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ABSTRACT

Aim and Objective: The purpose of this study was to investigate magnitude and direction of forces generated in the maxillary anterior region with engagement of arch wires into slots of conventional and self-ligating brackets during initial leveling and alignment stage of orthodontic treatment.

Materials and Method: Three-dimensional models of Damon Q (Ormco, Glendora, California) and Mini 2000 (Ormco, Glendora, USA) brackets (upper 3 to 3) were modeled using micro computed tomography. A 3D orthodontic model was designed to replicate moderate crowding in the dental arch with all supporting structures. The simulated malocclusion represented a maxillary central incisor displaced 3.8 mm lingually and 3.16 mm gingivally. 0.014” Copper-Nickel-titanium (CuNiTi) wire was engaged in Damon Q and Mini 2000 brackets for alignment on the same model and force magnitude and stresses generated were measured with ANSYS Mechanical R19.0 software.

Results: Damon Q brackets delivered light continuous forces when compared to Mini 2000 brackets. Stresses generated on teeth and periodontal ligament (PDL) are lesser with Damon Q as compared to Mini 2000 brackets. Tooth deformation was more with Damon Q brackets as compared to Mini 2000 brackets.

Conclusion: Adult orthodontic cases, especially with compromised periodontal health, can be treated more efficiently with minimum patient discomfort and complications such as root resorption with Damon Q brackets and 0.014” CuNiTi wires.

Keywords: Self-ligation, MBT brackets, Damon Q, Finite element analysis, Copper-Nickel-titanium.

INTRODUCTION

Fixed appliances have come a long way since their introduction in the 1900’s by EH Angle to treat malocclusions. Advancement in design, materials and technology, has permitted development of newer brackets and techniques including passive self- ligation and clear aligners. This in turn, has led to improved clinical efficiency with better outcomes and improved comfort for patients. However, newer techniques and brackets require robust scientific evidence for their incorporation into routine clinical practice.

Self-ligation is not a new concept. It was first described by Stolzenberg in 1935 as the Russell Lock edgewise attachment. Since then, many innovations and improvements have been made which has led to many of them being commercially available. Core advantages of self-ligating brackets include lower friction with reduced forces, less chair side assistance and faster archwire removal and ligation. Each advantage has potential clinical benefit individually and in combination [1].

Damon brackets are passive self-ligating brackets which are used in conjunction with copper NiTi wires. NiTi alloys are preferred during alignment because of their wider working range and higher spring back properties. According to Sachdeva, addition of copper in NiTi archwires reduces hysteresis which brings the deactivated force closer to the activated force and stabilizes the super elasticity characteristic. Copper-Nickel-titanium (CuNiTi) wires exert more homogeneous force thereby providing faster and more efficient tooth movement [2,3]. Studies [4,5] conducted on copper NiTi wires have found better mechanical properties with lower deactivation range compared to NiTi.

During orthodontic treatment, light orthodontic forces within limits of physiological tolerance should be applied to trigger biological reactions in the periodontal ligament (PDL) and associated bone to produce tooth movement without tissue damage and with maximum comfort for the patient [6]. Orthodontists should build a solid background in the biomechanical principles that control the adverse effects of orthodontic appliances. The selected archwire-bracket combination is a primary determining factor in the force level applied to a tooth during orthodontic treatment. Self-ligating brackets are increasingly replacing conventional brackets for many reasons; a major advantage is their reduced frictional properties compared to conventional brackets, especially when coupled with smaller archwires used in the initial levelling and alignment stage. Shivpuja et al[7] found that self-ligating brackets with copper NiTi wires displayed significantly lower levels of frictional resistance which produced more physiological tooth movement by not interrupting blood supply. This passive self-ligation system works with more alveolar bone regeneration, less proclination of anterior teeth, greater amounts of lateral expansion and less discomfort and root resorption for patients [8].

The magnitude of forces generated with the engagement of wire in the bracket slot varies depending on type of ligation, wire properties, inter-bracket distance, number of teeth ligated and frictional behavior at the bracket/archwire interface [9]

Friction generated between the wire and bracket affects efficiency of tooth movement. Various factors affecting frictional resistance in orthodontic tooth movement are method of ligation, play between bracket slot-wire interface, inter-bracket distance, bracket and archwire materials and archwire size have been extensively studied in orthodontics using different mechanical devices [10,11]. However, with the advent of finite element analysis (FEM), biomechanics along with estimation of stress-strain distribution has become simpler and more accurate. The reliability of FEM depends on the loading configuration, geometry of the structure and material properties. The accuracy of FEM analysis may differ from the real world scenario by up to 20 % [12,13] .Major advantage of FEM over other methods is the dynamic estimation of altered mechanical response in alveolar bone and PDL when the tooth is simulated during orthodontic tooth movement.

