The Measurement of Utility Archwire Forces

T. R. White, D.D.S.
A. A. Caputo, M.S., Ph.D.
S. J. Chaconas, D.D.S., M.S.

Force magnitude and force direction (tip, torque, etc.) are basic factors of obvious importance in orthodontics. However, the determination of forces in most orthodontic appliances is a difficult proposition and, consequently, knowledge of the forces at work in orthodontic appliances is limited. Many studies have examined the issue of threshold and optimum forces and the appropriate appliance design to achieve specified forces.[1-10] This study is directed toward the measurement of forces (force magnitude and direction) delivered by orthodontic archwires.

Only the most elementary orthodontic devices, such as finger springs of a removable appliance, have mechanics that are straightforward enough to be readily understood from the standpoint of engineering mechanics. Even the relatively uncomplicated segmented arch for retracting canines can be deceptively complex and involve unexpected forces with concomitant undesired tooth movement.[4,11] A continuous archwire can involve an array of forces that defies analysis.[3]

Understanding the force distribution of an appliance is an exercise in engineering mechanics. Although significant work in this area has been accomplished by Burstone and others,[1-6,10-13] the studies have been limited to analytically manageable situations like canine retraction on segmented arches.

The primary objective of this study was to develop a methodology for determining the forces delivered by any continuous or segmented archwire. To bypass the analytical complexity of continuous archwire force analysis, an apparatus was constructed which is capable of measuring the force characteristics along a continuous wire. It consists basically of posts containing orthodontic brackets into which wire is inserted. The posts simulate tooth positions and record the forces transmitted by the wire. The mandibular utility archwire (UAW)[13] was selected for analysis.

Materials and Methods

An experimental apparatus was designed with the capability of receiving an orthodontic archwire in a series of edgewise brackets, as shown in Figure 1 and Figure 2. The framework was adjustable to permit the simulation of any arch form or malocclusion.

The framework of the apparatus consisted of a stainless steel platform (a breadboard plate), stainless steel rods (1/8″ diameter), and stainless steel sleeves which receive the rods. Set screws were machined into the sleeves so that the rods could be gripped rigidly within the sleeves. The framework was adjusted by sliding and/or rotating the rods within the sleeves. A diagram of the framework is shown in Figure 3. The framework consisted of commercially available components.

Each orthodontic bracket was mounted on a post and positioned at the end of the framework, as shown in Figure 3. The brackets were conventional .018″ Siamese edgewise

From the Orthodontic and Biomaterials Sections, Dental School, UCLA, Los Angeles.

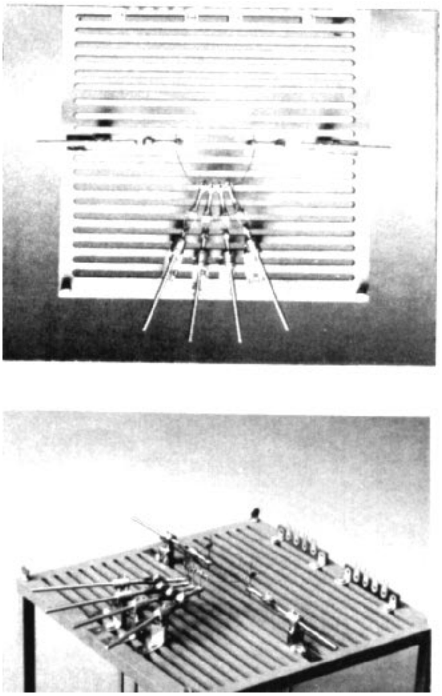

Fig. 1 Over-all views of apparatus used to measure forces delivered by the utility arch-wire.

