Original Article

Biomechanics of Torque from Twisted Rectangular Archwires

A Finite Element Investigation

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ABSTRACT

Objective: To evaluate the magnitudes of initial and subsequent sequential deactivational third-order moments generated in rectangular twisted archwires (either when the archwires are actually twisted before insertion in the standard edgewise bracket slots or when they are indirectly twisted in the preadjusted slots of the modern edgewise brackets) in order to judge their biologic acceptability.

Materials and Methods: A finite element study was carried out with the MSC Patran/Nastran interface. Three-dimensional models were constructed with 170 nodes of upper 0.017- × 0.025-inch and 0.019- × 0.025-inch archwire segments extending bilaterally from the maxillary central incisors to the first premolars. Required twists were applied at the appropriate locations to derive the applied and reactionary moments both initially and during the time needed for complete deactivation.

Results: The results indicated that a round-tripping possibility does exist in certain clinical procedures. Furthermore, the moments produced could be quite high, thereby enhancing the possibility of root resorption.

Conclusions: Twists in rectangular archwires may be used only when reciprocal torque is needed on adjacent teeth. In other situations, alternative torquing methods should be considered.

KEY WORDS: Torque; Archwire twist; Biomechanics

INTRODUCTION

Faciolingual control over root positions of all the teeth is of vital importance for optimal esthetic, functional, and health outcomes of orthodontic treatment and for the stability of results. The third-order relationship of a rectangular archwire in the rectangular bracket slots is expected to provide such control over the roots. This archwire–bracket slot relationship is altered in either of two ways: the operator may actually twist the archwire when using standard edgewise brackets, or the archwire may be indirectly twisted by the built-in torque in preadjusted edgewise (PAE) brackets. Strangely enough, the reciprocal effects on the adjacent teeth from these twists are rarely considered. Although the empirical clinical practice appears to be effective in controlling root positions, a sequence of teeth movements from the time the torque is applied until the archwires are deactivated needs to be evaluated in order to detect if any round-trip root movements occur during these clinical procedures.

Over the years, many authors[1–3] have acknowledged that the torquing mechanism is not well understood. Reciprocal torque in the opposite direction on the adjacent teeth was mentioned as early as 1933 by Brodie[1] and later by others, such as Thurow.[4] However, the complexity that arose on account of this reactive effect was not considered seriously until Isaacson et al[5] focused attention on it in 1993. They hypothesized that if four teeth in a row, with the brackets placed at equal distance from one another, are connected with a straight piece of rectangular wire, and if progressive incremental torque

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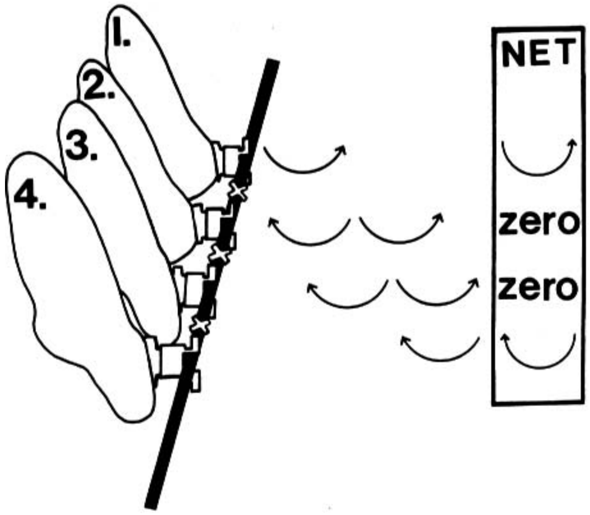

Figure 1. Interplay of applied and reactive moments in progressive incremental torque (reprinted from Isaacson et al,[5] reproduced with permission from American Association of Orthodontists).

is built in the archwire for moving the roots of three consecutive teeth in the same direction, only the roots of the first and last teeth will experience torquing moments in opposite directions. The middle teeth will experience no moments at all because of neutralization of the applied moments by reactive moments (Figure 1).

If this hypothesis is correct, it would apply to any group of three or more teeth. A common clinical practice that is analogous to the above situation is where incremental torquing bends are placed for torquing the roots of maxillary central and lateral incisors in the lingual direction.[6] The incremental twists for attaining such torque are placed on both sides between the upper lateral incisor and cuspid and between the central and lateral incisors. Applying the above reasoning to this group of three teeth (central incisor, lateral incisor, and cuspid) on either side, the central incisor and the cuspid roots should experience torque in lingual and labial directions, respectively, whereas the lateral incisor root should experience no moment at all. In clinical practice, however, both the lateral and central incisors undergo lingual root torque over a period of time. Even allowing for some differences between this situation and the above hypothetical one (namely, that in the clinical situation a curved segment of archwire connects the teeth and not a straight length and that the brackets are not equidistantly placed), an explanation to bridge the gap between the theory and practice is needed.