Thus, the purpose of this study was to evaluate forces generated with two bracket systems, conventional 0.022"MBT brackets (Mini 2000;Ormco, Glendora, Calf) and Damon Q passive self-ligating brackets,0.022" (Ormco, Glendora, Calif) using 0.014'' CuNiTi archwire (Ormco, Glendora, Calif).Biomechanical changes in loaded tissues and the mechanisms of tissue response with force application are difficult to study because stress/strain in a periodontal ligament cannot be measured directly and must be derived from mathematical models. Therefore, the brackets were scanned and modelled using micro CT for FEM analysis to give accurate findings according to selected parameters.

The parameters evaluated were:

1. The amount of force generated in the maxillary crowded anterior region with engagement of 0.014''CuNiti arch wires into slots of conventional MBT 0.022'' and Damon Q 0.022" brackets during initial leveling and alignment stage of orthodontic treatment.
2. Stresses generated on the lateral incisor and its PDL were compared between both bracket systems to make conclusions.

Total deformation of the teeth were evaluated and compared between both conventional MBT and passive self-ligating Damon system.

Table 1- Average Material Property Values

S.No:	Linear- elastic materials parameters	Young's modulus of elasticity (MPa)	Poisson's Ratio
1.	Alveolar bone	13800	**0.30**
2.	Tooth	20000	**0.30**
3.	PDL	1	**0.45**
4.	Brackets(stainless steel)	180000	**0.3**
5.	**Copper Niti**	**36800**	**0.30**

MATERIALS AND METHOD

Fabrication of a finite element model:

Two types of brackets were selected in this study: Conventional MBT (Mini 2000, Ormco, Glendora, Calif, USA) and Damon Q brackets (Ormco, Glendora, Calif). All brackets had 0.022'' slot size and were made of stainless steel. The brackets were scanned and finite models of 4 brackets (maxillary left central incisor to maxillary right canine) were generated. Initially, three-dimensional (3D) solid models of two brackets Mini 2000 and Damon Q were constructed using a micro CT Skyscan 1271-Bruker scanner for 45 minutes.0.014'' CuNiTi (Ormco, Glendora, Calif) archwire was also modeled and constructed.

A 3D computer aided drafting (CAD) model of the upper arch obtained from Turbo Squid (TurboSquid, New Orleans, LA, USA) served as the base for teeth. From this CAD model, modifications were made using Solid works 16.0 to alter tooth geometry according to dental anatomy literature. A crowded 3D model of a right and left central incisor, right lateral incisor and right canine of the maxillary dental arch was constructed from the CAD model. The lateral incisor was moved 3.8 mm lingually and 3.16 mm gingivally from its normal position in the dental arch in order to simulate moderate crowding. The three-dimensional model, which comprised of tooth, PDL and alveolar bone, was reconstructed and analyzed with ANSYS Design Modeler R19.The periodontal ligament was constructed on the root surface with 0.25 mm width. Supportive bone was modeled in a 2 mm thick layer, with underlying cortical bone.3D solid models of brackets were bonded to the teeth models (maxillary right and left central incisor, right lateral incisor and right canine) and an 0.014'' CuNiTi archwire was inserted into the bracket slots of both bracket types. The volumetric data in digital imaging and communication in medicine (DICOM) format was imported to Materialise Mimics Research 20.0 software for conversion into stereo lithography (.STL) format 3D models. Based on these 3D models, finite element models were generated with the help of meshing. ANSYS Mechanical R19.0 software was used to carry out the analysis. Teeth, PDL, bone, brackets and wire were meshed by 4 node-tetrahedral and hexahedral finite elements. A total of 1691456 elements were connected by 523759 nodes for Mini 2000 brackets and 1885715 elements were connected by 647722 nodes for Damon Q brackets (Figures 1, 2).

Assignment of material properties

The material property values used were obtained from previously conducted finite element studies [6,14]. The mechanical properties assigned to the elements assumed to be homogenous, isotropic (same in all directions) and linear-elastic (linear relationships between the components of stress and strain). The linear elastic parameters of materials used in this study are described in Table 1.