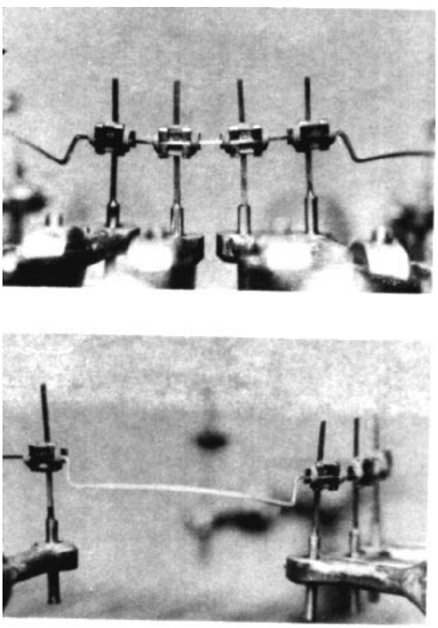

Fig. 2 Front and side views of apparatus with wire in place.

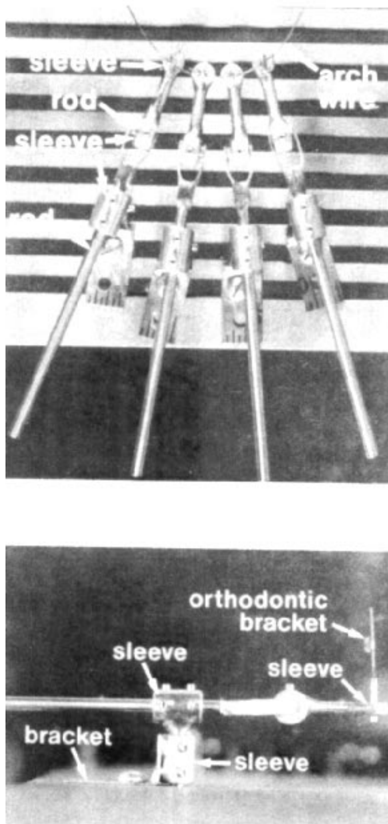

Fig. 3 Top and side close-up views of components of post and sleeve assembly.

brackets. They were welded to .016″ × .022″ Blue Elgiloy posts. The lower end of each post was enclosed in stainless steel tubing. The end enclosed in tubing was inserted in a sleeve attached to the framework.

The apparatus was adjusted to place the orthodontic brackets in positions that represent the locations of mandibular incisors and first molars. An average size arch form was used.

When an activated archwire is inserted in the brackets, the posts that hold the edgewise brackets flex (i.e., are strained) in response to the stress. The amount of strain is related to the level of stress. Since the strain on the posts can be measured, the stress delivered by the wire can be deter-

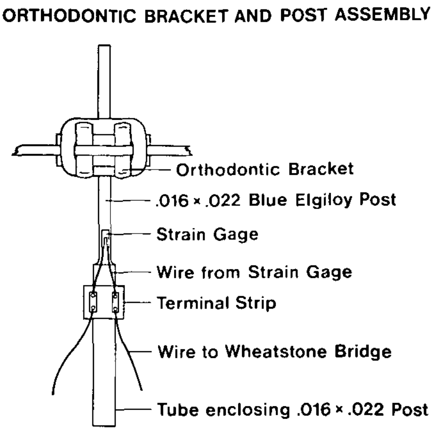

Fig. 4 Schematic representation of orthodontic bracket and post assembly.

mined. This is the conceptual basis of the apparatus. The specific design and methodology for stress measurement is described as follows.

Semiconductor strain gauges were bonded to the posts that held the orthodontic brackets. The wires from the gauges were soldered to terminal strips attached to the posts, as shown in Figure 4. This illustration depicts one face (buccal) of the post. The opposing face (lingual) of the post had a strain gauge and terminal strip as well, so that there were two gauges and two terminal strips per post. The gauge mounting arrangement in Figure 4 is suitable for measuring intrusive (or extrusive), buccolingual, or torquing forces. In the experimental setup one post was fabricated in this manner.

A second gauge-mounting arrangement placed gauges on the mesial and distal faces of the post assembly. This post served to measure tipping forces.

The gauge-mounting arrangements described above were designed specifically for intrusive, extrusive, and tipping forces. The measurement of rotational forces would require a different strain gauge arrangement which was not included in this study.

Another consideration pertaining to the gauge-mounting arrangement is that torquing forces cannot be differentiated from buccolingual forces by the apparatus. Consequently, the archwires used in this experiment were not activated in a buccolingual direction.

