Evaluation of rotational control and forces generated during first-order archwire deflections: a comparison of self-ligating and conventional brackets


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SUMMARY The purpose of this study was to compare the activation and deactivation forces generated during first-order archwire deflections when different sizes and types of NiTi wires are paired with conventional and self-ligating brackets (SLBs) and to evaluate the rotational control between these same archwire and bracket combinations. Four maxillary premolar SLBs (Damon 3MX, SmartClip, Carriere, and In-Ovation R) and one conventional twin bracket (Victory) were paired with seven archwires [0.014, 0.016, 0.018, 0.016 x 0.022 Ultra Therm (thermal A,80-90°F), 0.016, 0.018 SPEED Supercable, and 0.017 x 0.025 Turbo]. A cantilever test design was used and 10 trials per bracket/archwire combination were performed. Load/deflection data were captured over 4 mm first-order archwire deflections. Forces generated were compared across all bracket/archwire combinations. Among thermal archwires, for a given deflection, forces increased with increasing archwire size. Supercable archwires displayed less force than their same size thermal counterparts. The Turbo archwire generated force values in between those of 0.016 and 0.018 thermal archwires. Rotational control improved with increasing wire dimensions and for a given archwire size. Rotational control among brackets generally ranked as follows: In-Ovation R > SmartClip > Carriere and Damon 3MX.

Introduction

First-order tooth movement, such as derotation of teeth, relies on the first-order (i.e. bucco-lingual) intrabrace couple, established by the two points of contact between the bracket, archwire, and ligature (Smith and Burstone, 1984). Traditionally, elastomerics or steel ties have been used to ligate the archwire to the bracket. These conventional ligation methods firmly seat the archwire in the bracket slot, essentially eliminating any first-order slop in the system, thereby providing the necessary rotational control (Bednar and Gruendeman, 1993). Rotational control describes the efficiency of the archwire/bracket system to fully correct rotations. If the wire is not fully seated in the bracket, then there is some loss of rotational control (Yeh et al., 2007). This loss of rotational control readily appears when using self-ligating brackets (SLBs).

In recent years, SLBs have flooded the market and become popular with orthodontists due to claims regarding improved treatment efficiency, among other proposed advantages (Eberting et al., 2001). Much of the research efforts on self-ligation have focused on the potential for decreased friction, particularly as it relates to sliding mechanics (Thorstenson and Kusy, 2001, 2002, 2003, 2004). The second-order (i.e. occluso-gingival) couple between the bracket and archwire provides the uprighting moment as teeth tip during space closure. However, since the ligation method affects the bucco-lingual slot dimension and the seating of wire in the bracket, it would appear to play an increased role in first-order couples, thereby affecting rotational control. Furthermore, scientific data are scarce in the evaluation of self-ligation and its effects on rotational control (Pandis et al., 2008a).

In addition to ligation methods and bracket dimensions, the archwire size plays a major factor in rotational control. For SLBs, larger dimension archwires improve rotational control by decreasing bucco-lingual slop in the system. However, larger dimension archwires generally do not have the force profiles needed to engage them into brackets on misaligned teeth. In an effort to decrease force levels, manufacturers have developed thermal and multi-stranded NiTi archwires, which may allow for earlier engagement of larger dimension archwires; hence, earlier rotational and torque control.

The amount of rotational control for any given archwire/bracket combination can be calculated geometrically using the known variables: effective bracket width, bracket slot...
depth, and archwire depth (Kusy and Whitley, 1999). However, the bracket dimensions and ligation method vary with type of bracket; therefore, for any given wire size, the rotational control for each bracket may be different. While placing larger size archwires would increase rotational control, their traditionally higher force levels prevent engagement of these wires early in treatment. However, with new advances in archwires, this may no longer be the case.

The objectives of this study were:

1. To compare the activation and deactivation forces generated during first-order archwire deflections between different NiTi wire sizes and types when paired with conventional and SLBs.
2. To evaluate the rotational control, or amount of first-order bracket play, between different NiTi wire sizes and types when paired with conventional and SLBs, as well as to compare the experimental amount of bracket play with that predicted mathematically.

