Orthodontic Displacement and Stress Assessment: A Finite Element Analysis

Aim: The aim of the study was to analyze the stress distribution and displacement of palatally impacted maxillary canine and its adjacent teeth (lateral incisor and first premolar) when orthodontic extrusion forces were applied on the impacted canine.

Materials and methods: A three-dimensional finite element model of a maxilla containing a palatally impacted canine was constructed. Forces of 50, 70, and 100 gm were loaded on the impacted tooth.

Results: There was a steady increase in the initial rate of displacement and the von Mises stress of the periodontal ligament (PDL) in the three teeth when the magnitude of the force that was applied onto the canine increased. The initial rate of displacement was more in the first premolar tooth as compared with lateral incisor and the impacted teeth.

Conclusion: The rate of displacement in relation to the first premolar was more as compared with the lateral incisor, indicating that the first premolars had the maximum anchor loss. The use of minimal forces is ideal to extrude the impacted canines, as observed from the study that the PDL stress increases with increase in the magnitude of force.

Clinical significance: The use of finite element analysis (FEA) can help us to understand how biological tissues (tooth, PDL, alveolar bone, etc.) would respond to the orthodontic forces that are being applied on them. Individual virtual models customized to the patient’s clinical situation can be obtained and tested for various orthodontic force applications.

Keywords: Extrusion, Finite element analysis, Impacted canine, Orthodontic disimpaction, Orthodontic tooth movement, Palatally impacted canine.


INTRODUCTION
Impacted permanent maxillary canine is seen in 1 to 2% of the population. The most common teeth to be impacted are the third mandibular molars while the maxillary canine is the second most common tooth to be impacted with a prevalence rate of 1.5%. The condition is more than twice as common in girls (1.2%) than in boys (0.5%). A permanent tooth with delayed eruption of tooth, whose root is developed to its length and that is not expected to erupt within a reasonable time, in these circumstances, is termed as impacted tooth. Canine impaction is found palatal to the arch in 85% of cases and labial/buccal in 15%. Palatal displacement of the maxillary canines, with a prevalence rate of 0.8 to 5.2%, is defined as the developmental dislocation to a palatal site, often resulting in tooth impaction and requiring combined surgical and orthodontic treatment.

The etiology of ectopic canine is multifactorial. The maxillary canine is the last tooth to erupt in the upper arch with a deciduous predecessor, and, therefore, is most susceptible to environmental influences, such as crowding. The exact etiology of palatally impacted maxillary canine is unknown; however, two common theories may explain the phenomenon: the guidance theory and the genetic theory. Guidance theory proposes that the congenitally missing lateral incisors, supernumerary teeth, odontomas, transposition of teeth, and other mechanical determinants interfere with the path of eruption of the canine. The second theory states that there is genetic influence for its displacement.

The distance and direction of movement of impacted canines during treatment are determined by the canine’s initial vertical and horizontal positions. During tooth movement, changes in the periodontium occur, depending on the magnitude, direction, and duration of force applied. The knowledge of the reactions of the supporting structures in orthodontic treatment is still incomplete because histological techniques used today can provide only limited information. The force, magnitude, and direction are important factors in evaluating orthodontic appliances and its tissue reaction, and it greatly influences
the treatment success. For the same reason, a clinical study in which force variables are controlled is likely to provide more information than the data taken from a patient in day-to-day orthodontic practice. The finite element method, which was introduced as one of the numerical analyses, has become a useful technique for stress analysis in biological systems.7

Finite element analysis is progressively used in the field of orthodontics due to its ability to deliver detailed, yet precise information regarding stress on load application. It is stated that the data obtained from FEA are more accurate than any of the other experimental methods currently in use. It also allows for complete control over the variables in use, while studying a homologous sample.8 In such circumstances, a three-dimensional geometric model in a computer helps us to conduct experiments without the involvement of patients as the experiment model. Based on the application of FEA in the field of orthodontics, the same was used in this study with an aim to analyze the stress distribution on the PDL and displacement of palatal-impacted maxillary canine lateral and the first premolar during orthodontic extrusion.