Semiconductor strain gauges operate on the principle that the electrical resistance of the gauge changes as it undergoes strain. The conventional method of measuring this change is to use a Wheatstone bridge as shown in Figure 5. The strain gauge is shown as a resistance "A". "D" is an equivalent resistance (often an identical gauge placed in an unstrained location). "R_1" and "R_2" are proportionate resistances that result in a voltage of zero across the galvanometer (G) when the gauge is in an unstrained condition. The imposition of a strain on the gauge (A) causes a resistance change which results in a voltage across the galvanometer. The voltage

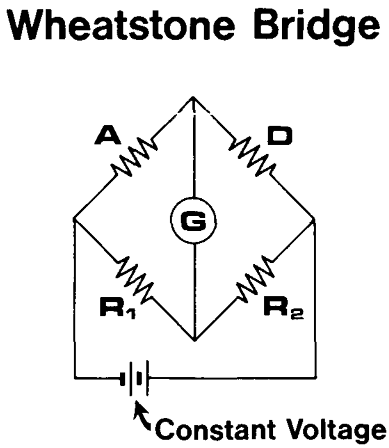

Fig. 5 Schematic representation of the Wheatstone bridge arrangement used for force measurements. The strain gauges are indicated as resistances A and D. Fixed resistances R_1 and R_2 are equal to the strain gauge resistances in the unstrained condition. G is the galvanometer which measures voltage drop when the gauges are strained.

change may be related to stress by imposing a set of known weights and recording the corresponding voltage changes.

The procedure described above was used in this study. An oscilloscope served as the galvanometer, and a constant 1.0 volt DC source was used. The arrangement of resistances in the Wheatstone bridge was modified according to the type of stress measured (i.e., intrusive force vs. torquing force). More detailed descriptions of strain gage principles and utilization are presented in References 15 and 16.

The measurement of the forces produced by a given archwire involved ligation of the wire in place with one tooth position being occupied by the post containing strain gauges. Force measurements were taken for each tooth position by transferring the post containing gauges to each tooth position in succession. In this way the intrusive force, torquing force, and tipping force delivered to each "tooth" (post) were determined.

Since the UAW has several component bends, measurements were made on wires having certain bends included (and other bends not included) to identify the respective contributions of the various bends. Specifically, the following series of bends were made in succession with force measurements being made at the end of each adjustment:

1) 30° molar tip back,
2) 30° molar tip back plus wire torque:
    a) 5°-10° labial root torque on incisors
    b) 45° buccal root torque on molars,
3) 30° molar tip back plus wire torque, plus 30° molar rotation.

Molar expansion was not included in any of the test wires since the apparatus cannot differentiate between buccolingual forces and torquing forces.

The bends outlined above were selected since they represent a typical utility archwire. In the clinical situation the design of the UAW would vary in accordance with the individual case.

The measurements described above were made on three test wires. The wires were formed by one operator who attempted to form the wires as similarly as possible. Blue Elgiloy wire, size .016″ × .016″ was used. The arch form was Brader #52, the anterior segment was 30 mm, the buccal bridge segment was 26 mm and the step-down bend was 3.5 mm. The wires were not heat treated, as prescribed by the designers of the utility archwire.[14]

Results

The results are presented in Figures 6, 7 and 8; they are graphic presentations of the average forces of the three test wires. The types of forces are displayed for each of the component bends.

There are several factors that may contribute to inaccuracy in the data. Some of these factors are listed and discussed as follows:

1) Sensitivity of the device. A force of approximately two grams was required to make a readable deflection on the oscilloscope.

2) Fluctuation and "noise." The readings on the oscilloscope were obscured by fluctuation and noise. The resulting error was judged to be as much as 10%. Factors like voltage variation, electrical heating of the strain gauge, air currents, and humidity caused these phenomena.