Table 2– Forces and Stresses generated with Mini 2000 and Damon Q

S No:	Particulars	Mini 2000(N)	Damon Q (N)
1.	Force generated in X axis	0.20×10^{-12}	0.19×10^{-12}
2	Force generated in Y axis	0.45×10^{-12}	0.36×10^{-12}
3	Force generated in Z axis	0.72×10^{-12}	0.55×10^{-12}
4	Resultant Force	0.47×10^{-12}	0.12×10^{-12}
5	Stress on Lateral incisor	0.52×10^{-4}	0.50×10^{-4}
6	Stress on lateral incisor root	0.35×10^{-4}	0.32×10^{-4}
7	Stress on periodontal ligament	0.32×10^{-5}	0.20×10^{-5}
8	Total Deformation of Lateral Incisor(Tooth Movement)	0.71×10^{-6}mm	1.0×10^{-6}mm

Boundary conditions and Loading configuration (Figures3, 4).

In the finite element model, the following boundary conditions were applied. The model is a fixed one mounted in alveolar bone. To simplify numerical calculations, we fixed the orthodontic wire rigidly in the bracket of the lateral incisor. Tension load (200mg) was placed on both ends of the wire. The friction coefficient between wire (CuNiTi) and bracket (stainless steel) was at a maintained constant of 0.3mm.

Force application

The 3D models of Mini 2000 and Damon Q were attached to the maxillary left and right central incisor, right lateral incisor and right canine models. The finite model of 0.014'' CuNiTi archwire was inserted into the bracket slots. The tooth was moved using force applied by the wire when inserted into the slots of the bracket. By using FEM, stresses were converted into force and compared between two bracket systems.

RESULTS

Numerical simulations of a crowded maxillary anterior model with 0.014'' CuNiTi wire in two different bracket systems Mini 2000 and Damon Q were performed using ANSYS Mechanical R19.0 software program. The magnitude of forces and stress generated were recorded by the FEM software package and the results are discussed as under:

Table 3– Direction of force	
Sign(+/-)	**Direction of force**
+X	Mesial force
-X	Distal force
+Y	Extrusive force
-Y	Intrusive force
+Z	Labial force
-Z	Lingual force

A. Force comparison with engagement of 0.014'' CuNiTi into Mini 2000 and Damon Q bracket slots during alignment of maxillary anterior teeth in X-axis, Y-axis and Z-axis(Tables 2, 3,Figures 5, 6)

(1) *X-axis*F_X in this study represents force component in the mesio-distal movement. Figures 5 and 6 show resultant force components obtained after initial wire engagement in the brackets. Table 2 shows force values obtained from two bracket systems after initial wire engagement. The wire induced a mesial force for both bracket systems. The forces generated by Damon Q (0.19x 10^{-12} N) did not differ significantly from Mini 2000 brackets (0.20x 10^{-12} N).

(2) *Y- axis*F_Y component in this study denotes a force component in the intrusive-extrusive axis. The wire clearly induced an extrusive force for both bracket types. The magnitude of force produced depends on amount of displacement of the tooth throughout the total path (Extrusive-Intrusive) of movement. Damon Q brackets exhibited a force of 0.36x10^{-12} N which was significantly lower as compared to Mini 2000 which exhibited a force value of 0.45x10^{-12}N.

(3) *Z-axis*F_Z component represents the force component in the labio-lingual axis. The wire clearly induced a labial force for both bracket types. In the labio-lingual direction, Damon Q (0.55x10^{-12}N) showed relatively lower forces than Mini 2000 (0.72x10^{-12}N).

B. Resultant overall forces generated with engagement of 0.014'' CuNiTi into Mini 2000 and Damon Q bracket slots during alignment of maxillary anterior teeth (Table 2).

The forces generated with engagement of 0.014'' CuNiTi in Mini 2000 brackets were considerably higher than Damon Q brackets during alignment of maxillary anterior teeth. Damon Q generated a force value of 0.12x10^{-12}N while Mini 2000 generated a net force of 0.47x10^{-12}N during alignment of maxillary teeth.

C. Stresses generated on lateral incisor and its root with engagement of 0.014'' CuNiTi into Mini 2000 and Damon Q bracket slots during alignment of maxillary anterior teeth (Table 2, Figures 7,8)

Figures 7 and 8 explain stress distribution patterns in the lateral incisor. For both Mini 2000 and Damon Q brackets, highest Von Mises stresses were concentrated at the middle third of the lateral incisor crown during tooth movement. However, stresses generated on the lateral incisor were slightly higher for Mini 2000 (0.52x10^{-4}MPa) than Damon Q (0.50x10^{-4} MPa.