MATERIALS AND METHODS

A cone-beam computed tomography (CBCT) image of the maxilla of an individual who was diagnosed with a unilateral palatally impacted canine was obtained from the database of the Department of Oral Medicine and Dental Radiology from the university (Fig. 1). The Institutional Ethical Clearance was obtained for this study. The palatally impacted canine in the CBCT image was positioned under Sector I classification according to Lindauer classification of the palatally impacted canine (Sector I—position of palatally impacted canine is in the area distal to a line tangent to the distal heights of contour of the lateral incisor crown and root).9 The CBCT scan data of the maxilla were processed using MIMICS 13 software. Here, the Digital Imaging and Communications in Medicine images of the CBCT scan were selected and converted into binary stereolithography format. Further, this was converted into a geometric model consisting of surfaces and lines. Once the surface model was obtained, it was exported to finite element modeling tool, the hypermesh version 11.0 (Fig. 2).

All teeth were aligned, and the bone covering the palatal surface of the impacted canine was removed in the finite element model, exposing it to the palatal vault such that a virtual eyelet attachment could be placed for the application of load on it. Using Ansys version 14.5, the arch wire with a cross-section of 0.019 × 0.025 inch, orthodontic braces, and a simple eyelet attachment for the impacted canine were modeled by beam 188 elements. The vertical positioning of the crown tip was approximately at the apical third of the root of the lateral incisor and was not in contact with it on the palatal side. The thickness of the PDL was considered to be uniform (0.25 mm). The material properties assigned were the Young’s modulus (or modulus of elasticity) and the Poisson’s ratio, and they were assumed to be isotropic and homogeneous (Table 1).

<table>
<thead>
<tr>
<th>Materials</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone</td>
<td>13,700</td>
<td>0.3</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>1370</td>
<td>0.3</td>
</tr>
<tr>
<td>Tooth</td>
<td>18,600</td>
<td>0.3</td>
</tr>
<tr>
<td>PDL</td>
<td>0.69</td>
<td>0.45</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>200,000</td>
<td>0.3</td>
</tr>
</tbody>
</table>
The top of the maxillary bone was constrained in all the directions, and a load in the local coordinate system was applied. Forces of 50, 70, and 100 gm were applied on the models derived from the previous studies involving orthodontic extrusion of the palatally impacted canine.10-13 The force was directed from the main archwire at a point from the center of the wire spanning between the mesial surface of the first premolar bracket to the distal surface of the lateral incisor bracket and to the eyelet attachment on the palatal impacted canine. The vector of the force acting on the impacted teeth was a combination of the buccal and extrusive components.

RESULTS

The results were produced in colorful band, with different colors representing various stress levels and displacement, where red indicates areas with the highest stress, and blue the lowest. The units of von Mises stress on PDL of the teeth are expressed as Megapascals (MPa), and the initial rate of displacement in microns or millimeter (mm) is given. The von Mises stress on the PDL and the displacements of the three teeth, such as lateral incisor, palatally impacted canine, and the first premolar on the impacted side of the maxilla were only evaluated. The transparent net diagram in the displacement pictures of teeth indicates its original position, with the colored teeth being its displaced position postload application (Fig. 3).

When three loads of increasing magnitude (50, 70, and 100 gm) were applied on the models, there was a steady increase in the rate of initial displacement in the three teeth, but the displacement of the first premolar was the maximum as compared with the lateral and the impacted canine (Table 2). The von Mises stress on the PDL of the three teeth gradually increased with increase in magnitudes (Table 2).

DISCUSSION

Management of impacted canines has been an age-old process in the field of orthodontics. An impacted tooth triggers few esthetic and functional disorders depending on the region of the defect; if the impaction is located in the anterior region, the need to reposition the impacted teeth into the arch becomes the ultimate goal. With this
in mind to achieve maximum results and for long-term prognosis, a collaboration between oral surgeons and orthodontists is essential.\textsuperscript{14} The orthodontic force needed to extrude an impacted tooth often produces side effects, such as intrusion of the adjacent teeth that acts as an anchor. Successful extrusion and alignment of such teeth require efficient mechanics to reduce the side effects.\textsuperscript{15}

