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The effects of a newly designed twin-slot bracket on severely malpositioned teeth—a typodont experimental study

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SUMMARY The aims of this study were to design a twin-slot bracket featuring two horizontal slots and to examine its efficiency in tooth displacement. Based on the structure of a traditional edgewise bracket, an additional slot was added to a twin-slot bracket and the prototype products were fabricated for the typodont experiments. The orthodontic correction of malpositioned canines was conducted on a typodont to examine the efficiency of the twin-slot bracket in tooth displacement compared with a single-slot edgewise bracket. Three modalities of tooth movement requiring a heavy force moment, namely, axial rotation, mesiodistal tipping, and bodily translation, were conducted. The canine positions before and after simulation were measured and the changes identified. Statistical analysis was undertaken using a *t*-test to determine the significance of the differences in canine repositioning between the two bracket types.

The results showed that in the twin-slot bracket group, the treatment changes in the canine position by derotation and uprighting were 40 ± 3 and 25 ± 2 degrees, respectively, compared with 20 ± 5 and 10 ± 2 degrees in the edgewise group ($P < 0.01$). When retracted into an extraction space with an initial 10 degrees of mesial tip, the mesiodistal angulation of the canines in the twin-slot bracket group remained unchanged while in the edgewise group the canines became distally tipped by 5 ± 2 degrees ($P < 0.01$). The twin-slot bracket significantly increased the bracket width without reducing the interbracket span and therefore can generate increased force moments within the bracket, leading to an improved manipulation in tooth repositioning.

Introduction

The fundamental mechanism of edgewise and straight-wire brackets lies in their rectangular-shaped slots and their interaction with the engaged archwires. Within each individual bracket, the interface between the archwire and the slot constitutes a mechanical lever in which a force moment results (Smith and Burstone, 1984; Drescher *et al.*, 1991). The force moment therefore becomes essential to orthodontically correct malpositioned teeth. According to the rules of mechanical forces, the mesiodistal dimension of the bracket is an important factor determining the magnitude of the force moment (Marcotte, 1990). Wide brackets are efficient in generating certain modalities of tooth movement that require rigid force moment, such as axial rotation and mesiodistal angulation/tipping (Rinchuse *et al.*, 2007). Wide brackets are also particularly advantageous when the extraction site is closed by sliding teeth along an archwire where a translatory tooth movement is needed to secure paralleling of the tooth roots (Proffit *et al.*, 2000). Apart from the bracket width, the distance between the brackets in adjacent teeth, the interbracket span is another factor affecting bracket working efficacy. An adequate interbracket span facilitates the activation of the springiness and elasticity of the flexible archwires which is the energy source of the force moment within the bracket (Creekmore, 1976; Ireland and McDonald, 2003). Apparently, an increase in the bracket dimension will result in a decrease in interbracket span.

One of the most important elements governing bracket design is therefore the balance between these two opposing components—the maximum bracket width with the adequate interbracket span. It is widely accepted that the maximum practical width of a wide bracket is about half of the width of a tooth (Proffit *et al.*, 2000). In modern orthodontic brackets, however, the bracket width is limited and is further reduced for aesthetic reasons (Parkin, 2005). With some bracket types such as tip- and straight-edge brackets, the offsetting disadvantages of the reduced width of the slot are partially compensated for by having an extensive bracket base. While the tendency of narrow brackets is favourable for adequate interbracket span, the force moment is however decreased and therefore may not be sufficient to facilitate displacement of severely malpositioned teeth (Frank and Nikolai, 1980; Kusy and Whitley, 1999; Ireland and McDonald, 2003).

The evolution of bracket design began with the ancestral structure of the vertically positioned slot in the ribbon arch appliance to the pure rectangular horizontal slot in the traditional standard edgewise to the contemporary pre-adjusted brackets in the straightwire technique, and to the current design of the self-ligating brackets system (McManaman and Woodside, 2000; Katsaros and Dijkman, 2003). It is interesting to note that despite the numerous bracket designs, one feature has remained unchanged: there is only one single horizontal slot on the facial facet

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of the bracket. In some design variations, such as the Tip-Edge Plus, In-Ovation and 'R' brackets, an additional horizontal slot is enclosed within the bracket base and is not open to the labial surface (Parkhouse, 2007), therefore only allowing for engagement of segmental auxiliary archwires.

