Endodontic treatment is often indicated in teeth severely damaged by caries or trauma. The loss of tooth structure, due to the cause itself, and moreover, due to the access cavity preparation, leads to changes in the biomechanical properties of teeth. As a result, the risk of tooth fracture increases, and the longevity of the restoration is compromised. This is particularly the case in premolars, owing to their specific morphology and position in the tooth arch. They are subjected to higher masticatory forces than the front teeth, but their crowns are not as massive as the molar crowns. In addition, if mesial-occlusal-distal (MOD) cavity is present, the tooth susceptibility to fracture is increased due to the loss of the marginal walls, and this effect is even more severe in endodontically treated teeth due to the access cavity preparation.

Therefore, planning the restoration of such teeth has been debated in literature. Traditionally, the optimal way of restoring premolars with an MOD cavity and massive tissue loss, would be a full crown. Owing to technological progress and the introduction of dental resin composite materials and adhesive systems of improved characteristics, nowadays composite resin fillings are often the restoration of choice in endo-treated teeth. Composite fillings alone might not be sufficient to ensure the longevity of an endodontically treated tooth with an MOD cavity. Therefore, additional procedures, such as the palatal and buccal cusp reduction, and/or fiber-reinforced composite posts, are used in an attempt to improve the longevity of the restoration. Finite element analysis is nowadays a widely-used research method in biomedical sciences, due to its precision and a variety of possibilities in the calculations of stress and strain in complex three-dimensional (3D) biomedical models. Recently, modern bioimaging techniques, such as computed tomography (CT) and micro-computed tomography (μCT), are used to gain information for the creation of high quality 3D models of complex biostructures which contributes to the accuracy of FEA.

The aim of this study was to determine the effects of these procedures on von Mises stress values and distribution in dental tissues and restorative materials using finite element analysis. Based on CT scans of an extracted second upper premolar, six 3D endodontically treated tooth models (MOD, MODP, MODPB, MOD+P, MOD+P, MODPB+P) were created. Each model was subjected to a summary force of 150 N on the occlusal surface simulating the normal biting pattern and maximal von Mises stresses were calculated. MODP seems to reduce von Mises stress values in dental tissues and P seems to transfer some of the stresses from dental tissues to the composite filling.
MATERIALS AND METHODS

This study was conducted using an intact second upper premolar, extracted for orthodontic reasons. The tooth was chosen due to its lack of caries destruction, fractures and morphological abnormalities (Fig. 1a).

The extracted tooth was immediately cleaned of soft tissue residues and scanned using a multilayer CT scanner (SOMATOM Sensation 64 Cardiac, Siemens, Munich, Germany). A total of 110, 88 and 47 slices with 0.5 mm resolution were made along the x, y and z-axis, respectively. The 42 slices along the z axis, which contained useful information were imported into the AMIRA software (Visage Imaging, San Diego, CA, USA), in order to carry out tooth tissue segmentation. The segmentation was enabled by the different degrees of mineralization of the enamel, dentin and the pulp, which correspond to a certain grayscale intensity. Further, the contours of the segmented tissues were imported into SolidWorks 2014 software (Dassault Systèmes SolidWorks, Waltham, MA, USA), where a 3D solid model of an intact maxillary second premolar was created (Figs. 1b, c). Moreover, based on the contours of the generated 3D solid model, and on literature data, periodontal ligament and alveolar bone were created around the tooth (Fig. 1c). From the model of an intact premolar, six models with large MOD cavities were created for the present investigation. The width of the MOD cavity isthmus was simulated to be 5.35 mm, and the gingival wall of the cavity was placed 1 mm above the cementoenamel junction. Also, access cavity preparation, rotary root canal endodontic instrumentation with ProTaper Universal instruments up to size F3 (Dentsply Maillefer, Ballaigues, Switzerland), and canal obturation with gutta-percha were simulated. In the models without a FRC post, a glass-ionomer (Fuji II, GC, Tokyo, Japan) was placed at the access cavity floor, extending 2 mm into the root canal orifice, and the MOD cavities were restored with direct resin composite (Gradia posterior, GC). In the models with a FRC post (Postec Plus, Ivoclar Vivadent, Schaan, Liechtenstein), post insertion was simulated leaving the apical 5 mm of the gutta-percha filling intact. Additionally, a 100 µm thick layer of luting cement (Variolink II, Ivoclar Vivadent) was created between the post and dentin. In both sets of models, 2 mm cusp

Fig. 1 Tooth model generation sequence: (a) extracted second upper premolar, (b) computed contours of dentin, enamel and pulp, (c) parts of the 3D solid tooth model, (d) boundary conditions, (e) occlusal loading points, (f) meshed tooth model.
reduction of the palatal, or both the palatal and buccal cusp were simulated. Hence, six final models were created: MOD, MODP, MODPB, MOD+P, MODP+P, MODPB+P.