3) Positioning of orthodontic brackets and placement of archwire. The procedure of transferring the post bearing the strain gauges inevitably

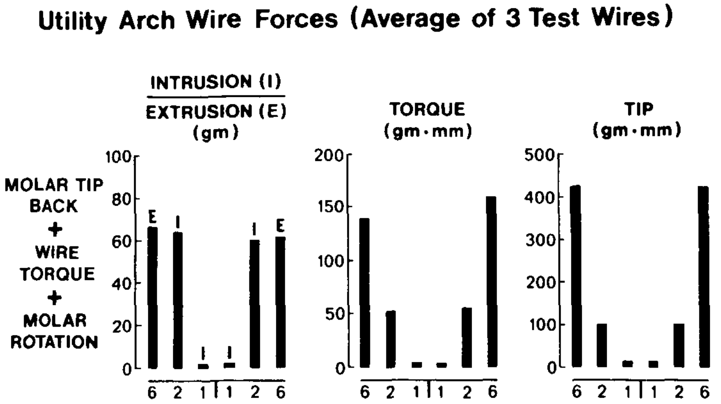

Fig. 6 Forces delivered by a utility archwire with molar tip back.

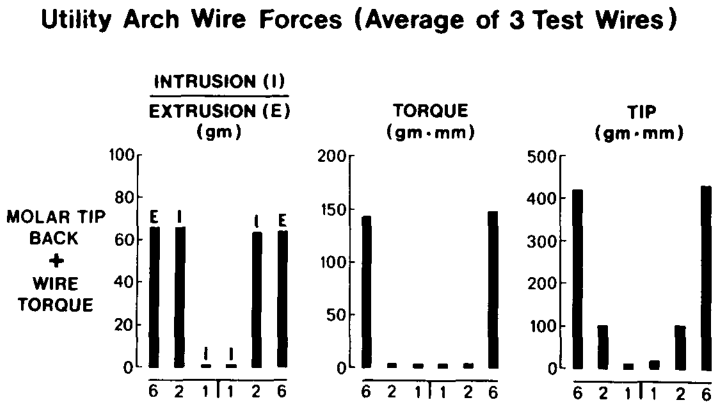

Fig. 7 Forces delivered by a utility archwire with molar tip back and wire torque.

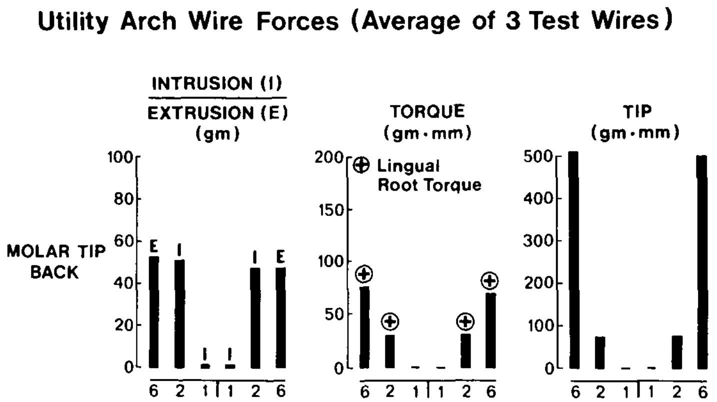

Fig. 8 Forces delivered by a utility archwire with molar tip back, wire torque and molar rotation.

resulted in some change in bracket positioning from measurement to measurement. The resulting error was judged to be approximately 10% based on trials involving repositioning.

The above-mentioned factors could be additive and result in an error of over 20%. However, the errors tend to cancel so that the mean error would be something less than 20%.

In addition to the errors in measurement described above there is some level of inaccuracy associated with wire bending. This was one reason for including three test wires in the study. Examination of the data indicates significant variation between the wires although the operator strived to make the wires the same. Because of the errors associated with measurement, it is not possible to isolate the variation in data resulting from wire bending factors.

Discussion

Intrusive Forces

The archwire operates essentially as a series of two-tooth force systems,[3] where the activation in the wire segment between two given teeth is absorbed largely by those teeth. This is illustrated by the data which show that the utility archwire (UAW) forces are delivered primarily to the molars and lateral incisors. Minimal force is transmitted to either central incisor in the experimental apparatus.

Clinically, the lateral incisor would move in response to the stress, and the archwire segment spanning the distance between the central and lateral incisors would be stressed in turn. As the lateral incisor continued to move, the stress would build up in this segment to the point where the central incisor would then move in concert with the lateral incisor. In this way a steady state of equilibrium would be reached. The resulting force distribution between the incisors is uncertain, but the lateral incisor would presumably bear the greater load, since the central incisor would move under the minimal necessary force.

