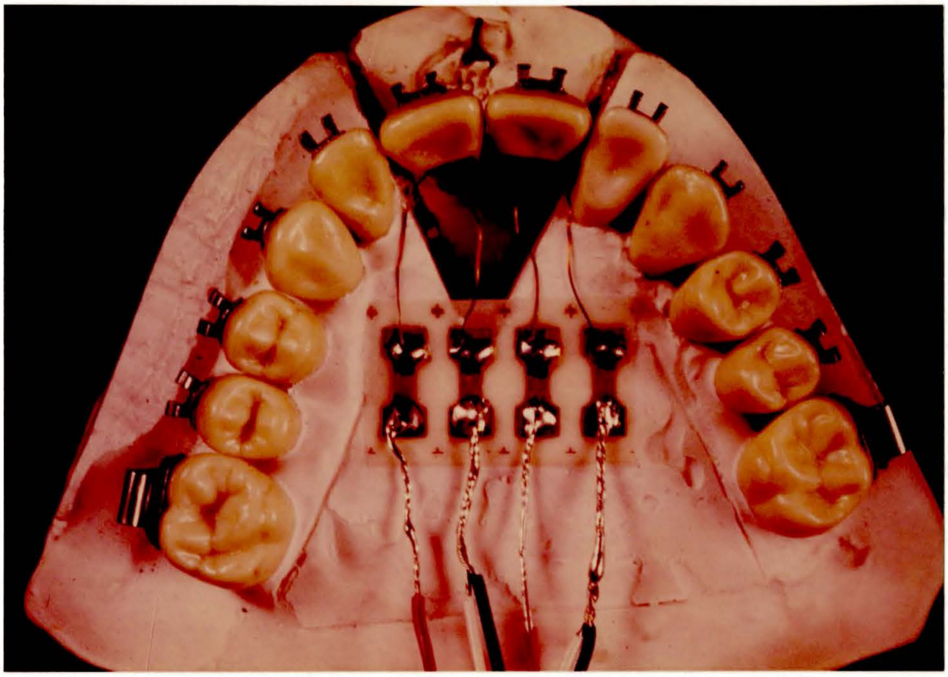

Figure 12. Top View of the Dental Set-up and Strain Gauge Wiring.

strain gauges and the strain indicator. This was a result of improper wiring in the instrument, resulting in an open circuit. The situation was corrected by adding a 120 ohm strain gauge to complete a circuit on the switch and balance unit. (See Figure 13). The strain gauge resistor was wired to the two terminal posts marked D1 in the upper left corner of the switch and balance unit. (See Figure 4).

The 0.018 x 0.025 inch blue and yellow Elgiloy arch wires were not included in this study because of problems encountered in seating these wires in the central incisor brackets. They could not be fully engaged in the brackets by finger pressure alone. When one of the 0.018 x 0.025 inch blue Elgiloy wires was being placed with the aid of an orthodontic plier, the right central incisor bracket was broken free from the tooth. It was replaced as close to the original position as possible, but some variation from this position resulted, as seen from the data for strain gauge number two. Due to this unfortunate occurrence, the data for strain gauge number one should be more seriously examined as being reliable. The left central incisor bracket was also broken off of the tooth near the end of the data collection. From the experiences with data from the right central incisor after the bracket was replaced, it was decided to omit the