Each tooth structure, as well as restorative materials, were assigned the appropriate material properties (Table 1) and were considered to be linear elastic. Further, boundary conditions were set at the outer surface of the alveolar bone (Fig. 1d) and all the models were loaded at three points on the occlusal surface (Fig. 1e), the slope of the palatal cusp, and at the mesial and distal marginal ridges, simulating the normal biting pattern, with a resulting force of 150 N, since the bite forces in maxillary premolars were found to be between 100 and 300 N \(^{15}\). Meshing and FE analysis was also performed in SolidWorks. SolidWorks is a general 3D design program with various add-ins, one of which is the “Simulation” package that can be used for various FEA. In this study, the classical static analysis was used. Within “Simulation” we used solid mesh with following input parameters: Curvature based mesh, maximum element size was 2.30906 mm, minimum element size was 0.230906 mm, number of elements: 91589-115707, number of nodes: 146296-178650, mesh quality was high. Ninety seven point three percent of elements with aspect ratio smaller than 3 and only 0.0253% of elements with aspect ratio greater than 10 were obtained. Maximum aspect ratio was 37.618. All elements with aspect ratio greater than 3 were in non-critical places where the stresses were low (Fig. 1f). After meshing the models, the von Mises stresses for the enamel, dentin and the restorative materials were calculated and stress distribution was presented.

**RESULTS**

*Maximum von Mises stress values*

When comparing maximum von Mises stress values in all the tested models (Table 2), it can be noticed that cusp reduction influenced maximum von Mises stresses in the enamel, in the sense that the values of the stresses were lower in MODP and MODPB cavities, regardless of the use of a post. The lowest maximum values of von Mises stresses for enamel and dentin were found in the MODP model. This model also showed higher values of stresses in the filling compared to other models without a FRC post. Further, the MOD+P showed the highest stress values for the resin composite filling out of all the tested models, and the highest stresses in the post and the cement, as compared to other models with FRC.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus [MPa]</th>
<th>Poisson’s ratio</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel</td>
<td>84,100</td>
<td>0.20</td>
<td>13)</td>
</tr>
<tr>
<td>Dentin</td>
<td>18,600</td>
<td>0.31</td>
<td>13)</td>
</tr>
<tr>
<td>Periodontal ligament</td>
<td>70</td>
<td>0.45</td>
<td>13)</td>
</tr>
<tr>
<td>Alveolar bone</td>
<td>15,000</td>
<td>0.30</td>
<td>13)</td>
</tr>
<tr>
<td>Gradia posterior</td>
<td>6,700</td>
<td>0.22</td>
<td>41)</td>
</tr>
<tr>
<td>Postec Plus</td>
<td>48,000</td>
<td>0.24</td>
<td>*</td>
</tr>
<tr>
<td>Fuji II, GD</td>
<td>10,800</td>
<td>0.30</td>
<td>42)</td>
</tr>
<tr>
<td>Variolink II</td>
<td>6,000</td>
<td>0.30</td>
<td>13)</td>
</tr>
<tr>
<td>Gutta-percha</td>
<td>100</td>
<td>0.49</td>
<td>10)</td>
</tr>
</tbody>
</table>

*Acquired from the manufacturer (Ivoclar Vivadent)*

<table>
<thead>
<tr>
<th>Cavity design</th>
<th>Enamel</th>
<th>Dentine</th>
<th>Filling</th>
<th>FRC post</th>
<th>Luting cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOD</td>
<td>86.7</td>
<td>33.6</td>
<td>134.0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>MODP</td>
<td>56.6</td>
<td>29.2</td>
<td>142.9</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>MODPB</td>
<td>63.2</td>
<td>34.8</td>
<td>139.4</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>MOD+P</td>
<td>80.5</td>
<td>34.8</td>
<td>146.1</td>
<td>15.4</td>
<td>8.1</td>
</tr>
<tr>
<td>MODP+P</td>
<td>58.2</td>
<td>35.2</td>
<td>142.1</td>
<td>14.6</td>
<td>6.2</td>
</tr>
<tr>
<td>MODPB+P</td>
<td>63.6</td>
<td>37.8</td>
<td>136.0</td>
<td>14.4</td>
<td>6.3</td>
</tr>
</tbody>
</table>
As for the variations seen in models with and without a FRC post, the most prominent differences were found between the MOD and MOD+P model. The maximum values of von Mises stresses in the enamel were lower in the MOD+P model, while the stresses were higher in the filling as compared to the MOD model.