The main aims of this study therefore were (1) to design a new bracket structure featuring two horizontal slots on the bracket facial surface, in an attempt to increase the bracket width without reducing the interbracket span, and (2) to examine the efficiency of this bracket design in manipulating rotational, tipping/uprighting, and translatory tooth movement via a typodont experiment.

Materials and methods

Bracket design and prototype products

The preliminary design for the prototype bracket was based on that for a traditional standard edgewise appliance. There were two parallel slots on the facial facet of the bracket, with a separation width of 0.4 mm. This width separated the two slots but did not significantly increase the bracket height. The size of the slots was 0.022 × 0.028 inch. The overall size of the bracket was 2 × 3.5 mm^2. The cross-sectional shape of the slots was rectangular (90 degrees) with no built-in prescriptions (Figure 1). The prototype brackets and the corresponding molar tubes were professionally fabricated and were authorized for laboratory experimentation (Chinese National Patent Approval No. IL032 29330.5).

Typodont experiment

The efficiency of tooth movement with the twin-slot bracket was tested and compared with that of an edgewise bracket. Three modalities of orthodontic tooth movement that require a considerable force moment were simulated and examined: labiolingual derotation, mesiodistal tipping/uprighting, and mesiodistal bodily translation.

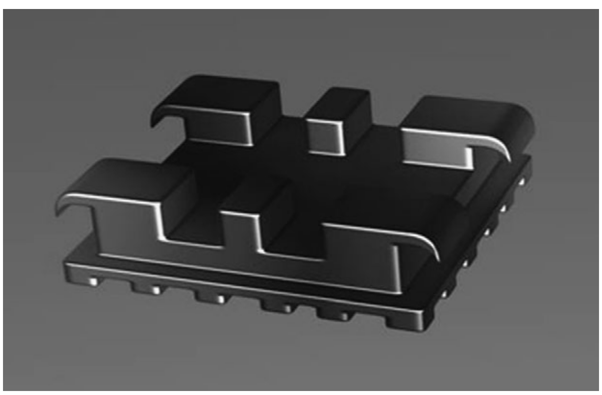

Figure 1 The twin-slot bracket featuring two parallel slots. The slots size is standard 0.022 inch and the space between the slots is 0.4 mm.

A prototype typodont was fabricated simulating a Class I malocclusion with the maxillary canines severely malpositioned. The typodont wax was shaped on the typodont frames (Orthostudy Articulator 610-100, 3M Unitek, Monrovia, California, USA) to form alveolar bone and the dental arches (Figure 2a). The two upper premolars were extracted. In the upper left quadrant, the canine was rotated 70 degrees mesiolingually (Figure 2b). The degree of rotation was determined by engaging a 5 cm long segment of 0.0215 × 0.028 inch wire into the bracket slot on the canine and measuring the angle of the intersection between this segmental wire and the archwire running through the whole dental arch. In the upper right quadrant, the canine was positioned with 40 degrees distal crown tipping (Figure 2c). Engaging the segmental archwire vertically through the bracket slot on the canine and measuring the angle of the intersection between this segmental arch and the main archwire also helped to quantify the degree of tipping.

Ten sets of typodonts were duplicated from the prototype as previously described (Pancherz *et al.*, 2001) and divided into two equal groups. The typodonts in the experimental group were bonded with the twin-slot brackets and in the control group with standard 0.022 inch edgewise brackets (Xinya, Hangzhou, China). All the archwires used were preformed (Orthoform, 3M Unitek). The efficacy of the twin-slot bracket was examined via typodont simulation of the following modalities of tooth movement.

Canine derotation and uprighting: In the experimental group, the twin-slot brackets were tied with two 0.014 inch nickel–titanium (NiTi) round archwires engaged separately in the two slots. The edgewise brackets in the control group were tied with single 0.014 inch NiTi round archwire. The typodonts were then submerged into a 50°C water bath (HH-W21-600, Shanghai, China) for 50 minutes.

