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Conclusions: Mechanically reconnecting the remaining tooth structures has a direct positive effect on stress distribution and deformation of the remaining structures.

Clinical relevance: Reinforcing ETT in a non-invasive direct approach is efficient in terms of preserving sound tooth structures, reducing the time of treatment and eliminating the laboratory steps required to create the restorations.

1. Introduction

After endodontic treatment, practitioners are facing several therapeutic possibilities for the restorative procedure. With the evolution of dental adhesive systems and techniques, everyday’s practice is heading towards maximal conservation of tooth structures [1], since this approach has demonstrated a better long term prognosis of the treatment [2]. The endodontic procedure is known to weaken the tooth and to increase the risks of fracture. This is mostly due to the tissue removal required to access the root canals [3], and not due to dehydration since it was shown that this last factor was actually not very significant [4,5]. In many studies, cusp fractures were very often associated with weakening of the tooth structure due to endodontic treatment but it was also shown that an endodontic treatment with the preservation of the proximal ridges did not have a severe effect on the fracture resistance of the tooth [6]. Some authors suggested that endodontically treated teeth (ETT) with a conservative occlusal access cavity can be safely treated with a simple direct restoration. On the other hand, most of the studies agree that MOD cavities on ETT need to be treated with a cusp covering restoration [7–9]. In amalgam restorations, the remaining buccal and palatal walls become completely separated after a MOD cavity. This means that there would be nothing left to retain the remaining walls from deflection during the mastication. This is why a higher rate of cusp fracture was observed on teeth restored with non-bonded restorations such as amalgams [10]. Adhesively placed resin composite restorations were thought to solve this problem as it was assumed that they reduced the deflection of the walls by adhering to them [11]. The aim of this study was to evaluate the mechanical reinforcing effect of reconnecting the buccal and lingual walls of a large MOD cavity on an endodontically treated lower molar, through a novel non-invasive technique. Finite Element Analysis (FEA) was applied to compare stresses due to functional loading in the restored tooth. It was assumed that re-establishing the macromechanical link between the remaining walls of a cavity would increase the fracture resistance of the tooth.
2. Material and methods

2.1. Generation of the models (pre-processing)

An extracted intact mandibular human first molar was used to create the three-dimensional (3D) numerical models. A micro-CT scanner (SkyScan 1076 micro-CT, SkyScan, Aartselaar, Belgium) was used to scan the tooth at a spatial resolution of 15 μm. The software NRecon (NRecon 1.6.9.16, SkyScan, Aartselaar, Belgium) was used to reconstruct the images issued from the micro-CT scanner. The slices were then used to build the models with the image processing software OsiriX (OsiriX 3.9, Geneva, Switzerland). The different tissues of the tooth were separated by a process known as segmentation in order to better analyze them since they have different material properties. Segmentation is based on radiodensity, and it is performed by defining a range or thresholds of pixel density for every tissue. Pixels that have the same or very near values of density are grouped and selected together. Since the density of enamel is different from the density of dentine, at the end of this step, two 3D regions were obtained, one for enamel and one for dentine, and were saved as stereo lithography files (STL-files). In order to optimize the models for the FEA, the STL files were then remeshed, which is a process that reorganizes the geometry of the 3D object without changing its shape. After obtaining a valid mesh structure, two thirds of the roots were cut to reduce the time of the analysis, and a support cylinder was modeled. The parts were finally reassembled to obtain an intact tooth model (“Int”).

A 3D content-creation program (Blender 2.70, Amsterdam, the Netherlands) was then used to simulate the different cavities and restoration procedures, by performing multiple Boolean operations on the intact tooth model. Three other models were then created: Unrestored MOD cavity on an ETT (“Unrest”), MOD cavity on ETT restored with resin composite (“Norm”), MOD cavity on an ETT reinforced with a ring (“Ring”) (Fig. 1).