**Von Mises stress distribution**
Maximum stresses were mostly located in the loading areas. Another area under high stresses was the cervical portion of the palatal part of the crown (Figs. 2, 3, 4). High-stress areas were distributed similarly within all the tested models. However, in models with FRC posts,

![Fig. 2 Stress distribution in tooth tissues and restorative materials: (a) MOD, (b) MODP, (c) MODPB, (d) MOD+P, (e) MODP+P, (f) MODPB+P.](image)

![Fig. 3 Stress distribution in tooth tissues and restorative materials — cross section: (a) MOD, (b) MODP, (c) MODPB, (d) MOD+P, (e) MODP+P, (f) MODPB+P.](image)
the surface of the cementoenamel high-stress area was reduced (Figs. 4d–f).

Moreover, the stresses distributed throughout the entire tooth models were higher in the models without posts (Figs. 2, 3). Also, it can be noticed that stresses concentrated in the FRC posts were higher than in the surrounding dentin, in the corresponding models (Fig. 3).

DISCUSSION

The present study investigated the influence of cusp reduction and FRC post use on the von Mises stress values and distribution in a CT-scan based 3D model of a second upper premolar. Both cavity design and the FRC post use influenced stress values and/or distribution in the six investigated models, which requires the rejection of the null hypothesis.

With the advance in materials technology, properties of the composite materials have improved significantly. Hence, dental composites are most often the material of choice in the restoration of endodontically treated teeth. Dental composite restorations are often used in combination with posts and crowns. The use of composite materials in endodontic therapy is becoming more common, and they are often preferred over traditional metal-ceramic restorations due to their aesthetic properties and ease of use.

Cusp reduction was the most influential factor in the maximum von Mises stress value changes in the enamel. The values were markedly lower in MODP and MODPB models, regardless of the use of a FRC post. These findings are in accordance with the results of certain studies. Lin et al. recommend a cusp reduction of at least 1.5 mm in order to increase the fracture resistance of premolars. Kantardžić et al. found using the FEA method that the reduction of the palatal cusp reduces stresses in the enamel significantly. Certain in vitro studies showed that endodontically treated premolars restored using partial ceramic or full composite onlays had a higher fracture resistance as compared to other techniques used, while another group of authors found that cusp capping does not influence fracture resistance significantly. In the present study MODP and MODP+P showed the lowest values of maximum von Mises stresses in the enamel, which could indicate that bucal premolar cusp reduction is not necessary. This protocol would be more in accordance with the concept of minimal intervention dentistry. Therefore, only palatal cusp reduction would be advisable, which is reasonable in the case of
the upper second premolar, since one of the loading points is located on this cusp, and it is very common in everyday dental practice that the palatal portion of the premolar fractures13,20.

Another interesting finding can be noticed in maximum von Mises stress values in MOD and MOD+P models. The fact that MOD+P model showed lower stresses in the enamel and higher in the restorative materials could imply that a portion of the stresses was transferred through the FRC post to the composite52 in the absence of protective role of cusp reduction. Perhaps this could be the reason that such outcomes were not present in MODP and MODPB cavity designs.

Stress distribution was similar in all the tested models in the present study. The maximum stresses were located on loading areas and at the cervical portion of the palatal aspect of the crown. This is again in agreement with the fact that the fracture of the palatal portion of the crown is the most often failure mode of endodontically treated upper premolars with MOD cavities restored with composite resin13,28. It is apparent that the surface areas of high von Mises stress values were reduced in models with FRC posts. This could be due to the fact that some of the stresses from the outer structures were transferred to the FRC posts27. Another interesting fact that can be seen from the results of the present study, regardless of the maximum stress values, is that von Mises stresses were slightly lower throughout the whole models with FRC posts (Fig. 3). Although the maximum von Mises stress values were not seemingly significantly different between the models with and without FRC posts, the more favourable distribution of maximum stresses in the models with posts could influence the longevity of the restoration over the years of use in intraoral conditions4,9). Numerous in vivo, in vitro and FEA studies have shown that the use of FRC posts and composite cores decreased the stresses in dental tissues1,4,9,11,35-37). Certain clinical studies with a follow up period of 26, 38 and 6 years33) revealed a beneficial influence of fiber post insertion on the tooth survival in endodontically treated premolars. In ivi studies have also linked the use of FRC post to better fracture resistance in endodontically treated premolars1,28. Krastl et al. 29) even suggested a 3 mm intracanal composite anchorage of endodontically treated premolars as a valid alternative to conventional posts in terms of fracture resistance. On the other hand, certain authors found no significant differences in fracture resistance of premolars restored with or without post insertion and cusp reduction4,31). However, if the success of the restoration over time would be evaluated, not only by fracture resistance, but also in the terms of marginal integrity and discoloration, as well as the integrity of the restoration, then the role of post insertion could be perceived differently. It is possible that the post decreases cuspal deflection11 by absorbing a certain amount of occlusal loads, which could on the long run reduce marginal leakage and infiltration39.