The probable explanation is that the effects mentioned by Isaacson et al[5] are the initial effects of a torqued archwire on the teeth. As the torque starts to express on the end teeth in the group (central incisor and cuspid in this case), thereby causing their displacement, the applied torquing moments on them would gradually diminish, as would the corresponding reactionary moments on the middle teeth (lateral incisor in this case). The twists in the archwire may then start acting on the middle teeth, and ultimately these teeth might be torqued. However, a step-by-step construction needs to be worked out to detect if any round-trip movement takes place during this whole process. Other situations such as twists in the archwire for torquing two teeth in the same direction or torquing a single tooth and the effects of a "straight" archwire in the pretorqued brackets need to be similarly studied.

These considerations are related not only to the mechanical efficiency of the appliances we use routinely, but also to their biologic effects that could be harmful, because round-trip root movement has been implicated in root resorption.[7] Furthermore, the magnitudes of torquing moments generated by archwires in various dimensions and of various materials need to be estimated, because it is also postulated that excess torquing moments may be responsible for damage to the roots or the cortical plates.

Therefore, we believe there is a need to investigate the above issues related to torsional behavior of the edgewise rectangular archwires. Thus, the present study was undertaken with the following aims and objectives:

a. To verify the hypothesis of Isaacson et al[5] regarding the effects of progressive root torque on a group of four teeth from a straight length of wire as well as from the curved portion of an archwire initially and after some tooth movement.
b. To determine the actions and reactions in an edgewise archwire when twisted for producing torque in different situations and how the effects might alter over time in order to ascertain if there is any round-trip movement involved.
c. To explore the effects of built-in torque on upper anterior teeth in one of the PAE appliances.
d. To estimate the moments generated by archwires of different sizes and materials when twisted for the above torquing actions in order to judge their biologic suitability.

MATERIALS AND METHODS

The finite element method (FEM) is an excellent engineering tool to study problems of this nature. Its accuracy in analyzing the stresses and strains in objects such as an archwire is very high when it is provided with correct material properties, structural configuration, and loads. We used the Patran/Nastran FEM software for our study.

Three-dimensional (3D) models of an edgewise

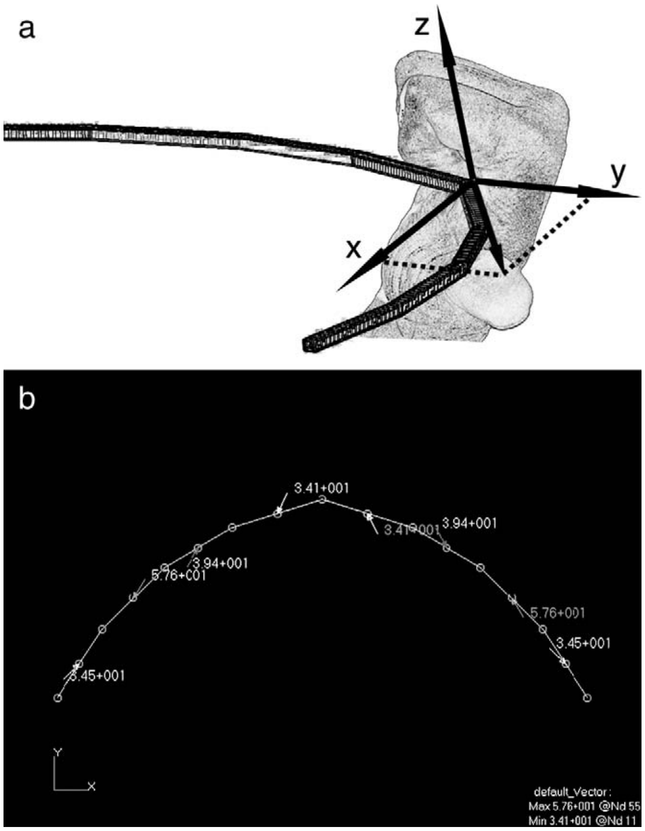

Figure 2. (a) Global co-ordinate system showing the twist (resolved) along global x- and y-axes according to the right-hand thumb rule. (The rule implies that when the thumb points in the axis of direction of rotation, the direction in which the remaining fingers curl indicates the sense of direction of twist or moment). (b) Finite element model depicting moments generated.