Canine distal translation: Before canine retraction, all upper canines in both groups were adjusted into an ideal position with 10 degrees of crown mesial tipping with no rotation. Two 0.016 inch stainless steel (SS) archwires were engaged in the twin-slot brackets in the experimental group and a 0.018 × 0.025 inch SS rectangular archwire in the control group. The same magnitude of force loading of 150 g with elastic power chains (MiKro-StiK C-1, 3M Unitek) was used in both groups between the canine and the first molar to generate canine distalization. The typodonts were then immersed into the 50°C water bath for 30 minutes. The final degree of canine tipping was measured, using the approach described earlier.

Data collection and statistical analysis

Measurements of the canine positions before and after typodont treatment in both groups were conducted by one author (ZH). The measurements were repeated three times for each parameter and the average reading was taken as the final measurement. The data were processed with the

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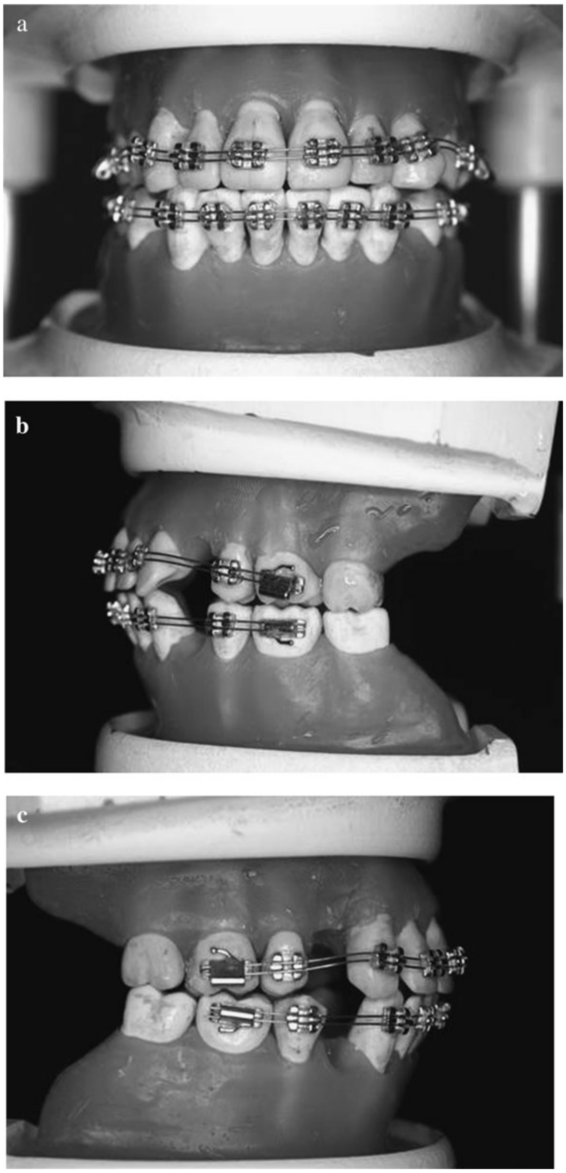

Figure 2 The typodont experiment examining the effectiveness of tooth displacement with the twin-slot bracket. The typodont simulates a Class I malocclusion with crowding where the two archwires are engaged in the twin-slot brackets (a). Orthodontic correction of a maxillary left canine which is mesiolingually rotated (b) and the maxillary right canine which is distally tipped (c).

Statistical Package for Social Science (Windows version 10.4, SPSS Inc., Chicago, Illinois, USA). A *t*-test was performed to identify differences in correction of the malpositioned canine between the two groups.

Results

The parameters indicating canine positions before and after the simulated orthodontic treatment and the statistical analysis showing the differences in treatment outcomes between the twin-slot and edgewise brackets are given in Table 1.

To test the effect on tooth derotation, the upper left canine was originally set to be mesiolingually rotated by 70 degrees (Figure 2b). In the twin-slot group, with the use of two 0.014 inch NiTi archwires, the canine malposition was reduced to a residual rotation of 30 ± 3 degrees, indicating a treatment change of 40 degrees. This was significantly greater than that in the control group where only a rotating correction of 20 degrees was obtained by engagement of one 0.014 inch NiTi archwire ($P < 0.01$).

To test the effect of the twin-slot bracket on tooth uprighting, the upper right canine was engaged with two 0.014 inch NiTi archwires and was repositioned from its original distal tipping of 40 degrees (Figure 2c), into a distally tipping angulation of 15 ± 2 degrees, indicating a treatment change of 25 degrees. In the control group, a single 0.014 inch NiTi archwire acting with edgewise brackets reduced the canine tipping to 30 ± 2 degrees, a treatment change of 10 degrees ($P < 0.01$).