Similarly, highest Von Mises stresses in the lateral incisor root were concentrated at the middle 3rd of the tooth root for both brackets. Among two bracket systems, stresses generated on the lateral incisor root were higher for Mini 2000 (0.35x10^{-4} MPa) than Damon Q (0.32x10^{-4} Mpa).

D. Stresses generated in the periodontal ligament of lateral incisor with engagement of 0.014'' CuNiTi into Mini 2000 and Damon Q bracket slots during alignment of maxillary anterior teeth (Table 2, Figures 9A, 9B)

Figures 9A and 9B show Von Mises stresses on the periodontal ligament of the lateral incisor. The maximal Von Mises stress on the PDL of the lateral incisor is caused at the cervix of the tooth. The stress generated on the PDL of the lateral incisor was markedly higher for Mini 2000 (0.32x10^{-5} MPa) than Damon Q (0.20x10^{-5} MPa).

E. Total deformation of the lateral incisor with engagement of 0.014'' CuNiTi into Mini 2000 and Damon Q bracket slots during alignment of maxillary anterior teeth (Table 2, Figures 10,11)

Figures 10 and 11 denote total tooth movement of the lateral incisor. With both the Mini 2000 and Damon Q brackets, during alignment of maxillary arch, total tooth deformation was appreciably higher for Damon Q (1.0x10^{-6}mm) as compared to Mini 2000(0.71x10^{-6} mm.).

Fig.1 Meshing of Mini 2000 brackets attached to teeth incorporated with elements and nodes.

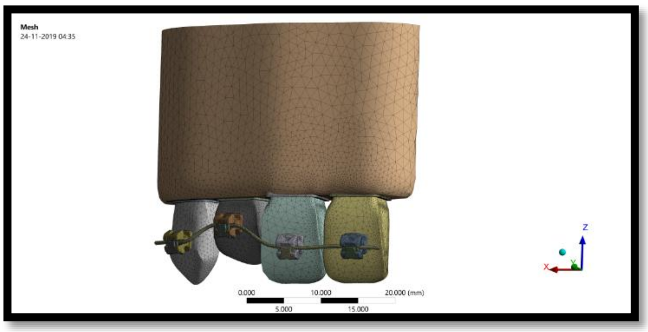

Fig.2 Meshing of Damon Q brackets attached to teeth incorporated with elements and nodes

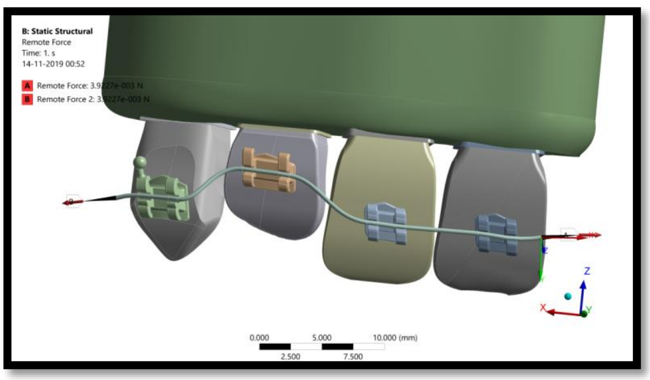

Fig.3 200mg force applied at both the ends of the wire in Mini 2000 brackets

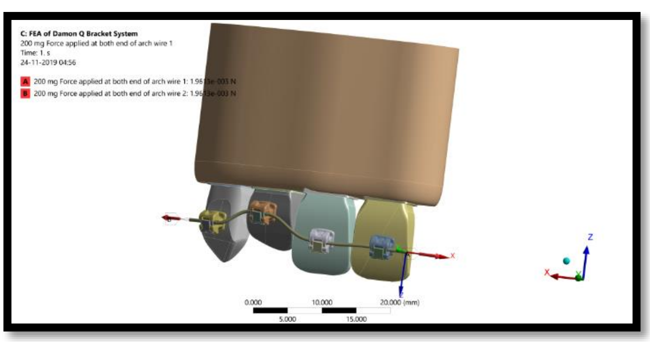

Fig.4 200mg force applied at both the ends of the wire in Damon Q brackets.