archwire were created both as a straight length and as the anterior segment of an upper archwire (Figure 2). The archwire span included four teeth bilaterally from the central incisor to the first premolar and was made with 170 nodes. The length of the archwire was 6.06 cm according to the average crown sizes. Known material properties of stainless steel viz Young's modulus (1.79×10^5 Nmm^2) and Poisson's ratio (0.3) were assigned. As per the expert's (author SA) advice, it was not necessary to model the brackets because application of appropriate boundary conditions at the bracket locations replicates the precise archwire-bracket interface. The analysis made use of the 3D beam element from the Nastran element library. This element is capable of accurately modeling axial, flexural, and shear deformations. An elastic analysis was carried out iteratively to account for geometric nonlinearity and large deformations.

The archwire was modeled in the xy-plane of the global coordinate system. All torquing forces were applied along the plane of the archwire as forced rotational displacements. The torsion of the wire was applied as a rotational displacement, with the axis of rotation coinciding with the plane of the wire. This simulated twisting of the wire was performed as if torque were introduced into it. Because the software did not permit application of boundary conditions in directions other than along the global coordinate axes (ie, the x-, y-, and z-axes), the twists had to be resolved along the x- and y-axes. This is shown in Figure 2a. The last tooth in the group was restrained from all movements including rotations. In some cases this tooth was the first premolar, whereas in others it was the canine or even the lateral incisor. This was performed to simulate a cinch-back.

Table 1. Comparison of moments generated by twisting 0.018- $\times$ 0.025-inch stainless steel wire by 1° in laboratory and FEM studies[a]

Range of play	Mean play	Experiment range of moments produced	Mean value of moment–experimental, Nmm	Moment generated in FEM study, Nmm
2.98–6.31	4.6	3.24–4.79	3.86	3.39

[a] FEM indicates finite element method.

The accuracy of this approach was validated by simulating the classic laboratory study of Meling et al[8] in the same software and comparing the findings with the original study. A twist of 1° was applied to a straight-length 0.018- $\times$ 0.025-inch SS wire, engaged in three brackets spaced at 4 mm, in order to compute the moments generated. The values obtained by the FEM closely matched those in the experimental study (Table 1).

After completing this step, torquing moments in 0.017- $\times$ 0.025-inch and 0.019- $\times$ 0.025-inch archwires were studied. The desired torquing displacements, to simulate applied twists in the archwire or those from built-in torque in the brackets, were applied at the correct locations on the archwire models for computing applied moments.

The reactive moments (both initial and also over time from wire relaxation as a result of tooth movements) arising in the archwire at other locations were then derived by the FEM (Figure 2b).

The procedure for deriving the sequence of altering moments consequent to tooth displacements was as follows:

a. Initial twisting bends of 10° each were applied at the desired locations, and the reactionary moments at various other locations were obtained by FEM computations. (One tooth outside the group of teeth under consideration was included as the anchor tooth, which provided the resistance for applied and reactionary moments to become effective.)
b. To simulate gradual tooth movement and conse-

quent deactivation of the archwire, the teeth subjected to the above moments were permitted root displacements (by altering displacement boundary conditions) in small steps of 1.5° to 2°, which is the average root displacement per month seen in clinical experience. The resulting changes in the applied and reactionary moments were derived by the FEM.

c. The teeth continuing to experience sizeable moments were further permitted root displacements of 1.5° to 2°, and the change in applied and reactionary moments was again computed.
d. The process was continued in the same step-by-step fashion until the moments on all teeth were reduced to approximately 5 Nmm, which was considered the threshold moment needed for causing root displacement. At this point, the archwire was deemed to have been effectively deactivated by the displacement of roots of all teeth.

However, certain simplifications and assumptions had to be accepted as dictated by the nature of the study:

a. The software assumes that the archwire fits precisely in the bracket slot without any play (eg, it assumes a slot height of 0.019 inches for the archwire having the dimension 0.019 × 0.025 inches). Although this is not the clinical reality, it does not affect the applicability of findings to the clinical practice; what is depicted here is the clinically effective torque that acts on the teeth after the archwire-bracket play has been overcome. Thus, assuming that in a given clinical situation the archwire-bracket play is 10° and that a tooth is subjected to a torque of 10°, it would actually mean that a twist of 20° has been given in the archwire to overcome the 10° play. Because this play generally is uniform in all the brackets for any given archwire, the assumption of "no play" is fully justified.
b. The facts that the slot sizes in reality are slightly larger and the wire sizes are slightly smaller than the ones stated by the manufacturers and that the archwire edges are beveled were disregarded.
c. It was also assumed that all the brackets were perfectly leveled and aligned.