To examine the effect on bodily tooth translation, the upper first premolars in both groups were extracted and the canines were initially positioned at a normal mesiodistal angulation (10 degrees mesially tipped), simulating a scenario where a canine was to be distalized into the extraction space. Using the same magnitude of retraction force, the canines sliding along the two 0.016 inch SS archwires with the twin-slot bracket resulted in an unchanged tipping angulation (10 ± 2 degrees mesially tipped), while there was an obvious distal tipping of −5 ± 1 degrees in the canines with a single 0.018 × 0.025 inch SS archwire with edgewise brackets, indicating poor bodily movement.

Discussion

The force moment within the bracket slot generated by the interaction between the archwire and the bracket slot is critical for the force exerted from the archwire to be transferred to the malpositioned tooth (Liaw *et al.*, 2007). In the scenario of root torque movement, as the engagement of a twisted rectangular wire into the slot creates two-point contacts at the edge of the wire, the size of the archwire is important to generate the necessary moment (Proffit *et al.*, 2000; Rinchuse *et al.*, 2007). In the circumstances of mesiodistal tipping and labiolingual rotation, the two-point contacts are located at the marginal edges of the bracket slot; the bracket width therefore is critical to induce adequate force moment (Rinchuse *et al.*, 2007). While it is widely recognized that the geometric structure of the bracket, especially the slot width, determines the efficiency of the force moment, the interbracket span, on the other hand, remains another crucial factor affecting the effectiveness of tooth displacement. It has been established that a sufficient interbracket span enables the flexible archwire to activate its springiness caused by deflection (Schudy and Schudy, 1989). A wider bracket is favourable to develop an adequate force moment, but the subsequent decrease in the space between

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Table 1 Treatment changes of malpositioned canines in the typodont: twin-slot versus single-slot edgewise brackets (unit: degrees)

	Derotation	Uprighting	Distal translation
Initial malpositioning	Mesially rotated 70	Distally tipped 40	Mesially tipped 10 (ideal)
Post-treatment positioning with the twin-slot bracket	30 ± 3 (40)	15 ± 2 (25)	Mesially tipped 10 ± 2 (0)
Post-treatment positioning with the edgewise bracket	50 ± 5 (20)	30 ± 2 (10)	Distally tipped −5 ± 1 (15)
t-test (*P*)	<0.01	<0.01	<0.01

the brackets will reduce the effective length of the archwire segments between the supports (Proffit *et al.*, 2000). Conversely, an increase of the interbracket span by reducing the brackets width also causes adverse consequences. There have been some reports indicating that the reduced dimension of orthodontic brackets compromises the effectiveness in some modalities of tooth displacement, especially those requiring excessive force moments (Moore and Waters 1993; Hemingway *et al.*, 2001; Yang *et al.*, 2001). The correction of severely buccolingually rotated and mesiodistally tipped teeth was found to be difficult using small-size self-ligating brackets (Bednar and Gruendeman, 1993; Read-Ward *et al.*, 1997; Redlich *et al.*, 2003), and distal bodily translation of the canine into an extraction space was difficult to achieve using brackets with a limited width (Tidy, 1989; Schumacher *et al.*, 1991; Ireland and McDonald, 2003).

In the present study, the bracket structure featuring two parallel slots was designed in an attempt to enhance the force moment without compromising the interbracket span, and the typodont simulation was undertaken to examine its efficacy in tooth repositioning. The typodont models with bases of heat-softened wax were used in this study with the maxillary canines either severely over-rotated or over-tipped (Figure 2b,c). The typodonts also simulated the scenario where the maxillary first premolars were extracted requiring canine retraction into the extraction spaces by sliding. The interaction between the archwires and the brackets was activated on immersion of the typodonts into a heated water bath. The results were compared with those of a matched control group bonded with standard edgewise brackets.