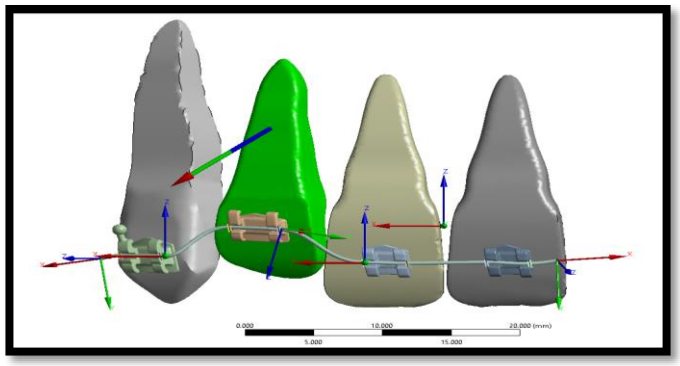

Fig.6 Force resultant with Damon Q bracket

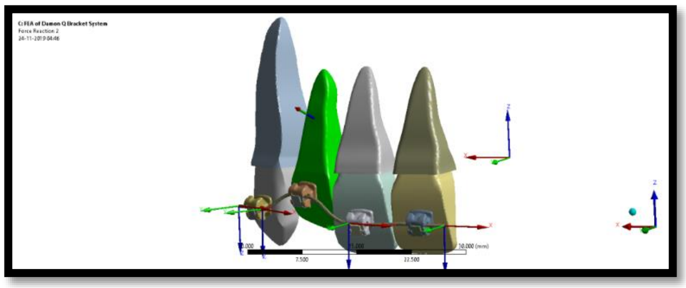

Fig.7 Stress on lateral incisor and its root with Mini 2000 bracket.

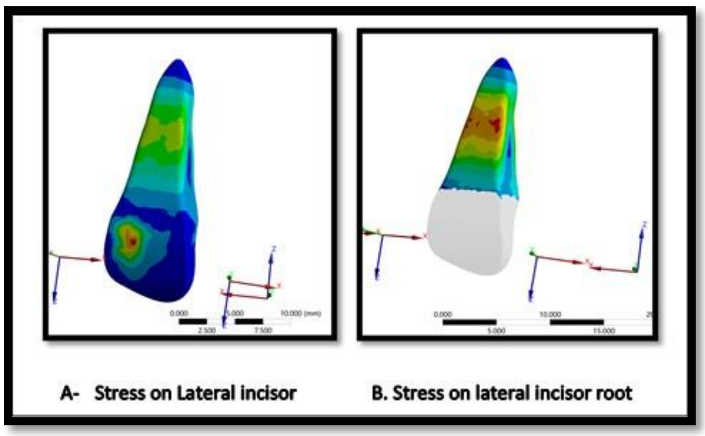

Fig.8 Stress on lateral incisor and its root with Damon Q bracket.

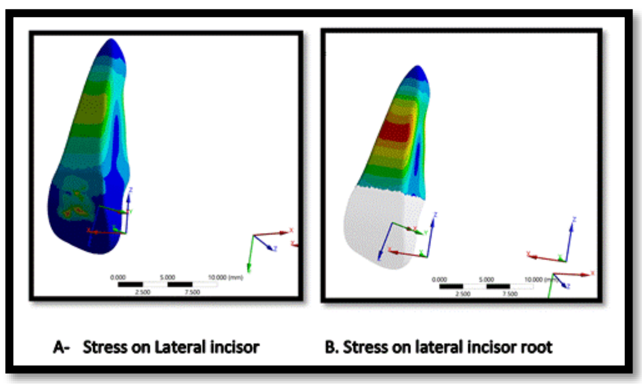

Fig. 9a Stress on lateral incisor PDL with Mini 2000 bracket.