Hypotheses

1. Large dimension multi-stranded NiTi archwires can produce activation and deactivation forces comparable to small dimension NiTi archwires, when used with conventional and SLBs.
2. Brackets with increased effective bracket width and/or decreased bracket slot depth will provide improved rotational control.

Materials and methods

Part I

The first part of the study focused on evaluating different archwire/bracket combinations during first-order archwire deflections. A cantilever test design was used and archwire deflections were performed using a Tinius Olsen H1-KS (Tinius Olsen Inc., Horsham, Pennsylvania, USA) mechanical testing machine. A 12 mm segment of archwire, cut from the visually straight posterior section of a preformed archwire, was ligated into the bracket and extended 5 mm beyond the termination of the bracket slot to the point of force application (Figure 1). This amount of extension was arbitrarily chosen as an average clinical interbracket distance. The archwire was loaded and unloaded over a range of 4 mm at crosshead speeds of 3 mm/minute until a force value of 2 g, 0.5 mm/minute until a force value of 5 g, and 10 mm/minute for the remainder of the deflection.

The archwire types and dimensions tested are listed in Table 1. The brackets, including the method of ligation, are described in Table 2. All brackets were maxillary premolar brackets with MBT prescriptions. Gray elastomerics from ClassOne Orthodontics (Class One, Carlsbad, California, USA) were used to ligate the archwire to the conventional twin bracket. Each archwire/bracket combination was tested 10 times with a new 12 mm segment of archwire for each trial. In the case of the conventional bracket, a new elastomeric was used for each trial.

The testing machine consisted of a vertical load cell (50 N maximum load) and a vertical moving carriage encased in a plexiglas cabinet for temperature control. The temperature inside the cabinet was set at 100°F to ensure that the thermal archwires were thermally active. The wires were left inside the setup for at least 5 minutes prior to testing to allow time for them to acclimate to the temperature inside the cabinet. The testing machine recorded force–deflection data.

Part II

The critical angle (Figure 1) describes the amount of bracket play in the system and can be calculated for any bracket/archwire combination using the following equation (Kusy and Whitley, 1999):

\[
\theta_c = \cos^{-1} \left( \frac{(\text{depth})^2 - (\text{width})^2}{(\text{depth})(\text{slot}) - ((\text{width})^2 + (\text{depth})(\text{slot}) + (\text{width})^2)} \right)\right)^{1/2}.
\]

A Vertex 220 Measuring Machine (Micro-Vu Corp., Windsor, California, USA) was used to accurately measure
the effective bracket width and bracket slot depth for each of the four SLBs (Table 3). Archwire depths were measured using a digital caliper (Mitutoyo, Japan). Each dimension was measured three times to generate average values (Table 4). These measurements were used to calculate the predicted critical angles, or amounts of bracket play, for all bracket/archwire combinations.

To evaluate the reproducibility of the experiments, measurements for four wire types with all bracket type combinations were performed at a second time point. Second time point measurements were obtained through double measurements for all the brackets with the following archwires: 0.016 Ultra Therm, 0.016 × 0.022 Ultra Therm, 0.016 Supercable, and 0.017 × 0.025 Turbo wires at 3 mm of activation and deactivation. Additionally, all the measurements for the wire sizes and bracket outer and inner widths were repeated. All measurements were performed by a single examiner (RP), who mounted all the wires and bracket couples, and later verified by a second examiner (NJ). Intra-examiner and inter-examiner reliability analysis was performed for all double measurements for the two different time points. An intraclass correlation coefficient was obtained for all double measurements yielding results between 0.96 and 0.99 for all bracket combinations, wire sizes, and for all bracket outer and inner widths measurements, indicating excellent reproducibility.