RESULTS

The results were obtained as resultant of twisting force (torquing) and bending of the archwire. This was displayed as arrows pointing in the direction around which the resultant moment was generated. Because the bending of the archwire has to be negated before insertion into the brackets, it was not taken into account. Hence, only the moment along the plane of the archwire was to be considered. This was not displayed in the pictorial output and had to be read from the text output file. The torque moment at each bracket (in Nmm) was calculated from the torque developed in the mesial and distal elements. This was then tabulated for each bracket.

Because the teeth were not modeled, the amount of tooth displacement was not determined in this study. However, tooth displacement was assumed to be in the direction of the torque developed in the wire.

The results are presented in the following groups of tables (positive values indicate lingual root torque, and negative values indicate labial root torque):

Table 2. Initial moments produced by progressive incremental torque in a straight length of wire, and the subsequent alteration in the moments from 2° of root displacement at either end

	Torquing moments on each tooth, Nmm			
Activation, °	Tooth 1	Tooth 2	Tooth 3	Tooth 4
Tooth 1: 0 Tooth 2: 10 Tooth 3: 20 Tooth 4: 30	−19.5	0	0	19.5
Tooth 1: −2 Tooth 2: 10 Tooth 3: 20 Tooth 4: 28	−15.3	−3.8	4	15.1

Table 3. Initial moments from progressive incremental torque in a curved segment of archwire

	Torquing moments on each tooth, Nmm			
Activation, °	Right lateral	Right central	Left central	Left lateral
Right-lateral: 0 Right-central: 10 Left-central: 20 Left-lateral: 30	−19.46	8.97	−1.68	33.1

Verification of Isaacson's Hypothesis (Tables 2 and 3)

Table 2 confirms the veracity of Isaacson's hypothesis for a straight length of archwire. As can be inferred, only the end teeth experienced equal and opposite torquing moments in spite of giving incremental torque. Thereafter, when the end teeth moved by 2°, the middle teeth started experiencing moments. The results differed slightly when a curved section of the archwire was studied (Table 3).

Initial and Subsequent Altered Moments in the Actively Twisted Archwires in Nontorqued Brackets (Tables 4 to 6)

The results of application of progressive torque to the maxillary lateral and central incisors are given in

Table 4. Initial and subsequent altered moments during progressive incremental torque applied to lateral and central incisors

Amount of torque, °	Torquing moments on each tooth, Nmm		
	Central	Lateral	Canine
Central: 20 Lateral: 10	30.74	−6.53	−13.76
Central: 18 Lateral: 12[a] Canine: −2	22.53	−0.23	−8.11
Central: 16 Lateral: 12 Canine: −4	17.62	−0.14	−0.08
Central: 14 Lateral: 12 Canine: −4	12.91	3.69	−0.06
Central: 12 Lateral: 12 Canine: −4	8.11	7.58	−0.08
Central: 10 Lateral: 10 Canine: −4	6.8	4.97	2.64

[a] It is assumed that the root of the lateral incisor will move labially owing to the moment generated. This will increase the archwire-bracket angle, and hence the resultant torque will be 12°.

Table 5. Initial and subsequent altered moments during lingual root torquing of two central incisors

Amount of torque, °	Torquing moments on each tooth, Nmm		
	Central	Lateral	Canine
10	23.94	−19.46	
8	15.8	−9.15	−2.76
6.5	9.49	−1.22	−4.8
5	3.4	6.43	−6.9
Central: 5 Lateral: 3.5	5.8	1.71	−4.84

Table 4. Although the initial moment on the central incisor was quite high (30.74 Nmm) and that the cuspid experienced a negative moment of much lesser magnitude (6.53 Nmm), the lateral incisor experienced a negative moment (13.76 Nmm) and not a zero moment. With deactivation, the moment on the central incisor gradually reduced whereas the moment on the cuspid dropped sharply and continued to be close to zero. The interesting observation was that when the root of lateral incisor moved labially because of the initial negative moment, the moment soon reduced and reached a value close to zero. Thereafter, it changed into a positive moment that gradually increased and then reduced.