To design the “Unrest” model, a conservative endodontic access cavity and a large and deep MOD cavity were simulated by
performing a subtraction Boolean operation between the “Int” model (Fig. 2a) and a 3D object “Cutter” (Fig. 2b) that has the positive shape of the future cavity. Boolean operations permit to subtract, add or intersect different 3D objects. By positioning the “Cutter” in the wanted location of the future cavity (Fig. 2c), the common portion between the intact tooth and the “Cutter” can then be eliminated in order to obtain the unrestored model (Fig. 2d). The occlusal bucco-lingual width of the cavity was half the maximum bucco-lingual width of the tooth, and the cervical margin was 1 mm occlusal to the CEJ. All axial dentine was removed between the pulp chamber and the proximal boxes. The angle of divergence of the cavity walls was 5°. To design the “Norm” model, a series of Boolean operations was used between the “Int” and “Unrest” models in order to obtain the exact geometry for the composite restoration. To design the novel “Ring” model, a 2 mm wide unidirectional fiber-reinforced composite (FRC) band (ever-Stick C&B, stickTech Ltd., Turku, Finland) was modeled around the middle of the crown of the “Norm” model. The thickness of the ring was 1.5 mm.

In order to better understand the Ring model, an in vitro photograph is provided in Fig. 3. Another configuration of the band could also be possible as seen in Fig. 4; the proximal parts of the ring were crossed to the center of the cavity instead of using it as a ring shape. This configuration retains the same mechanical function between the buccal and lingual walls, and should permit the reconstruction of the proximal faces without any interference with the adjacent teeth.

### Table 1
The materials used in the study and their corresponding Young modulus, Poisson's ratio and Shear modulus.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Young modulus (GPa)</th>
<th>Poisson's ratio</th>
<th>Shear modulus (GPa)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel</td>
<td>84.1</td>
<td>0.30</td>
<td></td>
<td>[21]</td>
</tr>
<tr>
<td>Dentine</td>
<td>18.6</td>
<td>0.31</td>
<td></td>
<td>[28]</td>
</tr>
<tr>
<td>Resin Composite</td>
<td>10</td>
<td>0.24</td>
<td></td>
<td>[29,30]</td>
</tr>
<tr>
<td>Support Cylinder</td>
<td>14.7</td>
<td>0.30</td>
<td></td>
<td>[31]</td>
</tr>
<tr>
<td>Reinforcing Ring</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal</td>
<td>39</td>
<td>0.35</td>
<td>14000</td>
<td></td>
</tr>
<tr>
<td>Transverse</td>
<td>12</td>
<td>0.11</td>
<td>5400</td>
<td>a</td>
</tr>
</tbody>
</table>

a: Values from stickTech Ltd. (Turku, Finland).

2.2. Finite element analysis

The models were then introduced into a software for advanced engineering FEA (FEMAP 11.1, Siemens PLM software, Plano, Texas, USA). Different attributes were then created for each tissue to define the mesh size and the material properties. The Poisson ratio (ν), modulus of elasticity (E) and shear modulus of the oral tissues and restoration materials were determined from the literature and are presented in Table 1. All the materials were considered to be isotropic with the exception of the ring. The FRC ring was considered as an anisotropic material with its maximal Young modulus and stiffness in the longitudinal direction of the fibers. After meshing the parts, loads were defined on the buccal and lingual distal cusps with a constant value of 600N and an angle of 45° as shown in Fig. 5. The models were fixed by applying constraints in the x-, y- and z- axes on the support cylinder.

A static analysis was then launched, and two types of results were mainly studied in the post-processor: The displacement and the maximum principal stress values. After running the analysis, the results were opened side by side in Nastran X. The loads and constraints were then hidden to have a better view on the model. To study the deformation of the walls after loading, the distance change between the buccal and lingual walls had to be measured. To do that, two sets of paired reference nodes were chosen on both buccal and lingual surfaces of the enamel, on two different heights: the first set of pairs at the occlusal level near the cusp tips (OCC) and a second set of pairs at the cervical level 1 mm above the CEJ (CEJ). The coordinates of each node were recorded before and after applying the loads, and the distance between each two paired nodes was then calculated. The variation of the distance before and after applying the loads was represented in Fig. 6. To study the stress distribution in each model, the maximum principal stress values were extracted and represented on the 3D models in four different views and lateral sections (Figs. 7 and 8). The highest maximum principal stress values were also studied at four main zones: the interface between the cavity and the restoration, the
cervical enamel, the cervical dentine and inside the restoration (Fig. 9).

