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Three-dimensional finite element analysis in distal *en masse* movement of the maxillary dentition with the multiloop edgewise archwire

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SUMMARY The purpose of this study was to compare the effects of a multiloop edgewise archwire (MEAW) on distal *en masse* movement with a continuous plain ideal archwire (IA). Three-dimensional finite element models (FEM) of the maxillary dentition in which the second permanent molars had been extracted were constructed to include the periodontal membrane, alveolar bone, standard edgewise bracket (0.018 × 0.025 inch), stainless steel IA (0.016 × 0.022 inch), and MEAW (0.016 × 0.022 inch). The stress distribution and displacement of the maxillary dentition were analysed when Class II intermaxillary elastics (300 g/side) and 5 degree tip-back bends were applied to the IA and MEAW for distal *en masse* movement of the maxillary dentition.

Compared with the IA, the MEAW showed that the discrepancy in the amount of tooth displacement was lower and individual tooth movement was more uniform and balanced. There was minimal vertical displacement or rotation of the teeth using the MEAW when compared with the IA. The MEAW seems to have advantages for distal *en masse* movement of the maxillary dentition.

Introduction

There has been considerable research into orthodontic force systems and biomechanics. Many clinical and laboratory studies have confirmed the relationship between applied force and tooth movement (Storey and Smith, 1952; Reitan, 1957, 1964; Lee, 1965). Histological investigations have focused on the relationship between stress level and bone remodelling (Rygh, 1976; Reitan, 1985). As periodontal stress is transferred to the alveolar bone and induces bone remodelling and tooth movement, the amount of periodontal stress has been calculated to quantify simulated orthodontic tooth movement using computer-based programs (Williams and Edmundson, 1984; Tanne *et al.*, 1987, 1988; Fotos *et al.*, 1990; Andersen *et al.*, 1991; Chun and Nahm, 1991; McGuinness *et al.*, 1992; Cobo *et al.*, 1993, 1996; Lee and Nahm, 1994; Hwang and Suhr, 1994; Puente *et al.*, 1996; Park and Yang, 1997).

In Class II malocclusion subjects, distal *en masse* movement of the maxillary dentition is required to correct the molar relationship (Thurow, 1975; Graber and Newman, 1984; Williams and Edmundson, 1984; Bishara and Burkey, 1986; Basdra and Komposch, 1994; Jasper and McNamara, 1995). In subjects with well-positioned and well-shaped maxillary permanent third molars, mild crowding in the upper arch, good alignment of the lower arch and posterior crowding, extraction of the maxillary permanent second molar can eliminate the 'wedging' effect and facilitate correction of the molar relationship (Chang and Kim, 1984; Quinn, 1985; Chang and Moon, 1999).

There are several types of appliance for distal *en masse* movement (Thurow, 1975; Caldwell *et al.*, 1984; Muse *et al.*, 1993; Jasper and McNamara, 1995; Philippe, 1995; Orton *et al.*, 1996). The multiloop edgewise archwire (MEAW; Permachrome standard, 3M Unitek, Monrovia, California, USA) is considered to be an effective tool for distal *en masse* movement (Chang and Kim, 1984; Sato, 1992). It is a rectangular ideal archwire (0.016 × 0.022 inch) that contains several L-shaped loops of different sizes (Figure 1). The vertical component of the loop acts as a breaker between the teeth, lowering the interbracket load-deflection rate (LDR) and controlling the horizontal position of the teeth. The horizontal component of the loop also lowers the LDR and controls the vertical position of the teeth (Kim, 1987). Because of the decreased LDR in the MEAW, constant low forces can be applied, thus making physiological and efficient tooth movements possible (Yang *et al.*, 2001).