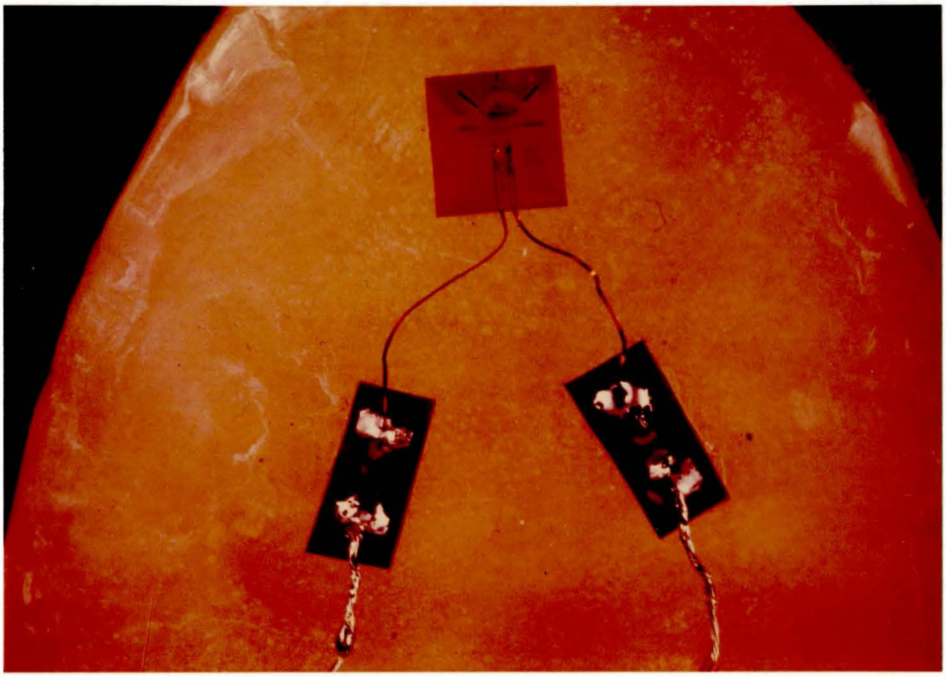

Figure 13. 120 Ohm Strain Gauge Connected as an External Resistance.

partial data for the 0.017 x 0.025 inch Nitinol and yellow Elgiloy heat treated arch wires from this study.

Some of the results obtained in this experiment were unexpected. Blue Elgiloy was found to generate a significantly greater force than stainless steel when arch wires of the same size were compared. This was in contradiction to data published in a Rocky Mountain Orthodontics booklet (1977) which indicated blue Elgiloy should deliver less force than stainless steel. Yellow Elgiloy was also found to generate a greater force than stainless steel, even though the booklet indicated that this would not be true.

Stainless steel heat treatment resulted in a significant increase in the forces of the wires. Backofen and Gales (1951) wrote that heat treatment resulted in an increase in the modulus of elasticity, an increase in tensile strength and a slight increase in percent elongation after moderate cold working, which is the situation in the archwires as received. Low temperature heat treatment increased tensile strength and the proportional limit (Wilkinson, 1962). In 1956, Kemler wrote that the proportional limit and the modulus of resilience could be increased by heat treating stainless steel. The increases were attributed to the relief of internal stresses built up in the wire by cold working. Wilkinson (1962) agrees that "...the tensile strength of cold worked stainless steel can be further increased by a low temperature heat treatment, presumably by releasing some of the residual stresses induced by the plastic deformation." Another explanation could be the partial conversion of austenite to martensite by the heat treatment. This possibility is supported by the increase in magnetic attraction of heat treated stainless steel when compared to the arch wires as received. Other evidence that supports an austenitic to martensitic conversion is the increase in brittleness that orthodontists have known about from clinical experience with heat treated stainless steel archwires. Regardless of the mechanism involved, a significant increase in the forces generated was the result. This was found to be a uniform phenomenon, i.e, heat treatment resulted in a significant increase in forces with the 0.016 x 0.022 inch, 0.017 x 0.025 inch and 0.018 x 0.025 inch stainless steel archwires.

The increase in force associated with heat treatment was also seen with the blue and yellow Elgiloy wires. Heat treatment affects Elgiloy wires by causing a known change in crystal structure according to Sandrik (1981). This effect is well known to clinical orthodontists and the use of Elgiloy wires is advocated by Ricketts, et. al. (1979) in both the as received and heat treated conditions.

It has not been stressed in the literature that heat treating stainless steel arch wires causes an increase in the forces applied to the teeth that is statistically significant to the same level as heat treating Elgiloy wires ($p < .01$). This phenomenon could be used clinically to increase the force of stainless steel arch wires.

A similarity of forces was noticed with D-Rect, Force-9 and Nitinol wires in the 0.016 x 0.022 inch and 0.018 x 0.025 inch sizes. These wires with lower forces make good starting wires in orthodontic treatment because they deliver a light force over a long working range, but the torquing capabilities are greatly diminished. The difference in force with increasing size was also found to be less with these wires compared to the stainless steel and Elgiloy wires.

The 0.018 x 0.025 inch stainless steel and Elgiloy wires deliver a greater force to the teeth as evidenced by the loss of a bracket early in this investigation. This indicates that these wires should be used clinically with a slight activation to avoid excessive force with resultant tissue trauma.