A clinical ramification of this process is that intrusive movement occurs with the lateral incisors before the central incisors resulting in an arching of the mandibular incisor segment. In other words, the lateral incisors are more intruded than the central incisors, a phenomenon that is apparent to users of the UAW.

The experimental apparatus is a relatively rigid framework which measures forces in a static situation and does not necessarily represent the force distribution determined by the dynamics of tooth movement. In the case of incisal intrusive forces the apparatus probably depicts the force distribution accurately only at the time of initial wire placement for the reasons given above. In the case of the forces on molars the apparatus probably gives a good approximation at all times, since the clinical tooth movement should not significantly alter the activation in the buccal segment of the archwire.

Assuming, as suggested above, that the intrusive force on lateral incisors remains disproportionately high (after steady state equilibrium is reached), then a modification of the archwire might be advisable to achieve a more even distribution of force. One possible modification that is used by some proponents of bioprogressive mechanics is to place a simple bow in the anterior segment of the UAW to intrude the central incisors with respect to the lateral incisors. A second alternative is the intrusive archwire concept proposed by Burstone.[5]

A parenthetical point that merits consideration is that it is unclear that an even distribution of force would result in faster tooth movement. The relationship between rate of tooth movement and force level has not been clearly established in the low range of forces under consideration. However, the modifications mentioned above might be useful for another reason, namely, to maintain the incisors on a level plane and avoid the arching of the incisors as observed.

Extrusive Forces

The extrusive forces delivered to the molar brackets were measured to be approximately equal to the intrusive forces delivered to the anterior brackets. This equivalency would be expected from engineering mechanics.

The clinical significance of extrusive forces on molars is uncertain. Molar extrusion may or may not occur depending on other factors. For example, the use of a segmented archwire engaging the posterior teeth might counteract the extrusive force of the UAW. The force of occlusion might also counteract the molar extrusion. This would be an interesting area for cephalometric study.

Tipping Forces (mesiodistal)

A significant level of distal crown tip is delivered to the lateral incisors. This is probably a result of the intrusive activation being delivered primarily to the distal wing of the lateral incisor bracket. Tipping of the lateral incisors has been noted clinically by users of the UAW. The modification of placing a simple bow in the anterior segment of the UAW that was suggested to evenly distribute intrusive forces will also serve to offset the distal crown tip noted in the lateral incisor.

The distal tipping forces delivered to the molars were measured to be above 400 gm-mm. This is the highest force level of any component in the UAW.

Torquing Forces

A significant amount of torque (lingual root) is transmitted to the incisors as a result of the intrusive force acting on the incisor brackets. This results from the fact that a moment arm is produced by the point of intrusive force acting at a distance from the tooth surface. The torquing force measured by the experimental apparatus is that force applied to the surface of the tooth.

The torquing force that results from the intrusive action of the UAW is offset by the placement of 5°-10° of torquing action (labial root torque) in the anterior segment of the UAW. In fact, this amount of torque in the wire results in a measurable level of labial root torque being delivered to the lateral incisors. This effect is intended by the designers of the UAW to insure that the incisors are intruded directly into medullary bone thereby avoiding impingement of root apices on the lingual cortical plate and avoiding labial crown tip.

When no buccal root-torquing action is placed in the posterior archwire segment, a lingual root-torquing force to the molars results when the UAW is engaged. This anomalous force was seen to result from the twisting action of the wire as it is bent (within the elastic range) to engage the brackets. Placement of the suggested amount of buccal root torque (45°) in the wire offsets this twisting factor and results in a significant level of buccal root torque being delivered to the molar brackets. The torque on molars is intended by the designers of the UAW to place the molar roots in cortical bone to increase the anchorage capability of the molars. Molar expansion is included clinically in the UAW so that the wire torque is expressed as buccal root torque as opposed to lingual crown tip.

Fig. 9 The phenomenon of corollary forces in a utility archwire is depicted in analogy to a tire iron. The forces operating on a tire iron as a result of a mechanic lifting at one end are shown.