In the finishing stages, engagement of stainless steel wires of high stiffness into fully programmed brackets could minimize individual tooth movement. L-loops and tip-back bends incorporated in the MEAW together with intermaxillary elastics can allow individual tooth movements and decrease the interbracket LDR. These make it possible to upright posterior teeth, change the inclination of the occlusal planes, correct the occlusal sagittal relationship and attain the correct intercuspation

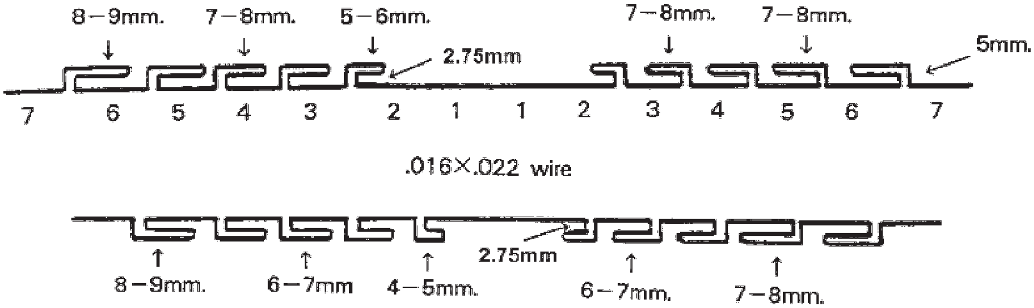

Figure 1 Diagram of the multiloop edgewise archwire.

in a significantly shorter time (Sato, 1992; Chang and Moon, 1999).

In general, distal tipping and distal bodily displacement together with vertical displacement are considered to occur during distal *en masse* movement of the dentition (Noyes *et al.*, 1943; Coben, 1966; Caldwell *et al.*, 1984; Muse *et al.*, 1993; Orton *et al.*, 1996). It is difficult to explain tooth movement with respect to the relationship between the line of action and the centre of resistance, as the true mechanical mediator is not the magnitude of the force itself, but the magnitude of the periodontal stresses around the teeth. The biological structures are activated in response to the changes in stress and strain that are applied to the tissue. In order to evaluate the true relationship between tooth movement and orthodontic force, it is necessary to quantify not only the force system applied to the teeth, but also the periodontal stress and strain generated by the orthodontic forces.

In this study, the anatomical structures and physical characteristics of the maxillary teeth, the periodontal membrane (PDM), and the alveolar bones were constructed using a three-dimensional (3D) finite element model (FEM). The effects of the MEAW on the distal *en masse* movements were simulated and compared with a continuous plain ideal archwire (IA).

Materials and methods

Construction of the 3D FEM

Maxillary dentition, PDM, alveolar bone, and brackets. A 3D FEM of each tooth was constructed according to Wheeler (1965) and aligned with reference to the facial axis (FA) point of Andrews (1972) (Figure 2). In order to establish the mesiodistal angulations of the teeth in Class II malocclusions, the maxillary dentition was arranged according to Noyes *et al.* (1943) and Choi and Yang (1984). The labiolingual or buccolingual inclinations of teeth were simulated based on the studies of Kim *et al.* (1992). The maxillary and mandibular dentition were established according to the normal arch shape of Roth (Tru-arch form, medium size, Ormco Company, West Collins Orange, California, USA).

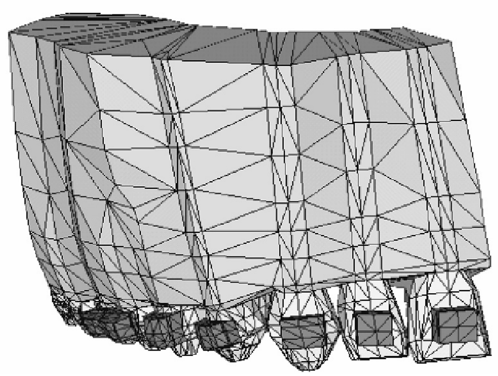

Figure 2 Oblique view of the three-dimensional finite element model of the upper right dentition. The model comprises the teeth, periodontal ligament, alveolar bone, and brackets.