3. Results

As seen in Fig. 6, the “Unrest” model (Fig. 1a) showed the highest distance change at both the OCC and CEJ level with a mean deviation of 340 μm at the OCC and 104 μm at the CEJ from the control model “Int” (Fig. 1d). The “Ring” model (Fig. 1c) and the intact tooth showed very similar results. The “Ring” showed a mean deviation of 4.7 μm at the OCC and 0.1 μm at the CEJ from the control model “Int”. The “Norm” model (Fig. 1b) showed a mean deviation of 10.7 μm at the OCC and 2.2 μm at the CEJ from the control model “Int”.

As seen in Figs. 7 and 8, the stress values in the “Unrest” model were much higher than all the other models with the stress concentrated at the cervical level of the root with more than 492 MPa in the lingual. The stress values at the cervical level for the “Norm”, “Ring” and “Int” were 48 MPa, 18 MPa, and 28 MPa respectively (Fig. 9). Another stress concentration zone was observed inside the composite resin restoration and the values for the “Norm” and “Ring” were 84 MPa and 130 MPa respectively. The stress values at the interface between the restoration and the cavity for the “Norm” and “Ring” were 28 MPa and 19 MPa respectively. High peaks of stress values were also observed at the most occlusal portion of the interface restoration/cavity in a very small area near the load location and the values for the “Norm” and “Ring” models were 93 MPa and 496 MPa respectively. The “Int”
Fig. 7. a. Image showing maximum principal stress values in MPa: Unrest. b. Image showing maximum principal stress values in MPa: Norm (NB: The composite restoration is hidden to show the stress distribution in the cavity). c. Image showing maximum principal stress values in MPa: Ring (NB: The composite restoration is hidden to show the stress distribution in the cavity). d. Image showing maximum principal stress values in MPa: Int.
Fig. 7. (Continued)
model showed a stress concentration of 160 MPa in the central groove.

4. Discussion

FEA is a reliable mathematical method used in mechanical engineering to visualize stresses in complex structures originating from civil engineering. Most of the new engineering concepts pass by this phase as it is a good tool to optimize the designs, to increase the accuracy and to reduce the number of physical prototypes. In dentistry, it is often applied and validated by comparing FEA-results with in vitro results [12,13]. For this study, it was crucial to limit the variables between the groups to the restorative technique only, to confirm whether the technique is beneficial or not. Knowing the limitations of in vitro studies such as the difficulty of having two molars with the exact geometry and tissues properties,

![Image showing lateral cuts with maximum principal stress values inside the models: a) Unrest, b) Norm, c) Ring, d) Int.](image)

Fig. 8. Image showing lateral cuts with maximum principal stress values inside the models: a) Unrest, b) Norm, c) Ring, d) Int.

![Graph showing highest maximum principal stress values observed at four main stress concentration zones (MPa).](image)

Fig. 9. Graph showing highest maximum principal stress values observed at four main stress concentration zones (MPa).
FEA may be the optimal method to simulate and compare different cavity designs and restorative procedures in an equally shaped tooth as a first step in evaluating the studied idea. The ring reinforced group exhibited the best results at both the stress and the deformation levels. The choice of material to use for the ring may be very wide. For this study, “everStick C&B” was used because of its high modulus of elasticity and resistance to fracture, and because it could be well bonded to the enamel in thin layers. Moreover, a lot of dentists are already familiar with the handling of such products. For the clinical application, the thin layer of less than 1.5 mm in thickness will not affect the patient’s comfort in the vestibular and lingual sides. A thin layer of flowable composite may be used to make the transition continuous between the tooth and the fibers. The positive results of this group validate the mechanical benefits of that technique, which is an essential step before investigating and optimizing its clinical aspect.