Although only relative forces were determined in this experiment, the information still has clinical significance. Since stainless steel wires are almost universally used in edgewise orthodontic treatment, they can be used as a benchmark against which the other wires in this investigation can be compared. This allows the clinician to use the data to find an appropriate wire that will give him more or less force as desired. The data may be used to judge which of the wires tested, or other wires with the same properties, would be most appropriate for a given situation. The data may also be used to see what increase in force can be expected as the size of the archwire is increased. By comparing the microstrain values in Table II, the clinician can choose a wire that will deliver a light force early in treatment when large discrepancies exist between teeth. As the teeth become better aligned a stiffer wire can be used for smaller movements while helping to prevent unwanted movement. Finishing torque of the maxillary central incisors, as simulated in this study, is a good example of a situation where a wire with greater force delivery over a short range would be desirable. Force control is an important aspect of orthodontics and the data for the wires tested can assist the practitioner in its accomplishment.

The advantage of an in vitro study, like the present one, is that the variables can be carefully controlled. Even with this control many problems are encountered in the apparatus as previously discussed. The present work may now serve as a starting point for future study in the forces of wires.

Some possible improvements can be suggested at this time. If the teeth were thinned by grinding on the labial and lingual aspects of the root surface, more strain could be obtained with the same force without sacrificing the rigidity in the mesiodistal direction. The surfaces of the teeth upon which the brackets are positioned could be left with a rough finish to facilitate the bond of the bracket to the tooth. Other useful information could be obtained by placing strain gauges on other teeth, e.g. on the lateral incisors and canines to observe the reactive forces using a similar instrument set-up to the one presently employed. The present study incorporated a sample size of six wires of each dimension used. The reliability of the results could be further enhanced by the utilization of larger sample sizes.

SUMMARY AND CONCLUSIONS

An experimental apparatus has been constructed to measure arch wire forces through the use of strain gauges. Plastic teeth were set in dental stone so that the orthodontic brackets could passively accept a preformed edgewise orthodontic wire, except at the central incisors where the roots were labially inclined. This dental set-up simulates a patient who needs lingual root torque to properly position the maxillary central incisors. The use of dental stone and plastic teeth was considered to supply sufficient rigidity to prevent lateral tooth movement, yet allowed measurement in the desired direction.

Strain gauges were placed on the lingual aspect of the maxillary central incisors to measure the strain induced on these teeth by the arch wires when they were ligated in the bracket slots. The electronic instruments used to measure the microstrain were wired to the strain gauges and functioned well after some modifications were added.

The following wire types and sizes were compared: stainless steel 0.016 x 0.022 inch, 0.017 x 0.025 inch and 0.018 x 0.025 inch; blue Elgiloy 0.016 x 0.022 and 0.017 x 0.025 inch; yellow Elgiloy 0.016 x 0.022 and 0.017 x

0.025 inch; D-Rect 0.016 x 0.022 inch, 0.017 x 0.025 inch and 0.018 x 0.025 inch; Force-9 0.016 x 0.022 inch, 0.017 x 0.025 inch and 0.018 x 0.025 inch; Nitinol 0.016 x 0.022 inch and 0.018 x 0.025 inch; TMA 0.017 x 0.025 inch; the stainless steel and Elgiloy wires listed above were also tested again after heat treatment.

The wide range of forces available from the wires tested was seen by the statistically significant differences between them. Heat treatment resulted in a significant increase in the forces of all three wire types and in each size of wire within the type tested.

It is hoped that the information gathered in this investigation can be used by both the orthodontics practitioner and further investigators into force production and characterization by orthodontic appliances. For the clinician the relative placement of the wires tested to each other can serve as a guide to force selection during treatment. Researchers may confirm the results of this study or through other modifications or additions build on the present results to supply additional information with forces from other wires.

REFERENCES

Andreasen, G. F. and Morrow, R. W.: Laboratory and clinical analyses of Nitinol wire. American Journal of Orthodontics 73: 142-151, 1978.

Andreasen, G. and Johnson, P: Experimental findings on tooth movements under two conditions of applied force, Angle Orthodontist 37: 9-12. 1967.

Angle, E. H.: The latest and best in orthodontic mechanism. The Dental Cosmos: 1143-1158, 1928.

Angle, E. H.: The latest and best in orthodontic mechanism. The Dental Cosmos: 164-174, 1929.