The 3D FEM of the PDM was constructed to fit outside the root. Based on the studies of Kronfed (1931) and Coolidge (1937), the thickness of the PDM was considered to be 0.25 mm evenly, although PDM thickness is different according to age, position, and individual variations.

The 3D FEM of the alveolar bone was fabricated to fit the teeth and the PDM. Because the distal force of the Class II elastics could not induce FEM changes at the area furthest from the tooth, the upper limit of the FEM was constructed at the base of palatal bone.

3D FEM of 0.018 × 0.025 inch standard edgewise brackets (3M Unitek) were made and attached to the crown such that the FA point was equal to the centre of the bracket slot.

Archwires. IA (0.016 × 0.022 inch) FEM were designed according to the normal arch shape of Roth and cinched at the distal part of the first molar tube. In addition, a hook was positioned between the brackets of the maxillary lateral incisor and canine for Class II elastics and 5 degree tip-back bends were applied from the first premolar to the first molar.

The FEM of the MEAW had the same size and arch form as the IA. After 5 degree tip-back bends were inserted, Class II elastics were applied to the first L-loop between the maxillary lateral incisor and the maxillary canine. The amount of torque in both archwires was adjusted to be passively related to the bracket slot, as the aim of this study was to investigate only distal *en masse* movement of the dentition.

Mechanical properties of the tooth, PDM, alveolar bone, bracket, and wire

The mechanical properties of the FEM were considered to have linear elasticity and isometric properties of the same quality. Young's modulus and Poisson's ratio for the tooth, PDM, alveolar bone, bracket, and wire were calculated according to Tanne *et al.* (1988) (Table 1).

Methods for modelling

3D quadrangular and hexagonal elements were used for the tooth and standard edgewise bracket models. The PDM was constructed with thin shell elements and the archwires with 3D beam elements. The number of elements and nodes used are shown in Table 2.

Simulation of forced displacement

When the archwire was inserted into the bracket slot with Class II elastics (300 g/side) (Figure 3a, b), forces were transferred to the points on which the orthodontic wire contacted the brackets (two points in each bracket). Forced displacement was simulated in the 3D FEM with the macro-deformation linear elastic method.

Establishment of the co-ordinate system

Using an imaginary line that passed through the FA point of the crown parallel to the occlusal plane, displacements could be measured at each point. The co-ordinate system consisted of X, Y, and Z axes perpendicular to one another. The X axis represented the mesiodistal direction, the Y axis the labiolingual or buccolingual direction, and the Z axis the vertical direction (Figure 4). It was possible to evaluate tipping, bodily displacements, vertical displacements, and rotations in three dimensions.

Table 1 Mechanical properties for the tooth, periodontal membrane (PDM), alveolar bone, bracket, and wire.

Material	Young's modulus (kgf/mm^2)	Poisson's ratio
Tooth	2.0×10^3	0.3
PDM	6.8×10^{-2}	0.49
Alveolar bone	1.4×10^3	0.3
Bracket	21.4×10^3	0.3
Wire	21.4×10^3	0.3

Table 2 The number of elements and nodes used in the study.

Number of 3D elements	Number of shell elements	Number of beams	Number of nodes
8087	842	61 (ideal arch) 231 (MEAW)	2140 2310

3D, three-dimensional; MEAW, multiloop edgewise archwire.

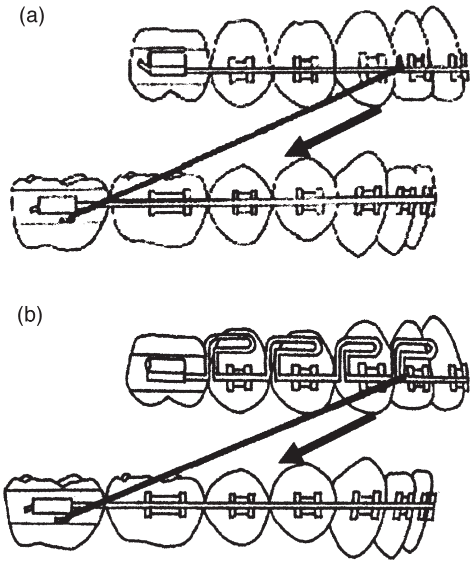

Figure 3 Schematic diagrams of the direction of force produced by (a) the ideal archwire and (b) the multiloop edgewise archwire with 5 degree tip-back bends and Class II elastics.