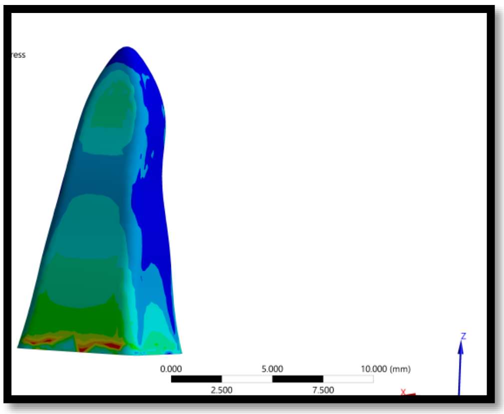

Fig.9b Stress on lateral incisor PDL with Damon Q bracket

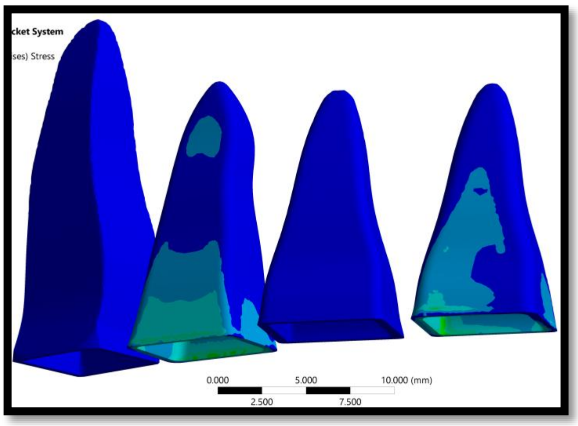

Fig.10 Total deformation with Mini 2000 bracket

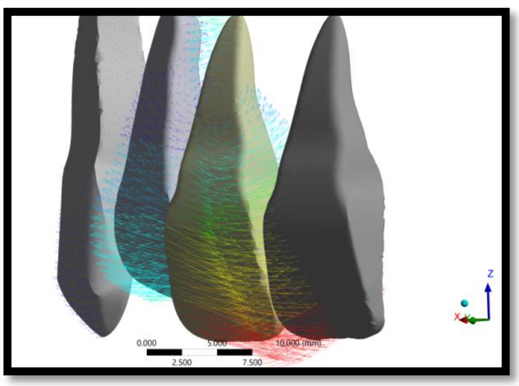

Fig.11 Total deformation with Damon Q bracket

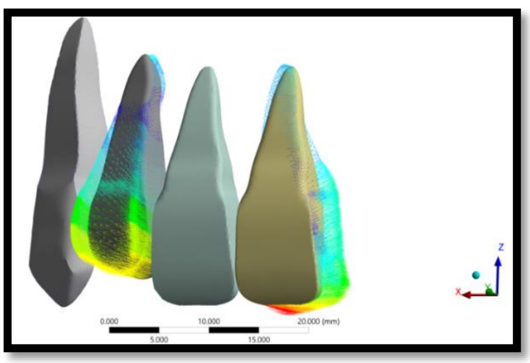

Fig.5 Force resultant with Mini 2000 bracket

DISCUSSION

The main objective of the study was to investigate the magnitude and direction of forces generated in the maxillary anterior region with engagement of 0.014’’CuNiTi arch wire into slots of Mini 2000 and Damon Q brackets during initial leveling and alignment stage of orthodontic treatment.

Current literature in the field of orthodontics on the magnitude of forces expressed during engagement of archwires into the slots of conventional and self-ligating brackets is limited not only due to rapid evolution of bracket and wire systems, but also because of development of more accurate measurement methods in the recent past. Finite element modeling and analysis has gained significant standing in orthodontics as a powerful and non-invasive tool to calculate stress, enable analysis of complex structures and for understanding tooth movements. It is a numerical technique which uses simulation to mimic complex biomechanical scenarios. Thus, FEM overcomes the previous disadvantages and mechanical errors associated with previous techniques used for measurement of magnitude of force generated by archwires [12]. As discussed before, one of the major contributors that affect the magnitude of forces generated with engagement of a wire in a bracket slot is the type of ligation. Bracket-wire interface varies significantly based on type of ligation mechanism. Elastomeric ties, stainless steel ligature ties, active and passive ligation bracket systems produce different and complex force systems [15] .Thus, with the intention of simplifying the procedure, the moment to force ratio was not taken into account.

Force component in mesio-distal movement in Damon Q did not differ from the Mini 2000 brackets. This is in contradiction with a study conducted by Seru et al who found that forces produced by conventional brackets were greater than those produced by Damon 3MX passive self-ligation brackets with the Orthodontic simulator system (OSIM) [16].In the extrusive –intrusive axis, both brackets showed an extrusive force because the forces are exerted on the incisal and gingival walls of the slot, which does not have remarkable variation between both bracket types. In this study, it was observed that Damon Q exerted lower forces as compared to Mini 2000.These results were in agreement with Pandis and Eliades [17].They found that self-ligating brackets exerted lower forces as compared to conventional ligated brackets. This reduction in force levels for self-ligating brackets in certain directions may be because of increased play of wires in the slot. Similar results were found by Montasser et al when they compared Smart clip, Time 3 and Mini Taurus conventional brackets [18]. In contrast, Alobeid et al found no significant difference in forces exerted by Damon Q and conventional brackets during intrusive-extrusive movement [19]