Cuspal deflection mainly occurs along the bucco-lingual axis. This happens since most of the forces during mastication on posterior teeth are directed laterally. In intact teeth, the proximal ridges are the main structures that oppose these forces and limit the micro-movements [14–17]. In upper molars, the oblique ridge might be a factor of why we see less mesio-distal cracks or cracked tooth syndrome compared to lower first molars [18,19]. In MOD cavities restored with a standard adhesive composite restoration, the main component that opposes the lateral forces and micro-movements is the adhesive layer and the remaining walls since the ridges are not present anymore. Adhesive resins have a Young modulus of around 4.3 GPa compared to 18.6 GPa and 84.1 GPa respectively for dentine and enamel. This means that the adhesive resin is much more elastic than dentine and enamel, which leads to a higher stress concentration in the cervical parts of dentine and enamel and inside the adhesive, which was confirmed by the stress results stated earlier. This has a direct effect on the remaining dental tissues and the quality and longevity of the adhesive layer.

Enamel and dentine’s mechanical properties have been subject of many studies [20–25]. Most of the authors tested either enamel or dentine in order to find the modulus of elasticity and the hardness. Enamel is considered to be a brittle material, while dentine is more elastic. Some authors also studied the mechanical properties of both enamel and dentine without separating them, and found that the overall properties were in between those of enamel and dentine, in the range of elastic materials [26]. By considering the tooth as an elastic material, the concepts of fatigue can then be applied [27]. The effects of fatigue were not examined in the present study as it is not possible to do so with FEA, but as seen in the results, mechanically reconnecting the remaining tooth structures, showed a decrease of the stress in most of the regions of the tooth and regrouped it inside the composite and the ring. In the case of the “Ring” model, the stress values at the cervical level were even lower than those observed in the intact tooth. This should increase significantly the resistance to fracture by fatigue of the dental tissues since the stress amplitude at the cervical zone decreases and in some zones gets under a certain value called endurance limit, and therefore the number of cycles before failure should increase. Another type of fracture is often caused by a single dynamic force exceeding the ultimate stress supported by the tissues. Reconnecting the remaining tissues redirects the stress into the ring which in such cases also increases the resistance to fracture of the tooth by redirecting the forces away from the weak points of the cavity. All of this paves in favor of the philosophy of minimally invasive dentistry, by favoring the deterioration of restorative materials which are replaceable, instead of damaging the dental tissues.

As it was mentioned earlier, the adhesive layer is also affected by the lateral forces since it is a main component that directs these forces in MOD cavities. It is true that adhesive systems were a huge leap forward in dentistry, and that adhesives are more than sufficient to retain certain restorative materials. What was shown in this study is that the adhesive may not be enough to maintain the original stress distribution that existed in the unprepared sound tooth. Most studies tried to find the perfect restorative material to increase the fracture resistance of the tooth and overlapped the fact that it will mainly be the task of the adhesive to transfer the stress to the remaining tooth structures and restorative material. Therefore, the adhesive bond is enough to provide retention for the restorative material, but until now is maybe not enough to fully restore the mechanical resistance to the tooth. A perfect marginal adaptation of a restoration is as important as the fracture resistance of the restored tooth since it’s the only barrier to prevent secondary caries and infiltrations. The present study showed that mechanically reconnecting the remaining tooth structures decreases the stress values at the interface between the tooth and the composite restoration. This subject will be investigated in following studies.

Planning a restorative treatment today is mostly guided by evidence based studies and by experts opinion. It was noted in the present study that even small variations between the cavity designs had an important impact on the distribution of the stress inside the tooth and the restorative materials. These variations can be the geometry features of the cavity, the quality of the cavity surface, the surface defects or the effect of discontinuity. Here comes the importance of the cavity design and the choice of the restorative technique that should be particular to every case. This is why in the future, the ideal solution would be to run a rapid FEA study for each clinical situation which would show the practitioner the flaws in the cavities, and even present a guide to the best restorative materials and techniques to use. This might sound like science fiction, but with the increasing presence of CAD/CAM systems in our clinics, it will be a matter of time before a simple user friendly software would be integrated in these systems which will be able to show us important data such as the stress concentration zones and the number of cycles before failure which could then be translated into years of service to choose the best treatment for the patients.

5. Conclusion

The results of this FEA study demonstrated that mechanically reconnecting the remaining tooth structures in a MOD cavity on an endodontically treated lower molar increases the resistance to fracture and reduces the stress values at the interface between the cavity and the restorative material.

Acknowledgement

The authors deny any conflicts of interest related to this study.

References