Computer system and program

The computer system used in this study was Indigo O2 (R5500 Silicon Graphics, Mountain View, California, USA) with the 3D FEM program ANSYS (Version 5.3, Swanson Analysis System Inc., Canonsburg, Pennsylvania, USA).

Results

When the IA was used with Class II intermaxillary elastics, the initial bodily displacements were concentrated

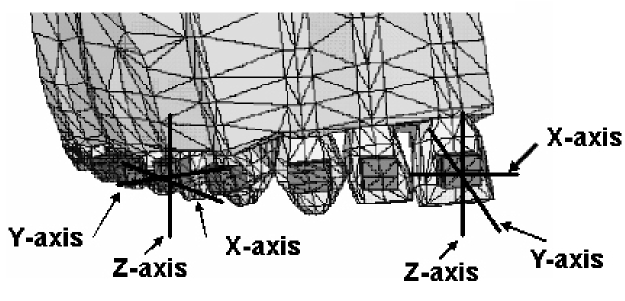

Figure 4 The reference co-ordinate system. X axis: mesiodistal direction, Y axis: labiolingual direction, Z axis: vertical direction.

on the anterior part of the dentition. The amount of mesiodistal and labiolingual bodily displacements was greatest on the maxillary lateral incisor, and decreased in the order of central incisors, premolars, and first molar. The amount of bodily displacements with the MEAW was lower than with the IA, but the values were similar (Figures 5 and 6).

Mesiodistal and labiolingual tipping movements with the IA were prominent on the lateral and central incisors, and distal tipping movements were identified on the posterior segments. With the MEAW, labiolingual tipping movements of the lateral and central incisors were more prominent than on other teeth, but the amounts were lower than with the IA. There were less mesiodistal tipping movements of the posterior teeth, especially at the first molar, when using the MEAW than with the IA (Figures 7 and 8).

For vertical displacements with the IA, extrusions occurred at the lateral incisor and the canine, and intrusion on the posterior teeth. The discrepancy between the amount of extrusion and intrusion was high. However, with the MEAW no teeth showed significant vertical displacements (Figure 9).

There were large rotational movements in the lateral incisor and the canine with the IA but these were not significant with the MEAW (Figure 10).

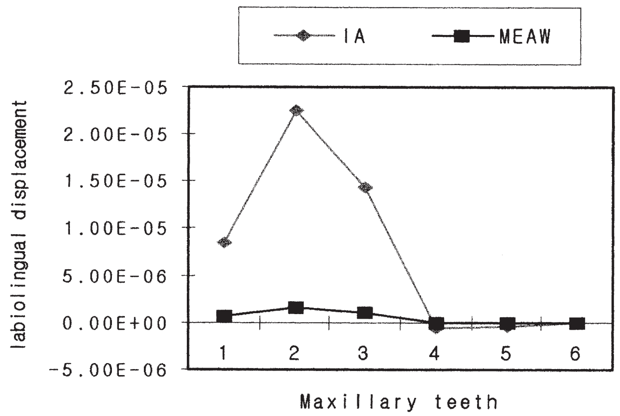

Figure 5 Comparison of labiolingual body displacement between the ideal archwire (IA) and the multiloop edgewise archwire (MEAW) with 5 degree tip-back bends and Class II elastics. +, lingual; –, labial. 1, right central incisor; 2, right lateral incisor; 3, right canine; 4, right first premolar; 5, right second premolar; 6, right first molar.