In the labio-lingual axis, although both brackets induced a labial force, Damon Q exhibited lower forces relative to Mini 2000 . These results were in agreement with the OSIM study conducted by Seru et al [16] where they compared conventional and passive self-ligating Damon 3MX brackets. They found that forces produced by conventional brackets were greater than Damon 3MX brackets. This might be because passively ligated brackets allow the wire to release its flexure, whereas conventionally ligated stainless steel wires prevent this release due to active ligation force. Similar results were observed in the OMSS study conducted by Montasser et al [18] where passive ligating brackets produced lower forces than conventional brackets. However, Alobeid et al [19] found no significant difference in the forces exerted between Damon Q and conventional brackets during labio-lingual movement. Pandis et al [17] also found significantly higher forces with Damon 2 than conventional appliances using the Orthodontic Measurement and Simulation system.

The forces produced by Mini 2000 were greater than those produced by Damon Q brackets during alignment of maxillary anterior teeth. Self-ligating brackets generate lower forces due to increased play of wires in the slot and lack of friction arising from contact of an elastomeric ligature outside the wings. Since, conventional brackets do not possess this fourth wall, the use of a new elastomeric ligature may also restrict archwire movement [9,17]. These results were in agreement with an in-vitro study by Bacetti et al [20]. They found that Damon 3MX brackets exerted significantly less amount of force as compared to conventional brackets for a 1.5 mm apically displaced canine [19]. On the other hand, Francisconi et al found that deactivation forces were significantly higher with Damon Q than conventional brackets [21].

Both Mini 2000 and Damon Q brackets recorded highest Von Mises stresses in the lateral incisor and its root, concentrated at the middle 3rd during tooth movement.

Stress generated on the lateral incisor and its root was higher with Mini 2000 as compared to Damon Q as orthodontic forces induced with Mini 2000 were greater when compared to Damon Q. However, Fercec et al [6] found maximum Von Mises stresses occurred at the apex of the tooth root in their study which is in disagreement with our results.

Highest Von Mises stresses were recorded on the PDL of the lateral incisor at the cervix of the tooth for both bracket types. Similar results were found by Fercec et al [6] and Cai et al [22]. Increased orthodontic forces generate more stress in the PDL, cutting off blood flow, resulting in cell death and hyalinization which delays tooth movement.

Total tooth deformation was higher with Damon Q as compared to Mini 2000 during initial alignment in the maxillary anterior arch. Storey and Smith [23] mentioned that quicker tooth movement was found with lighter forces when compared to higher forces. Damon Q brackets generate light continuous forces which are in optimum range reducing sub-optimal and excessive zone forces making tooth movement efficient and biological. Absence of light continuous forces in the optimum range for Mini 2000 evokes undermining bone resorption and causes less tooth movement to occur [24]. Harradine et al [25] and Pandis et al [26] found Damon self- ligating brackets to have higher efficiency than conventionally ligated brackets with the self-ligating group correcting malocclusion 2.7 times faster than conventional brackets. However, Miles et al [27], Scott et al [28], Fleming et al [29] and Fansa et al [30] found no significant differences in the alignment with self-ligating and conventional brackets. This can be attributed to the retrospective clinical study designs and previous generation of self-ligating brackets included in the study. In clinical studies, individual metabolic variations play a significant role and can lead to biased results. On the contrary, FEM eliminates these variations and delivers unambiguous biomechanical results while simulating clinical situations.

These findings suggest that Damon Q brackets are more effective in initial leveling and aligning without jeopardizing the health and integrity of the teeth and supporting structures. In multidisciplinary and adult orthodontic cases, Damon Q brackets can efficiently satisfy orthodontic requirements of low forces and faster tooth movement. Nonetheless, prospective randomized controlled trials should be carried out for detailed evaluation of efficiency.

CONCLUSION

1. Damon Q brackets exhibited light continuous forces in the biological range as compared to Mini 2000 brackets.
2. Damon Q brackets generated lighter forces with stresses generated in teeth and PDL also lesser as compared to Mini 2000 brackets.
3. Tooth deformation is more with Damon Q brackets as compared to Mini 2000 brackets.

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