Angle, E. H.: The latest and best in orthodontic mechanism. The Dental Cosmos: 260-270, 1929.

Angle, E. H.: The latest and best in orthodontic mechanism. The Dental Cosmos: 409-421, 1929.

Backofen, W. A. and Gales, G. F.: Heat treating stainless steel for orthodontics, American Journal of Orthodontics 38: 755-765, 1952.

Brumfield, R. C.: An experimental check on edgewise arch computations, International Journal of Orthodontia 23: 687-688, 1937.

Burstone, C. J. and Koenig, H. A.: Force systems from an ideal arch, American Journal of Orthodontics 65; 270-289, 1974.

Ford, D. R.: Histologic study of the changes in tissues of the periodontium of the Rhesus monkey with the application of torque force in the third stage of the Begg technique, American Journal of Orthodontics 60: 193-194, 1970. (Abstract).

Funk, A. C.: The heat treatment of stainless steel, The Angle Orthodontist 21: 129-138, 1951.

Hitchcock, H. P.: A simple method for torquing incisor roots, American Journal of Orthodontics 58: 455-458, 1970.

Jacobson, A.: Biomechanics of orthodontic forces. The Journal of the Dental Association of South Africa 21: 211-218, 1966.

Katsis, J.: Torquing forces coincident to archwire dimension and composition in the straight wire appliance. Chicago, 1979 thesis submitted for masters thesis, Loyola University.

Kemler, E. A.: Effect of low temperature heat treatment on the physical properties of orthodontic wire, American Journal of Orthodontics 42: 793, 1956. (Abstract).

Kohl, R. W.: Metallurgy in orthodontics, Angle Orthodontist 34: 37-52, 1964.

Mitchell, D. L. and Kinder, J. D.: A comparison of two torquing techniques on the maxillary central incisor, American Journal of Orthodontics 63: 407-413, 1973.

Moyers, R. E. and Bauer, J. L.: The periodontal response to various tooth movements, American Journal of Orthodontics 36: 572-580, 1950.

Mulligan, T. F.: A torsional analysis of stainless steel orthodontic wires. Alumni Bulletin Indiana University School of Dentistry p. 31, Spring, 1963. (Abstract).

Nikolai, R. J.: An optimum orthodontic force theory as applied to canine retraction, American Journal of Orthodontics 68: 290-302, 1975.

Perlow, J.: Universal torquing auxiliary, Journal of Clinical Orthodontics 7: 388-391, 1973.

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

Rauch, E. D.: Torque and its application to orthodontics. American Journal of Orthodontics 45: 817-830, 1959.

Reitan, K.: Effects of force magnitude and direction of tooth movement on different alveolar bone types, Angle Orthodontist 34: 244-255, 1964.

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

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

Ringenberg, Q. M.: The philosophy and technique of the edgewise appliance, American Journal of Orthodontics 56: 34-27, 1969.

Rocky Mountain Orthodontics booklet. Elgiloy and tru-chrome orthodontic treatment wires. Copyright 1977 by Rocky Mountain/Associates International, Inc.

Roth, R.: Louise Jarabak Memorial Lecture, University of Chicago, Chicago, Illinois. October 22, 1980.

Sandrik, J. L.: Personal communication March 16, 1981.

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

Schwartz, A. M.: Tissue changes incidental to orthodontic tooth movement, International Journal of Orthodontics 18: 331-352, 1932.

Sims, M. R.: Torque application to maxillary incisors, Australian Orthodontic Journal June: 5-12, 1972.

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

Steiner, C. C.: Power storage and delivery in orthodontic appliances, American Journal of Orthodontics 39: 859-880, 1953.

Steiner, C. C.: Force control in orthodontia, The Angle Orthodontist 2: 252-259, 1932.

Steyn, C. L.: Measurement of edgewise torque force in vitro, American Journal of Orthodontics 71: 565-573, 1977.

Stoner, M. M.: Force control in clinical practice I. An analysis of forces currently used in orthodontic practice and a description of new methods of contouring loops to obtain effective control in all three planes of space, American Journal of Orthodontics 46: 163-186, 1960.

Storey, E. and Smith, R.: Force in orthodontics and its relation to tooth movement, The Australian Journal of Dentistry February: 11-18, 1952

Storey, E.: The nature of tooth movement, American Journal of Orthodontics 63: 292-314, 1973.