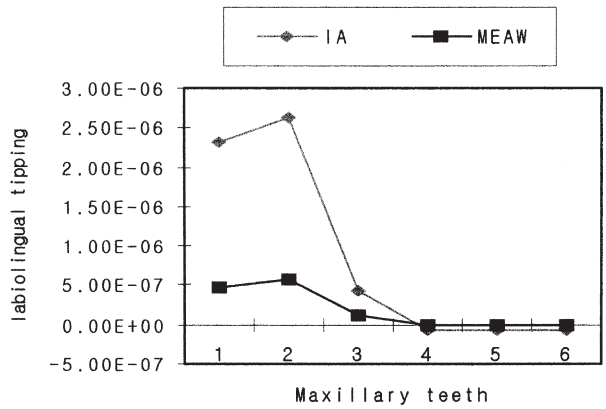

Figure 7 Comparison of labiolingual tipping between the ideal archwire (IA) and the multiloop edgewise archwire (MEAW) with 5 degree tip-back bends and Class II elastics. +, crown lingual tipping; –, crown labial tipping. 1, right central incisor; 2, right lateral incisor; 3, right canine; 4, right first premolar; 5, right second premolar; 6, right first molar.

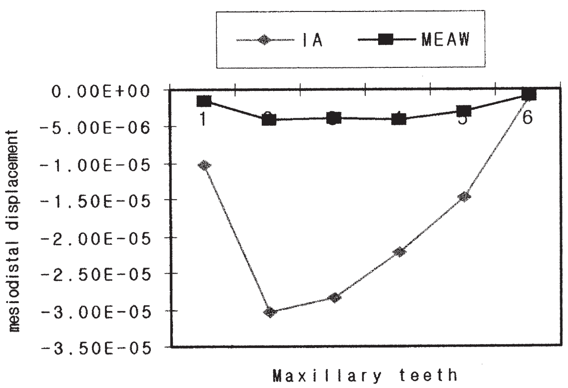

Figure 6 Comparison of mesiodistal body displacement between the ideal archwire (IA) and the multiloop edgewise archwire (MEAW) with 5 degree tip-back bends and Class II elastics. +, mesial; –, distal. 1, right central incisor; 2, right lateral incisor; 3, right canine; 4, right first premolar; 5, right second premolar; 6, right first molar.

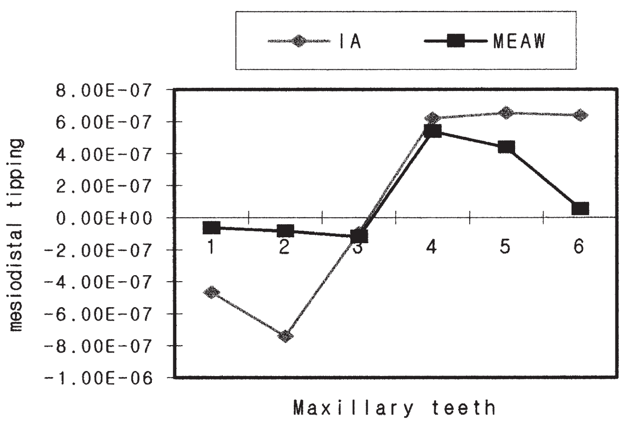

Figure 8 Comparison of mesiodistal tipping between the ideal archwire (IA) and the multiloop edgewise archwire (MEAW) with 5 degree tip-back bends and Class II elastics. +, crown mesial tipping; –, crown distal tipping. 1, right central incisor; 2, right lateral incisor; 3, right canine; 4, right first premolar; 5, right second premolar; 6, right first molar.