Table 7. Initial and altered moments in the use of MBT brackets (cuspid bracket −7°)

Amount of torque, °	Torquing moments on each tooth, Nmm			
	Central	Lateral	Canine	Premolar
Central: 17 Lateral: 10 Canine: −7	23.42	13.4	−42.56	(13.93)
Central: 15 Lateral: 8 Canine: −5	22.12	6.89	−31.79	(10.4)

The moments generated during torquing of two central incisors for lingual root torque (with twists placed between the central and lateral incisors on either side) are given in Table 5. Although the moments generated on the central incisors were close to the optimum recommended value (23.94 Nmm) and in the lingual direction as intended, the lateral incisors experienced a labial root torquing effect of slightly lesser magnitude (19.46 Nmm) that may or may not be desirable. During deactivation, the labial root torque on the lateral incisors reduced sharply and then changed to lingual root torque. The cuspids, which were resisting the displacement of the lateral incisors, experienced a labial root torque that gradually increased and then reduced slightly.

The moments generated during torquing of a single tooth (Table 6) by both 0.019- × 0.025-inch and 0.017- × 0.025-inch SS archwires on the right central incisor were very high initially (39.19 Nmm and 30.21/Nmm). Although the moments on the left central and right lateral incisors were not very high to begin with, these dropped sharply when some relaxation in the wire was permitted to simulate small amount of root movement.

Moments Generated in a PAE Setup (MBT Prescription and 0.019- × 0.025-inch SS Archwires)

The moments differed considerably in the lateral incisor and cuspid area, depending on whether the upper cuspid brackets had a positive torque, negative torque, or zero torque (Tables 7 and 8). With −7° of torque in the cuspid brackets, the negative moments

Table 6. Initial and subsequent altered moments during single-root torquing (in this case, the right central incisor)

SS archwire size, inches	Activation	Torquing moments on each tooth, Nmm				
		Right canine	Right lateral	Right central	Left central	Left lateral
0.019 × 0.025	10		−19.29	39.19	−15.37	
0.019 × 0.025	8	−2.82	−9.14	24.68	−4.1	−3.81
0.017 × 0.025	10		−14.96	30.21	−11.97	
0.017 × 0.025	8	−2.2	−7.11	19	−3.24	−2.96

Table 8. Initial moments in the use of MBT brackets (cuspid bracket 0° or 7°)

Amount of torque, °	Torquing moments on each tooth, Nmm			
	Central	Lateral	Canine	Premolar
Central: 17 Lateral: 10 Canine: 0	23.42	−0.58	−13.76	
Central: 17 Lateral: 10 Canine: 7	23.42	10.22	15.05	(−13.93)

Table 9. Initial moments generated with the use of inverted upper lateral incisor bracket and cuspid bracket having 7°, 0°, or −7° torque

Amount of torque, °	Torquing moments on each tooth, Nmm			
	Central	Lateral	Canine	Premolar
Central: 17 Lateral: −10 Canine: 7	57.67	−79.35	42.56	(−13.93)
Central: 17 Lateral: −10 Canine: 0	57.67	−65.37	13.76	—
Central: 17 Lateral: −10 Canine: −7	57.67	−51.39	−15.05	(13.93)

on the cuspids were very high (42.56 Nmm) but dropped suddenly with small amount of relaxation in the archwire. Another interesting observation was that though the upper cuspid with 0° built-in torque was expected to experience no torquing moment, it did experience a negative moment of sufficient magnitude to be clinically effective (13.76 Nmm).

As can be seen in Table 9, the moments generated on the central incisor when the lateral incisor bracket was inverted were very high in all three situations (57.67 Nmm), and the negative moments on the lateral incisor were extremely high (79.35 Nmm) when the cuspid bracket had built-in torque of 7°. Although they were of lesser magnitude when the cuspid had 0° or −7° torque, they were still quite high (65.37 Nmm and 51.39 Nmm). The moment on the cuspid with its bracket having built-in torque of 7° was also very high (42.56 Nmm).

Torquing Moments from Various Wires

The moments mentioned in all the above tables are for the SS archwires. As can be seen, they are often quite high. A rough estimation of the moments generated by the TMA and NiTi archwires of equivalent sizes for similar situations can be made from their torsional stiffness ratio, which is SS:TMA:NiTi = 10:3:1.