When the three forces of increasing magnitudes were applied on the model, the overall initial rate of displacement of the three teeth gradually increased. The rate of initial displacement was comparatively high in relation to the first premolar, followed by the impacted canine, and the least being the lateral incisor (Table 2). This difference in the displacement may be due to the variations in the tooth size, morphology, the alveolar bone height, or even the teeth inclinations.\textsuperscript{16,17} Tanne et al.\textsuperscript{16} in their FEA study, had stated that root length and alveolar bone height affect the pattern of initial tooth displacements both in the center of resistance and the centers of rotation. In another finite element study, they had stated that there was a correlation between different inclinations of tooth to the rate of displacement and the von Mises stress generated in the PDL.\textsuperscript{17} The reason for the maximum displacement in the premolars as compared with the lateral incisors in our models for the given clinical situation could be because root of the first premolar was comparatively short than the laterals and had only a single root instead of two roots, i.e., one buccal and one palatal. Added to that, the long axis of the first premolar and the lateral incisor to the occlusal plane differed. This by itself leads to a new topic of interest.

The von Mises stress on the PDL in all teeth increased with increase in the magnitude of force (Table 2). The periodontal stress on the first premolar was more followed by the lateral incisors and the least being in the palatally impacted canine, suggesting that, when orthodontic extrusion is applied onto the impacted teeth, there is minimal PDL stress irrespective of its impaction in the bone. It showed that even with the increase of the magnitude of the orthodontic extrusive forces in this study, the periodontal stress onto the PDL of the first premolar remained contently high and then was followed by the stress in the lateral incisor, and the least in the impacted tooth. This indicated that when the forces to extrude the palatally impacted canine increased, there were increased stresses in the PDL of the lateral incisor and the first premolar, which are acting as an anchor to bring the impacted tooth to occlusion. Periodontal response to orthodontic forces is a key for treatment goals. In such conditions, the extrusive forces have to be kept as minimal as possible. Excessive periodontal stress is a major cause for external apical root resorption.

A finite element study was conducted to see the periodontal stress distribution on impacted canine when forces in different vectors were applied to its long axis. Zhang et al\textsuperscript{18} had concluded, in their study that, when the direction of the force was in line with the long axis of the impacted tooth, the maximum stress is smaller and evenly distributed, which holds good for extrusion of the impacted tooth. When the direction of the force was placed at an angle to the long axis of the tooth, it becomes larger, so the maximum stress was also larger and the stress was concentrated to one area, and this might be deleterious to extrude the impacted tooth. Hence, when the traction angle is smaller between the tooth long axis and the direction of force, there are more advantages to the eruption of the impacted tooth. In the present study, to apply a force parallel to the long axis of the tooth would hold impractical, as we are bounded by various anatomical structures, such as other erupted teeth in the arch. Such biomechanical principles are inappropriate to obtain due to both esthetic and functional constraints. Hence, in this study, even though there was stress distribution in multiple areas of the PDL of the impacted tooth, there were concentrated stresses on the cervical one-third regions on the palatal side (Fig. 4).

Extrusion of a palatally impacted canine or any impacted teeth for that reason is time-consuming, and may cause side effects on the anchored teeth, if necessary precautions are not taken. This study helped us to understand where the maximum impact takes place between the three teeth. The use of FEA software at the time of orthodontic treatment planning of impacted teeth can help us to understand what exactly would happen within the biological tissues when we apply our biomechanics to disimpact it. Based on our clinical knowledge, we should be able to relate to the above phenomenon that has taken place in our study. One of the major drawbacks of the
software is that it is time consuming and is expensive. Another shortcoming is the unavailability of accurate mathematical properties for each tooth and bone in various areas, which, though not affecting the results too much, could make the result better if present.8

CONCLUSION

With the extrusion of palatally impacted canine, there is displacement in the first premolar and the lateral incisor, but the rate of displacement of the first premolar was more as compared with the lateral incisors. This indicates that there is a maximum side effect on the first premolar as compared with the laterals. The periodontal stress on the impacted teeth remained minimal as compared with the first premolar and the laterals, when the orthodontic extrusion forces were applied. So, for a given amount of force applied on the impacted teeth, there is rather more impact in the PDL of the anchoring teeth (laterals and first premolar). There are high chances of the anchor teeth moving when the magnitude of orthodontic extrusion forces increases. The use of FEA can help us to understand the biological response that takes place behind the scene when an orthodontic force is being applied on a tooth.

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REFERENCES