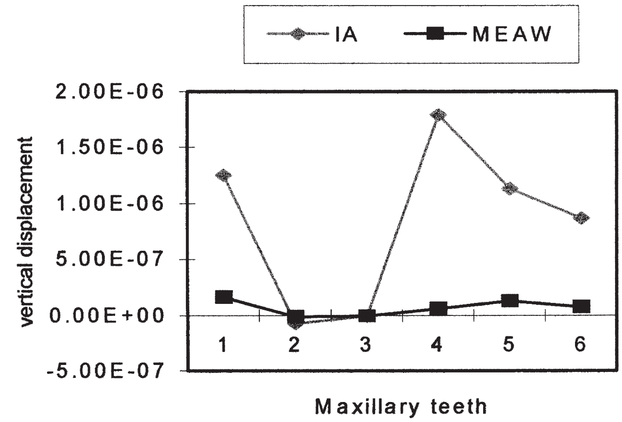

Figure 9 Comparison of vertical displacement between the ideal archwire (IA) and the multiloop edgewise archwire (MEAW) with 5 degree tip-back bends and Class II elastics. +, intrusive translation; –, extrusive translation. 1, right central incisor; 2, right lateral incisor; 3, right canine; 4, right first premolar; 5, right second premolar; 6, right first molar.

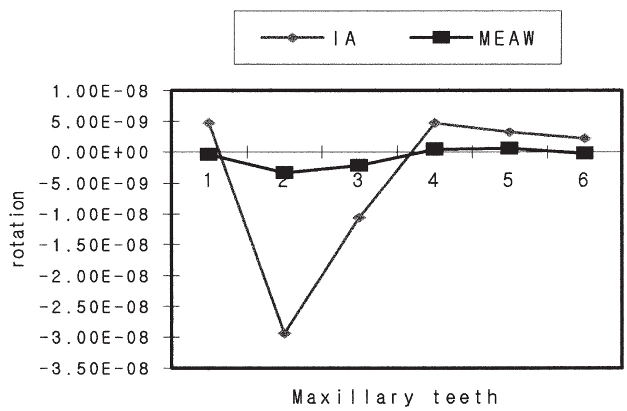

Figure 10 Comparison of rotation between the ideal archwire (IA) and the multiloop edgewise archwire (MEAW) with 5 degree tip-back bends and Class II elastics. +, mesiolingual rotation; –, distolingual rotation. 1, right central incisor; 2, right lateral incisor; 3, right canine; 4, right first premolar; 5, right second premolar; 6, right first molar.

Discussion

The PDM mediates selective resorption and deposition of the alveolar bone in response to orthodontic force. The true mechanical mediator for tooth movement is not the magnitude of the force itself, but the magnitude of the stress and strain in the PDM that is induced by the orthodontic appliance (Proffit, 1986). Quantification of the stress and strain in the PDM is important for evaluation of the relationship between the orthodontic force system and tooth movement. The FEM is useful for stress analysis (Tanne *et al.*, 1987). In the present study, initial tooth movements that occurred in the PDM were calculated with the FEM. While these initial movements should be differentiated from secondary movements mediated by continuous bone resorption in pressure and deposition on the tension sides, they cannot be completely separated (Tanne *et al.*, 1987).

Continuous tip-back bends are applied to obtain the required angulation changes. Premolars and molars can be uprighted simultaneously by means of these tip-back bends. According to Kim (1987), the typical magnitude of a tip-back bend is 3–5 degrees, and this can be increased if necessary. With the MEAW, when tip-back bends were only used in the upper arch, intrusion and labioversion were noticeable on the upper incisors, while the upper molars showed less intrusion (Chun and Nahm, 1991; Lee and Nahm, 1994; Jin and Yang, 1994). When the MEAW with tip-back bends and Class II intermaxillary elastics was used in the upper arch, there was lingual crown tipping and lingual bodily displacement of anterior teeth and intrusion, distal crown tipping and distal bodily displacement of the maxillary posterior teeth (Figures 5–10). These phenomena mean that distal *en masse* movement of the entire maxillary dentition was induced. Intrusion of the anterior teeth by tip-back bends was counteracted by the extrusive force of the Class II elastics, but intrusion of the posterior teeth was increased by tip-back bends and Class II intermaxillary elastics. This is similar to the result of Chun and Nahm (1991), who studied the MEAW with vertical elastics. Due to a difference in force direction between vertical and Class II intermaxillary elastics, stress levels from the anterior to the posterior teeth were more evenly distributed with the MEAW than with the IA (Figures 5–10). This is in agreement with the results of Lee and Nahm (1994).