Statistical methods

Statistical analyses were performed using SPSS version 17.0 (SPSS, Inc., Chicago, Illinois, USA). Data were examined to insure that the assumptions (normality of distribution and homogeneity of variance) for planned parametric statistical tests were satisfied in accordance with procedures recommended by Tabachnick and Fidell (2007). Analyses of variance (ANOVA) were used to examine differences in the mean activation and deactivation forces at 1, 2, and 3 mm of cantilever deflection across all bracket/archwire combinations, as well as to examine differences in bracket play across the same independent variables. Subsequent post hoc analyses using t-tests were used to examine specific combinations of variables by bracket/archwire type. The P-value for the main ANOVA analyses was set at 0.05. The P-value for the paired comparisons used a corrected value based on Bonferroni’s method to avoid inflating type I statistical error rates. By convention, any significant differences were reported by indicating P-values <0.05.

Results

Since deactivation forces are of main interest in clinical orthodontic tooth movement, these results are presented initially and in more detail.

Deactivation forces at 1 mm of cantilever deflection

Figures 2–8 provide the mean deactivation forces at 1 mm of cantilever deflection across all bracket/archwire combinations. Negligible forces (less than 2 g) were generated when the Carriere and Damon 3MX brackets were paired with all the round wires (P’s > 0.05), with the exception of 0.018 Ultra Therm. The In-Ovation R and SmartClip brackets paired with the 0.016 Supercable also generated negligible force magnitudes (P’s > 0.05). Within a particular wire type (i.e. Ultra Therm and Supercable), force magnitudes generally increased with increasing wire sizes (P < 0.05). However, the 0.016 and 0.018 Supercable wires generated less force across all bracket combinations compared to the same size Ultra Therm wire (P < 0.05). Although a larger sized wire, the Turbo wire generated significantly less force across each bracket than the 0.016 × 0.022 Ultra Therm (P < 0.05).

Deactivation forces at 2 mm of cantilever deflection

Figures 2–8 provide the mean deactivation forces at 2 mm of cantilever deflection across all bracket/archwire
combinations. Forces across all archwire/bracket combinations were greater than those generated at 1 mm of deactivation ($P$'s < 0.05) and increased significantly with larger archwire size across their respective type (i.e. Ultra Therm and Supercable; $P$'s < 0.05). The forces generated for the Supercable pairings were less than those for the same diameter Ultra Therm archwires ($P$'s < 0.05). The Turbo wire deactivation forces at 2 mm of deflection were most comparable to those of the 0.018 ULTH.

**Deactivation forces at 3 mm of cantilever deflection**

Figures 2–8 provide the mean deactivation forces at 3 mm of cantilever deflection across all bracket/archwire combinations. Similar trends described for forces at 2 mm of deflection were seen for those at 3 mm of deflection.

**Activation forces at 1 mm of cantilever deflection**

Forces at 1 mm of cantilever deflection across all bracket/archwire combinations were similar to the deactivation results at 1 mm of deflection. As expected, activation forces at 1 mm of archwire deflection were greater than deactivation forces at 1 mm of deflection ($P$'s < 0.05). Force magnitudes generated by the Turbo wire paired with the Carriere and Damon 3MX brackets most closely resembled those generated with the 0.018 Ultra Therm ($P$'s > 0.05), while

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**Table 3** Mean bracket dimensions (inches) measured using Vertex 220 Measuring Machine.

<table>
<thead>
<tr>
<th>Bracket</th>
<th>Inner width (inch)</th>
<th>Outer width (inch)</th>
<th>Effective width (inch)</th>
<th>Slot depth (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Victory</td>
<td>n/a</td>
<td>0.11450</td>
<td>0.11450</td>
<td>n/a</td>
</tr>
<tr>
<td>Damon 3MX</td>
<td>0.08420</td>
<td>0.09940</td>
<td>0.09180</td>
<td>0.02950</td>
</tr>
<tr>
<td>Carriere</td>
<td>0.09170</td>
<td>0.11700</td>
<td>0.10432</td>
<td>0.02890</td>
</tr>
<tr>
<td>SmartClip</td>
<td>0.13450</td>
<td>0.15860</td>
<td>0.14655</td>
<td>0.02780</td>
</tr>
<tr>
<td>In-Ovation R</td>
<td>0.11060</td>
<td>0.11640</td>
<td>0.14655</td>
<td>0.01970</td>
</tr>
</tbody>
</table>