DISCUSSION

Effects of Curvature in Modifying the Archwire Behavior

In recent years, it has been realized that the mechanics enunciated for two-dimensional models of straight length of wires need to be cautiously applied to the archwires, for the latter are 3D entities and their curvature is likely to affect the bending and torsional behavior. Isaacson et al[9] reported this in a subsequent article in connection with the "V" bend mechanics. Our study also noted this while assessing the veracity of Isaacson's hypothesis. It was validated in relation to a straight length of wire. However, when applied to the curved segment of the archwire, though the end teeth experienced moments in opposite directions their magnitudes were not the same. Furthermore, one of the two middle teeth experienced a moment close to zero, but the other middle tooth experienced a sizable amount of moment.

Possibility of Round-trip Movements in Certain Torquing Procedures

Our suggested explanation for the movement of middle teeth consequent to displacement of end teeth and gradual deactivation of archwires proved to be correct, as did our suspicion that some round tripping may occur during certain applications of torque.

Progressive incremental torque was introduced by the standard edgewise technique to overcome the reciprocal effects on the adjacent teeth from the wire twists. However, as was noted in the results, the root of lateral incisor in the simulated setup initially experienced a labial root torquing moment, which gradually reduced to zero and then changed to a lingual root torquing moment. This would mean that the lateral incisor is likely to experience some round tripping and that its total lingual root torque is much less than the torque undergone by the central incisor.

In the other situation simulating lingual root torque only on the maxillary central incisors (as in the treatment of a Class II division 2 situation), the roots of maxillary lateral incisors initially experienced an almost equal labial moment, which reduced sharply and then changed to a positive moment as the archwire deactivated. This again indicates a possibility of round-trip movement of the lateral incisors.

Torque Considerations in the PAE Appliances

The setup simulated in our study was the currently popular MBT prescription.[10] Other prescriptions have differing built-in torque values, but the trends noted here (in the specific case of MBT with upper cuspid brackets having negative torque) would apply to them also.

The high magnitudes of some of the moments observed in this study will not apply in clinical practice when untorqued archwires are used. This is because the largest archwire normally used is 0.019 × 0.025 inches, which has about 10° to 12° of archwire-slot play that will reduce the moments substantially. However, additional torque (up to 20°) is often needed in the 0.019- × 0.025-inch SS archwire during treatment, as per the recommendation of the proponents of the technique.[10] This added torque would overcome the archwire-slot play, and then the FEM values would be close to the moments that are likely to be generated in the clinical practice, when SS archwires are used.

Inversion of the maxillary lateral incisor bracket is often recommended[10] in cases where the lateral incisors are in-standing to begin with. One should keep in mind the possibility of developing extremely high moments in the SS archwires when following this practice.

Another observation worth noting is that the reciprocal effects on adjacent teeth might override the built-in torque, and the tooth may experience a moment quite different from the intended one.

Estimation of the Moments Generated by Archwires of Different Sizes and Alloys

The optimal values recommended by various authors such as Burstone,[11] Nikolai,[3] and Meling et al[8] for rectangular wire torque range from 20 Nmm to 10 Nmm for root movement and bodily translation. In general, torquing moments from heavy SS archwires are high and often above the physiologic limit, those from TMA archwires are generally within the physiologic limit, and those from NiTi archwires are below the physiologic limit. However, NiTi archwires would be the obvious choice in situations where very high moments are expected to be generated from SS archwires.

CONCLUSIONS

a. Twists in rectangular archwires seem to be appropriate only when reciprocal torque is required on the adjacent teeth, but one should be aware of high moments arising in full-sized or nearly full-sized SS archwires. The recommendation of Thurow[4] to use undersize archwires for this purpose is worth remembering.
b. This method to cause active root torque appears mechanically and biologically unsound for other applications, for high moments are often produced that drop suddenly when tooth movements start. Also, round tripping could occur in many instances.
c. The use of TMA archwires in preference to SS archwires may reduce these adverse effects but may not eliminate them completely. Alternative methods proposed by authors such as Thurow[4] (torquing spurs in round-base archwire), DeAngelis and Davidovitch[7] (use of Warren springs), and Isaacson and Rebellato[12] (torquing arches) deserve serious attention because the reciprocal reactions from these are spread on many (often distant) teeth and are controlled more easily.
d. The moments generated by the NiTi archwires, even those that are 0.019 × 0.025 inches, may be too low to bring about active torquing of teeth over long periods. However, they may prove beneficial when reciprocal torque is needed on adjacent teeth, especially when using preadjusted brackets, more so with some brackets inverted.

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