The correction of a mesiodistally tipped or labiolingually rotated tooth using flexible NiTi archwires is an essential procedure at the stage of levelling and alignment (Hemingway *et al.*, 2001). To obtain an efficient displacement of these types of malpositioned teeth, an increased bracket width with an adequate interbracket span which are contradictory, are required for enforcement of force moment and archwire activation. In the present experiment, with the same immersion time in the water bath, the rotated canines in the twin-slot bracket group were derotated by 40 degrees and the tipped canines were uprighted by 25 degrees, compared with 20 degrees of derotation and 10 degrees of uprighting achieved in the edgewise bracket group ($P < 0.01$). The results are consistent with those of Rinchuse *et al.* (2007) who contended that rotational and tipping control might be compromised with narrow brackets such as Speed SL, even though the interbracket distance is increased. When the deflected NiTi archwire is activated to rotate or upright a malpositioned tooth, the necessary moment is generated across the bracket at each marginal corner, and the bracket width therefore determines the length of the moment arm (Proffit *et al.*, 2000). As shown in Figure 3, if the moment arm in a standard edgewise bracket is r, the twin-slot bracket of the same width will have a $2 \times r$ moment arm. It is, therefore, reasonable to assume that, when engaged with double archwires, the force moment produced by the twin-slot bracket is twice that of a conventional single-slot bracket, without a subsequent decrease in interbracket space.

In severely crowded cases with extraction of the first premolars, retraction of the canine into the extraction site is critical for relief of crowding and, if necessary, for retraction of the incisors. As a result of the considerable distance between the canine and the second premolar, to bring the canine distally and maintain, a correct parallelism of the roots in relation to the adjacent teeth is not an easy procedure. Unfavourable positioning of the canine during retraction includes distal tipping, vertical elongation, and distolingual rotation (Schumacher *et al.*, 1999; Ireland and McDonald, 2003). In the present study, to verify the efficacy of the twin-slot bracket in canine retraction, two rigid 0.016 inch SS archwires were used along which the canine was moved distally by power chain activation. The results revealed that the canine bonded with the twin-slot bracket was moved into the extraction site with no change in mesiodistal angulation, while a distal tipping of 5 degrees was seen in the canine in the control group where a 0.018 × 0.025 inch SS archwire was used with the same amount of retraction force (Table 1). According to some studies, bracket width is important for angulation control during canine distalization and retraction of the anterior teeth with sliding mechanics, which require a considerable force moment (Thorstenson and Kusy, 2002; Yeh *et al.*, 2007). In order to retract the root of a canine tooth into a premolar extraction site parallel with the adjacent tooth, a moment across the bracket is needed to overcome the distal tipping tendency. The moment causing the tipping tendency (Mt) is determined by the retraction force (F) and the distance from the bracket to the centre of resistance (R), i.e $\mathrm{Mt} = F \times R$ (Bednar and Gruendeman, 1993; Proffit *et al.*, 2000). As shown in Figure 3, the physical

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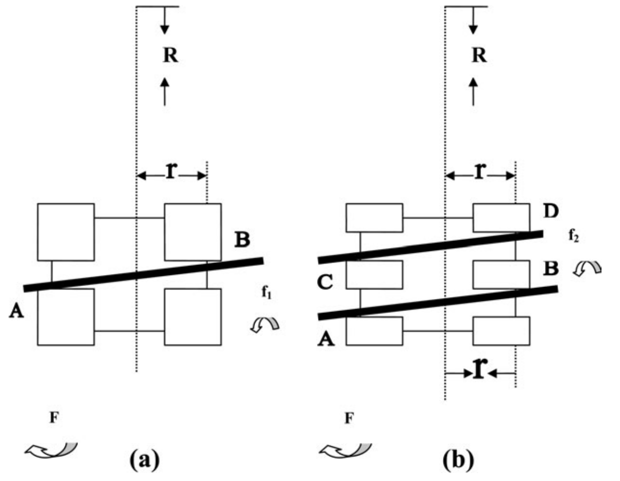

Figure 3 A schematic diagram depicting the differential force moments between the conventional edgewise (a) and twin-slot (b) bracket. As a result of an additional slot, the moment arm in the twin-slot bracket ($2 \times r$) is greater than that of the edgewise bracket ($1 \times r$). During sliding retraction of the canine by force F, the frictional resistance at each corner of the twin-slot bracket (f_2), which is generated to counter the distal tipping tendency induced by F, is decreased compared with that of the edgewise bracket (f_1). A, B, C, D, the contact points between the archwires and the slots; R, canine resistance distance.