**Table 4** Mean archwire depth (inches) measured using digital calipers.

<table>
<thead>
<tr>
<th>Archwire</th>
<th>Measurement #1 (inch)</th>
<th>Measurement #2 (inch)</th>
<th>Measurement #3 (inch)</th>
<th>Average (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.014 ULTH</td>
<td>0.01365</td>
<td>0.01370</td>
<td>0.01360</td>
<td>0.01365</td>
</tr>
<tr>
<td>0.016 ULTH</td>
<td>0.01595</td>
<td>0.01590</td>
<td>0.01590</td>
<td>0.1592</td>
</tr>
<tr>
<td>0.016 Supercable</td>
<td>0.01520</td>
<td>0.01495</td>
<td>0.01495</td>
<td>0.01503</td>
</tr>
<tr>
<td>0.018 ULTH</td>
<td>0.01770</td>
<td>0.01775</td>
<td>0.01770</td>
<td>0.01772</td>
</tr>
<tr>
<td>0.018 Supercable</td>
<td>0.01685</td>
<td>0.01695</td>
<td>0.01710</td>
<td>0.01697</td>
</tr>
<tr>
<td>0.016 × 0.022 ULTH</td>
<td>0.02160</td>
<td>0.02185</td>
<td>0.02165</td>
<td>0.02170</td>
</tr>
<tr>
<td>0.017 × 0.025 Turbo</td>
<td>0.02395</td>
<td>0.02415</td>
<td>0.02405</td>
<td>0.02405</td>
</tr>
</tbody>
</table>

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**Figure 2** Mean ($n = 10$) load versus deflection curve for 0.014 Ultra Therm.
Figure 3  Mean ($n = 10$) load versus deflection curve for 0.016 Ultra Therm.

Figure 4  Mean ($n = 10$) load versus deflection curve for 0.016 Supercable.

Figure 5  Mean ($n = 10$) load versus deflection curve for 0.018 Ultra Therm.
Figure 6  Mean \( (n = 10) \) load versus deflection curve for 0.018 Supercable.

Figure 7  Mean \( (n = 10) \) load versus deflection curve for 0.016 \( \times \) 0.022 Ultra Therm.

Figure 8  Mean \( (n = 10) \) load versus deflection curve for 0.017 \( \times \) 0.025 Turbo.
forces generated when paired with the other three brackets were less than the 0.016 Ultra Therm ($P$'s < 0.05).

**Activation forces at 2 mm of cantilever deflection**

Forces at 2 mm of cantilever deflection across all bracket/archwire combinations showed the same tendencies observed at 2 mm of deactivation. The Turbo wire forces were less than those of the 0.016 Ultra Therm ($P$'s < 0.05).

**Activation forces at 3 mm of cantilever deflection**

The mean activation forces at 3 mm of cantilever deflection across all bracket/archwire combinations showed similar trends described for activation forces at 2 mm.

**Predicted rotational control**

Predicted amounts of bracket play for the SLBs were calculated and are shown in Figure 9. Tables 3 and 4 provide the bracket and wire dimensions used in the calculation for bracket play. The Victory bracket was excluded because the amount of bracket play is theoretically zero. If the normal force of the elastomeric fully seats the wires in the bracket slot, then there is no bracket play in the buccolingual dimension.

As archwire depth increased, the bracket play decreased regardless of bracket type. Among SLBs, the Carriere and Damon 3MX brackets demonstrated the most amount of bracket play across wire sizes, followed by the SmartClip bracket. The In-Ovation R bracket demonstrated the least amount of bracket play among the SLBs, with zero bracket play upon placement of wires with an archwire depth greater than or equal to 0.022.

**Experimental rotational control**

These same trends in regards to bracket play could be seen experimentally as well. The deactivation forces decreased to zero for the Damon 3MX and Carriere brackets at about 1.25 mm of cantilever deflection, followed by the SmartClip at approximately 0.9 mm of deflection, and the In-Ovation R at about 0.8 mm of deflection. This same trend continues across each of the different archwires (Figures 2–8). The deflections required to generate 1 g of force were used to calculate experimental amounts of bracket play. We arbitrarily chose 1 g of force as the threshold for satisfying the rotational couple.