Corollary Forces Resulting From Wire Torque

The addition of torque to the wire results in increased intrusive force on incisors, increased extrusive force on molars, and increased distal crown tip on lateral incisors. The changes in force levels are small in each case. The principle of converting torquing force along an archwire into intrusive and extrusive forces (or vice versa) may be demonstrated by the analogy depicted in Figure 9. In this illustration a man is changing a tire and is shown using a tire iron to loosen a nut. The tire iron is analogous to one half of the archwire. The man applies an upward force to one end of the tire iron. This results in the following forces:

1) A twisting (torsional) force on the nut at the other end of the tire iron. This torsional force along the tire iron is equivalent to what orthodontists refer to as "torque."
2) An upward force on the nut tending to lift the car (or a downward force on the tire iron applied by the nut).

This combination of intrusive, extrusive, and torquing forces generated in the tire iron is similar in principle to the force combination observed in the UAW, although the situations are not fully analogous.

Corollary Forces Resulting From Wire Rotation

The addition of molar rotation to the archwire had no notable influence on the measured forces (namely intrusion/extrusion, tip, and torque) except for the torque delivered to the lateral incisors. The measured torque values increased with molar rotation. This result is misleading. The apparatus, as designed, does not differentiate between buccolingual force and torquing force. The ligation of a wire with molar rotation into the molar brackets changed the arch form by constricting the curve in the anterior segment which in turn resulted in a lingual force to the lateral incisors. The observed increase in the torque delivered to the lateral incisors was in reality a measure of this lingual force caused by the change in arch form. This fact was confirmed by remeasuring the wires with the anterior brackets repositioned to follow the altered arch form. This new arrangement resulted in no buccolingual force and the torque delivered to the lateral incisors was seen to be unaffected by molar rotation.

Molar rotation was the only component bend in the UAW that had a measurable influence on arch form when the wire was ligated in place.

The clinical implication is that the arch form in the anterior segment should be flattened when molar rotation is included in the UAW to account for the arch form changes that occur with wire ligation.

Force Level

The force level for incisor intrusion was measured to be greater than that intended by the designers of the UAW (suggested total: about 80 grams). This is not a significant finding, however, since the force level varies substantially with the amount of molar tip-back and the length of the buccal bridge. The 30° molar tip-back used in this study is a level that is merely suggested as a guideline, and the user must vary the tip-back to achieve the desired force level.

Intraoral Adjustments

Intraoral adjustments are commonly performed by users of the UAW but were not included in this study. A typical adjustment is to increase molar tip-back by placing a gable bend adjacent to the molar tip-back bend. Such adjustments obviously change force magnitude and can easily change force direction. This would be a fruitful area for study since intraoral adjustments have the potential for undesired effects.

Summary and Conclusions

An apparatus was constructed to measure the forces delivered by an archwire and was used to study the forces in the utility archwire.

The nature and magnitude of forces delivered by a wire to teeth were examined for a UAW of average dimensions. The various component bends were made sequentially to determine the relative contributions of the various bends.

The findings are summarized as follows:

1) In general, the prescribed bends in the UAW result in forces that coincide with the intended actions of the wire.
2) Activation placed in a given part of the wire expresses itself almost totally between the two adjacent teeth. The other teeth in the arch are affected indirectly, when the resulting tooth movement itself causes stress in successive sections of the archwire.
3) The force level is initially unequal between central incisors and lateral incisors. Unequal force levels probably persist as the incisors intrude.
4) A distal tipping-force is initially delivered to lateral incisors.
5) The extrusive force on molars equals the intrusive force on incisors.
6) Wire torque in the posterior segment has little influence on intrusive, extrusive, and tipping forces.
7) Ligation of a UAW with a molar rotation bend influences the arch form.

As a result, the following modifications in the UAW are suggested:

1) The placement of a slight vertical bow in the anterior segment to achieve an even force distribution between the central and lateral incisors.
2) Reducing the arch form curvature in the anterior segment when molar rotation is included in the wire.

Orthodontic Dept.
School of Dentistry
Univ. of Calif., Los Angeles
Los Angeles, California
90024

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