manifestation of this tipping moment is the contacts (A, B, C, D) between the archwire and the bracket at the marginal corners, which produce the frictional resistance f. In the present experiment, the retraction force and the resistance distance were identical between the twin-and single-slot edgewise bracket groups. To overcome the tipping moment Mt, the countering moment (Mc) at each corner of the single-slot bracket must satisfy the formula Mc = Mt, or $f_1 \times r = F \times R$ (Bednar and Gruendeman, 1993; Proffit *et al.*, 2000), therefore the frictional force at each corner is $f_1 = (F \times R)/r$. With the twin-slot bracket, as a result of the additional slot, the countering moment Mc would be distributed in, and shared by, the two slots; the formula therefore becomes $2 \times (f_2 \times r) = F \times R$, and the frictional resistance force at each corner is $f_2 = ½ (F \times R)/r$.

It is well established that when an extraction site is to be closed by sliding teeth along an archwire, a frictional resistance between the bracket and wire is encountered (Drescher *et al.*, 1989). As mentioned previously, the frictional resistance to sliding is affected by the force with which the bracket contacts the archwire. Mechanical analysis in this study revealed that the friction force at each corner of the twin-slot bracket is only half of the standard edgewise bracket, indicating that the twin-slot bracket enables the canine to move bodily during distal retraction.

The data from this typodont experiment points to the fact that the twin-slot bracket has a significantly increased bracket width but without interbracket span reduction. As an extensive bracket width is a fundamental factor that helps facilitate a strong force moment required for the displacement of a severely malpositioned tooth (Proffit *et al.*, 2000), an adequate interbracket distance, on the other hand, helps activate the springiness of the archwire which is the force source of the moment across the bracket (Hemingway *et al.*, 2001). The twin-slot bracket may provide a new approach where the enhancement of both factors is not contradictory.

In addition to increasing the bracket width, the twin-slot bracket may also be helpful when the use of two archwires becomes necessary. It is well accepted that in severely crowded cases, the engagement of two archwires can be adopted where the rigid main archwire reinforces the anchorage and the flexible auxiliary wire helps to reposition the severely malaligned teeth (Braun *et al.*, 1997; Parkhouse and Parkhouse, 2001; Banaie *et al.*, 2005). With conventional edgewise brackets, however, the engagement of the two archwires into a single slot is difficult clinically, and their respective functions might be compromised as a result of the two archwires being closely tied together.

The results from this study should be interpreted with caution as a wax-based typodont simulation was used to determine the mechanical properties of this newly designed bracket. Although typodont simulation has been widely used for orthodontic training (Jones and Volp, 1989) and also for studies on bracket positioning (Armstrong *et al.*, 2007) and the interactions between archwire and brackets (Henao and Kusy, 2004), there is no evidence that the relationship between force and tooth movement through the laboratory typodont resembles the corresponding relationship through alveolar bone. The reason behind the phenomenon that the twin-slot bracket doubles the rate of alignment may be that the force on the tooth bonded with the twin-slot bracket is doubled and the rate of wax flow is likely to be proportional to load. By contrast, *in vivo*, the rates of tooth movement are relatively insensitive to loading above a certain level (King, *et al.*, 1991), and it cannot be assumed that a similar benefit would be expected clinically. Furthermore, the observation from this typodont study that the twin-slot bracket effectively eliminates tipping in canine retraction is more interesting but less predictable. A possible explanation is that the two wires, being effectively held in their relative positions by their engagement in the anterior brackets, act almost as a rigid framework to control canine tip more effectively than a single wire. Again, one may not expect this effectiveness to happen clinically. To examine the biomechanical and biological response of alveolar tissue *in vivo* to this bracket, an animal experiment will be undertaken.

Conclusions

This study reports a newly designed twin-slot bracket featuring two parallel slots. The typodont experiment reveals that the twin-slot bracket is highly efficient in correcting severely malpositioned teeth with labiolingual rotation and mesiodistal tipping. The twin-slot bracket also secures a bodily translation of the canine during its retraction into an extraction space with sliding mechanics. An enhancement of the force moment across the bracket slots and an increase

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of the bracket width account for the increased efficacy of the twin-slot bracket in tooth movement compared with the conventional edgewise single-slot bracket.

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