In general, the amounts of bracket play decreased with increasing archwire depth, regardless of bracket type, with the Turbo wire providing the least amount of bracket play ($P < 0.05$; Figure 10). The Carriere and Damon 3MX brackets behaved similarly ($P$'s > 0.05) and had the greatest amounts of bracket play across wire sizes ($P$'s < 0.05). The In-Ovation R bracket demonstrated the least amounts of bracket play among the SLBs ($P$'s < 0.05).

**Discussion**

The focus of this research centered on rotational control during the alignment phase of orthodontic treatment. A cantilever model was chosen in an effort to eliminate the influence of sliding frictional resistance when measuring the activation/deactivation load. The influence of friction is limited because the wire is not required to slide through the bracket slot during deflection. A buccal deflection was utilized so that the force was imparted on the ligation mechanism.
Manufacturers provide force values for their wires based on three point load tests. For rectangular wires, these tests are conducted such that the force is applied perpendicular to the ribbon side of the archwire. Besides being a cantilever test as opposed to a three point load test, our wires were tested with the force applied perpendicular to the edgewise dimension. Hence, force magnitudes obtained in this study should not be expected to coincide with manufacturer published force values. For obvious reasons, the force magnitudes obtained do not provide an accurate assessment of actual force magnitudes that might be obtained in a true clinical situation. While force magnitudes may not represent true clinical values, the force values do allow for comparisons between wires.

Among Ultra Therm wires, forces magnitudes increased with increasing wire size across each bracket. With few exceptions, forces also increased with increasing activation and deactivation deflections. As expected, the forces generated for the Supercable pairings were less than those for the same diameter Ultra Therm archwires. The Supercable wires have been shown in previous studies to exert less force than thermally activated NiTi wires of similar gauge (Berger et al., 1998; Berger and Waram, 2007). The Turbo wire generated forces less than a smaller sized 0.016 × 0.022 Ultra Therm wire. In fact, the Turbo wire often demonstrated force magnitudes less than those of the 0.018 Ultra Therm.

We found that at 1 mm of deflection, some of the archwire/bracket combinations generated little, if any, force. This suggests that the critical angle was not yet satisfied by the system at 1 mm of cantilever deflection. Due to the bracket play remaining in the system, no rotational couple could be formed; hence, no additional rotational correction could be expected by these combinations. By 2 mm of cantilever deflection, all archwire/bracket combinations demonstrated forces, suggesting that the critical angles must have been satisfied between 1 and 2 mm of cantilever deflection. Bracket play values for the Carriere and Damon 3MX brackets support the findings at 1 mm of deflection.

When comparing among brackets, the bracket play for the Carriere and Damon 3MX pairings was consistently greater across all archwire sizes. Additionally, the Carriere and Damon 3MX behaved similarly for each combination. As a result of increased bracket play, the Carriere and Damon 3MX brackets have decreased rotational control compared to the other two SLBs. Approximately 8–10 degrees of rotation remain uncorrected when the Carriere and Damon 3MX brackets are paired with the 0.014 Ultra Therm. While having decreased bracket play compared to the Carriere and Damon 3MX, SmartClip exhibited greater bracket play than In-Ovation R. The In-Ovation R bracket displayed the best rotational control.

A closer look at the dimensions of the SLBs, particularly the bracket slot depth, helps explain the differences in performance. The Carriere and Damon 3MX brackets have a similar ligation mechanism, passive sliding doors, with similar slot depths. The SmartClip has a slightly smaller slot depth, while the In-Ovation R bracket has a considerably smaller slot depth due to the invading nature of its spring clip ligation mechanism. As a result of slot depth size, the
Carriere and Damon 3MX brackets exhibit more bracket play and less rotational control for a given wire size, contrary to the In-Ovation R bracket. For a given wire size, rotation control among SLBs generally ranked as follows: In-Ovation R > SmartClip > Carriere and Damon 3MX.