Sved, A.: The behavior of arch wires in fixed attachments, International Journal of Orthodontia 23: 683-686, 1937.

Wilkinson, J. V.: Some metallurgical aspects of orthodontic stainless steel, American Journal of Orthodontics 48: 192-206, 1962.

Wilkinson, J. V.: The effect of high temperatures on stainless steel orthodontic arch wire, Australian dental Journal, October: 264-268, 1960.

APPENDIX A

STATISTICAL SUMMARIES OF MICROSTRAIN DATA FROM STRAIN GAUGE NUMBER TWO

TABLE I

STATISTICAL SUMMARY OF MICROSTRAIN GENERATED BY 0.016 x 0.022 INCH ARCHWIRES
USING NEWMAN-KEUL'S MULTIPLE RANGE ANALYSIS OF VARIANCE
SIGNIFICANT DIFFERENCES AT LEVELS INDICATED

	D-RECT	NITINOL	FORCE-9	SSHT	BEHT	YE	YEHT
D-RECT	- -	$p > .05$	$p > .05$	$p > .05$	$p > .05$	$p > .05$	$p < .05$
NITINOL	$p > .05$	- -	$p > .05$	$p > .05$	$p > .05$	$p > .05$	$p < .05$
FORCE-9	$p > .05$	$p > .05$	- -	$p > .05$	$p > .05$	$p > .05$	$p > .05$
SSHT	$p > .05$	$p > .05$	$p > .05$	- -	$p > .05$	$p > .05$	$p > .05$
BEHT	$p > .05$	$p > .05$	$p > .05$	$p > .05$	- -	$p > .05$	$p > .05$
YE	$p > .05$	$p > .05$	$p > .05$	$p > .05$	$p > .05$	- -	$p > .05$
YEHT	$p < .05$	$p < .05$	$p > .05$	$p > .05$	$p > .05$	$p > .05$	- -

(SS = Stainless Steel, BE = Blue Elgiloy, YE = Yellow Elgiloy, HT = Heat Treated)

TABLE II

STATISTICAL SUMMARY OF MICROSTRAIN GENERATED BY 0.017 x 0.025 INCH ARCHWIRES
USING NEWMAN-KEUL'S MULTIPLE RANGE ANALYSIS OF VARIANCE
SIGNIFICANT DIFFERENCES AT LEVELS INDICATED

	D-RECT	TMA	SSHT	FORCE-9	YE	YEHT
D-RECT	- -	$p > .05$	$p > .05$	$p > .05$	$p < .05$	$p < .01$
TMA	$p > .05$	- -	$p > .05$	$p > .05$	$p > .05$	$p < .01$
SSHT	$p > .05$	$p > .05$	- -	$p > .05$	$p > .05$	$p < .05$
FORCE-9	$p > .05$	$p > .05$	$p > .05$	- -	$p < .05$	$p < .01$
YE	$p < .05$	$p > .05$	$p > .05$	$p < .05$	- -	$p < .01$
YEHT	$p < .01$	$p > .01$	$p < .05$	$p < .01$	$p < .01$	- -

(SS = Stainless Steel, YE = Yellow Elgiloy, HT = Heat Treated)

TABLE III

STATISTICAL SUMMARY OF MICROSTRAIN GENERATED BY 0.018 x 0.025 INCH ARCHWIRES
USING NEWMAN-KEUL'S MULTIPLE RANGE ANALYSIS OF VARIANCE
SIGNIFICANT DIFFERENCES AT LEVELS INDICATED

	FORCE-9	NITINOL	D-RECT	SSHT
FORCE-9	- - -	$p > .05$	$p < .05$	$p < .01$
NITINOL	$p > .05$	- - -	$p > .05$	$p < .01$
D-RECT	$p < .05$	$p > .05$	- - -	$p < .01$
SSHT	$p < .01$	$p < .01$	$p < .01$	- - -

(SS = Stainless Steel, HT = Heat Treated)

APPROVAL SHEET

The thesis submitted by William R. Caryl, Jr., D.D.S. has been read and approved by the following committee:

Dr. James L. Sandrik, Director
Professor, Dental Materials, Loyola

Dr. Joseph Gowgiel
Professor, Anatomy, Loyola

Dr. John Katsis, Jr.
Clinical Assistant Professor, Orthodontics, Loyola

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

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

April 20, 1981
Date

James L. Sandrik
Director's Signature