Most FEA studies published on the topic of post-endodontic restorations investigated the influence of post material, length and diameter on the biomechanical properties of endodontically treated teeth restored with prosthodontic crowns27,32-36. Therefore, it is difficult to compare the results of this FEA study to the information in the available literature. However, the results of these FEA studies influenced the choice of FRC post in the present study since it was shown that the use FRC posts has a tendency to decrease the stresses in the remaining tooth tissues10,11,35-37). Further, as previously mentioned, the beneficial influence of cusp reduction on stress and strain in the dental tissues of endodontically treated premolars was shown in certain FEA studies13,28,39. As to our knowledge, the influence of post insertion in the combination with a conservative composite filling and different cavity designs in the restoration of endodontically treated premolars has not yet been studied using the FEA method.

Strengths and limitations of the method used in this study should be mentioned. Firstly, homogeneous, linear elastic and isotropic properties were assigned to all the tooth tissues and restorative materials, while it is well known that some of these structures have neither of these properties38,39). The nonisotropic properties of the periodontal ligament (PDL) have especially been debated in literature33). However, it was found that the properties of the PDL do not influence significantly the validity nor the results of the FEA studies39). Also, inhomogeneities in teeth are at nano/micro scale, while standard programs for FEA, such as Simulation package for SolidWorks can mesh only millimeter structures, so certain simplifications usually need to be applied in FEA41). Further, the experiment performed in the present study was static, which means that time and temperature influence were not taken into consideration, and perfect bonding of all materials to dental tissues was assumed, which is impossible to achieve in practice. Dynamic FEA studies have been conducted which take into consideration more variables42). Hence, their results are assumed to be more accurate. However, these types of studies are still very variable, and should be more standardized in order to make comparable results33,43). Another important point to be discussed is the choice of von Mises stress criterion in the present study. Von Mises criterion is a scalar stress measure which combines the three principal stress values and identifies clearly the areas of the model that are under highest stress and are consequently more prone to fatigue failure. It is widely used in FEA studies44), including a large number of published studies on the present topic7,10,11,32,33,36,37). Hence, the authors have chosen this criterion as to easily compare results with other studies. Nonetheless, for a more detailed understanding of the influence of tensile, compressive and shear stress, principal stresses could be discussed separately, which the authors intend to do in some of the following work. Lastly, the experiment setting was made only on one model, with one type of loading, and the intraoral conditions would be much more complex. These facts could be perceived as strengths as well as weaknesses of the FEA method. The strength of FEA studies lies in the fact that it assumes constant conditions for all the investigated models, and the
variables are only the features that the examiners wish to investigate. Due to this fact, the influence of a specific factor on stress and strain values and distribution can be investigated, without the influence of potential error due to the practitioner, the patient, or the variability of tooth tissues which are common in clinical and in vitro studies. Also, the values and distribution of stresses can be evaluated and visualised in every crosssection, and at every point of the complex 3D model. Since the purpose of the present FEA study was to evaluate von Mises stress values and distribution in models of endodontically treated teeth with different restoration protocols in the physiological biting position, the current experiment setting was adequate for achieving this goal. The present FEA model was validated in an experimental study with a specific setup for the measurement of strain using dualview holographic interferometry. Due to the difficulty in collecting a homogenous sample of human premolars, it was performed on plastic tooth models created using rapid prototyping based on the FEA model. The results of the experimental study were comparable to the ones obtained in the numerical simulation, validating the accuracy of the model.

**CONCLUSIONS**

In conclusion, it can be recommended to dental practitioners that palatal cuspal reduction could be beneficial for the longevity of the tooth and the restoration.

Further, in a MOD cavity of two thirds of intercuspal width, without cuspal reduction, the use of a FRC post is recommended in order to reduce the stresses in the enamel.

Also, within the limitations of this study, it seems that the models with FRC posts have lower stresses distribution at the high-stress areas as well as throughout the whole tooth model. Long term influence of FRC posts is yet to be determined in prospective clinical studies.

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