As suggested by the predicted bracket play results, the experimental bracket play across each SLB decreased as the archwire depth increased. Practically, an orthodontist’s ability to affect rotational control lies solely in the choice of wire and filling the buccolingual slot dimension since bracket dimensions are set by manufacturers. When using SLBs, archwires must be built-up in order to obtain full rotational control. However, our results for the 0.017 × 0.025 Turbo wire might suggest otherwise. Traditionally, there is a tradeoff between force value and wire size because increases in wire size result in increases in forces. In order to keep force magnitudes low, smaller size archwires must be utilized early in treatment. However, as our results demonstrated, smaller round wires used in combination with SLBs result in increased amounts of bracket play, thereby preventing full rotational control. The Turbo wire exhibited the best rotational control of the wires tested due to its increased size but also demonstrated activation and deactivation force values similar to smaller, round thermal NiTi wires. The 0.016 × 0.022 Ultra Therm displayed activation forces at 3 mm of deflection that were more than double those of the Turbo wire. At 3 mm of deflection, activation forces for the 0.016 × 0.022 Ultra Therm exceeded 200 g. At such high force levels, ligation would be difficult and could result in bond failure at the bracket/enamel interface. With a force profile similar to smaller, round thermal NiTi wires, the Turbo wire would appear to be able to be ligated with considerable ease, deliver low constant deactivation forces, while also providing efficient rotational control. Additionally, some torque control could be expected earlier in treatment since the Turbo wire is rectangular.

Ligation differences between conventional brackets and SLBs affect archwire selection early in treatment. The normal force exerted on the archwire by the elastomeric in a conventional bracket/archwire interface plays a key role in activation of the wire in first-order archwire deflections. If the normal force applied by the elastomeric is strong enough to fully engage the archwire in the slot, then the bracket play is essentially zero. Therefore, the Victory bracket would be predicted to have the best rotational control. Practically, there can be some loss of rotational control if the force of deflection overpowers the normal force of ligation preventing full engagement of the wire in the bracket. This was clearly demonstrated in our study when the Victory bracket was paired with the 0.016 × 0.022 Ultra Therm. In certain instances, orthodontists have traditionally used metal ligature ties instead of elastomerics to ensure full wire engagement; however, there is a possibility of debonding the bracket if too much ligation force is applied using a metal ligature. Furthermore, at greater forces, the elasticity of the active spring or the closing door may have an impact on the moment generated and therefore rotational control (Pandis et al., 2008b).

One of the drawbacks of this study is that it does not take into account the effect that the oral environment has on elastomerics and how this might affect the amount of normal force applied to the archwire with time. An additional study to evaluate the effects of force decay (stretching over the bracket wings) and a wet field (artificial saliva) on elastomerics, and subsequently, their effects on the amount of bracket play and forces generated for first-order archwire deflections may be warranted.

Based on the design and in vitro nature of this study, it is reasonable to assume that values obtained do not accurately represent what may be occurring clinically. Numerous factors, including but not limited to, multiple bracket engagement, friction, interbracket distance, oral environment, amount of crowding, play a major role in the true clinical response (Nanda and Ghosh, 1997). Future clinical studies may be warranted to evaluate forces and rotational control among different archwire/bracket combinations. However, we believe this study furthers the knowledge about factors affecting rotational control, establishes trends among several popular archwire/bracket combinations, and provides a strong foundation for future clinical research in this area.

**Conclusions**

The focus of this research was on the relationship between archwire and bracket in forming a first-order couple to rotate teeth in the axial plane. We examined the first-order couple generated between NiTi wires paired with conventional twin and SLBs in an effort to provide clinical recommendations to improve efficiency of rotational correction. We concluded the following:

1. Among archwire types (i.e. Ultra Therm and Supercable), for a given deflection, forces increased with increasing archwire size.
2. Supercable wires displayed less force than their same size thermal counterparts.
3. The Turbo archwire generated forces equivalent to smaller round thermal archwires.
4. Rotational control improved with increasing wire dimensions.
5. For a given archwire size, rotational control among SLBs generally ranked as follows: In-Ovation R > SmartClip > Carriere and Damon 3MX. Differences in bracket slot depth appeared to be responsible for differences in rotational control.
6. With a force profile similar to smaller round thermal archwires, the Turbo wire may be ligated early in treatment and provide improved rotational control and initial torque control, particularly when used with SLBs.
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References