One side-effect related to the correction of Class II malocclusions is an increase in anterior overbite (Bien, 1951; Coben, 1966; Philippe, 1995). This must be considered in the selection of orthodontic appliances (Philippe, 1995). In this study, the amount of extrusive vertical displacement in the anterior teeth was less with the MEAW than with the IA (Figure 9). Therefore, the side-effects related to vertical tooth movements could be minimized with the MEAW.

Because Class II elastics were used, rotational moments developed in the archwire. For the IA, distolingual rotations of the lateral incisor and canine were prominent. In contrast, the rotation of each tooth with the MEAW was less than with the IA (Figure 10).

Appropriate and continuous orthodontic force will increase cellular activity to yield the desirable treatment result. One of the best indicators that can depict force is LDR. LDR means the external force that is required for the deflection of a unit length. In orthodontics it can be interpreted as a force that is generated from a unit length (Burstone *et al.*, 1961). Wires with high LDR are not recommended as they can apply high forces on the teeth which rapidly decrease with the movement of teeth (Brown, 1988). It has been reported that appropriate and continuous orthodontic force can be obtained with a decrease in LDR and an increase in the range of action (Burstone *et al.*, 1961). In this study, the MEAW induced lighter forces than the IA (Figures 5–10). These light forces are biologically advantageous and more useful for distal *en masse* movement as the LDR of the MEAW is lower than that of the IA (Kim, 1987; Chun and Nahm, 1991; Lee and Chang, 1992; Yang *et al.*, 2001). According to Yang *et al.* (2001), the average regional LDR of the MEAW for the maxillary arch is significantly lower than that of the IA (1:7.61). They showed that the L-loops of a MEAW had different LDRs due to the difference in the length of the horizontal loops. To facilitate precise tooth movements, a lower LDR is necessary for the segment of active tooth movement and a higher LDR for the anchorage units. A relatively higher LDR is necessary in the anterior than in the posterior segments for distal *en masse* movement.

Compared with the IA, the MEAW seemed to have two main advantages in distal *en masse* movement of the maxillary dentition. First, the discrepancy in the amount of tooth movement of the entire dentition was smaller than with the IA, even though the absolute amounts of tooth movement were lower than with the IA. Second, the stresses were more effectively distributed throughout the entire dentition rather than concentrated at certain points.

This study had some limitations as calculations were made using a mathematical model. The results were based on the fact that the thickness of the PDM was uniformly 0.25 mm. However, the thickness of the PDM is 0.25 mm (± 50 per cent) and it has an hourglass shape so that the centre is narrowest (Kronfed, 1931). This difference might induce unexpected tooth movements. After orthodontic force is applied, histological changes can alter the physical properties of the tissues and therefore Young's modulus and Poisson's ratio (McGuinness *et al.*, 1992). For these reasons, the secondary response could be different from the initial response of the PDM. In this study, the errors associated with the bony tissues, deformation of the bracket, forces of circum-oral muscles, and bite forces were not considered. To overcome these limitations it is necessary to develop a more accurate modelling technique and a time-dependent 3D FEM analysis.

Conclusion

Compared with the IA, the discrepancy in the amount of tooth movement was lower and the individual tooth movement was more uniform and balanced with the MEAW. The MEAW produced less vertical displacement and rotation of each tooth compared with the IA. Therefore, the MEAW is more appropriate for distal *en masse* movement of the maxillary dentition.

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