Finite element analysis of stresses in molars during clenching and mastication

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Statement of problem. During physiological functions of the masticatory system such as swallowing and chewing, teeth are subjected to variations in force application. Most in vitro analyses of stress have not analyzed the combined forces acting on teeth.

Purpose. The purpose of this study was to analyze the stresses induced in a mandibular molar during clenching and chewing of morsels with various elastic moduli.

Materials and methods. The investigation was performed by means of finite element analysis with the use of contact elements. Two-dimensional models of the mandibular first molar and the crown of the opposing maxillary molar were created. The computerized simulation evaluated the clenching and chewing of 4 morsels with different elastic moduli (similar to hard gum, tough meat, bone, and combination of hard gum and bone). The movement of the studied teeth was simulated in the frontal plane. Teeth models crushed morsels and closed into the maximal intercuspation position. The values of stresses in the mandibular molar were calculated during these situations.

Results. The study revealed that clenching of molars and chewing morsels of high elastic moduli resulted in maximal equivalent stresses within occlusal enamel. During mastication of morsels of low elastic moduli the stress concentration was located in the cervical region of the lingual side of the mandibular molar. Masticating a low-elasticity morsel containing a fragment of bone caused the highest equivalent stresses in the lingual wall and high tensile stresses in enamel near the central intercuspal fissure of the tooth studied.

Conclusion. During mastication of various morsels, maximal equivalent stresses occurred in occlusal enamel and in the cervical region of the lingual wall of the first mandibular molar. The more unfavorable and highest stresses were exerted during mastication of nonhomogeneous morsels. (J Prosthet Dent 2003;90:591-7.)

CLINICAL IMPLICATIONS
This finite element study demonstrated that hard tissue loss of mandibular molars weakened by carries or extensive restorations might predispose the lingual wall to fracture during chewing. When restoring mandibular molars, emphasis must be placed on protecting not only the functional cusps, but also the lingual cusps and axial wall.

Fracture of teeth poses a significant problem for both the patient and the dentist. A large proportion of fractured teeth are nonrestorable. Posterior teeth are most prone to fractures and in particular the mandibular first molars. Fractures occur twice as frequently in lingual cusps compared to buccal cusps. It has been speculated that the higher fracture potential of nonfunctional cusps in mandibular molars is related to their anatomical shape. Nonfunctional cusps are narrower and have thinner enamel; the angular inclinations of these cusps are smaller than the functional cusps. Thus, they are more susceptible to the horizontal vectors of masticatory forces.

Caries lesions and large restorations seem to be associated with most fractures. As the restoration becomes wider and deeper, fracture resistance of the residual tooth structure decreases. Teeth that have 3 or more surfaces restored are the most prone to wall fractures.

Tooth fracture results directly from combined forces acting intraorally. Masticatory forces, caused by contraction of the masticatory muscles, are transmitted to the teeth through the crushed morsel. The values of these forces depend on factors including gender, age, state of teeth, as well as the hardness of food, its consistency, and the phase of the masticatory cycle. Masticatory forces are the greatest in the region of the first molars.
Table I. Mechanical properties of materials used in models of first mandibular molar

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus E [MPa]</th>
<th>Poisson’s ratio ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel</td>
<td>83000</td>
<td>0.33</td>
</tr>
<tr>
<td>Dentin</td>
<td>18600</td>
<td>0.31</td>
</tr>
<tr>
<td>Periodontium</td>
<td>68.9</td>
<td>0.45</td>
</tr>
<tr>
<td>Morsel I</td>
<td>20</td>
<td>0.45</td>
</tr>
<tr>
<td>Morsel II</td>
<td>200</td>
<td>0.4</td>
</tr>
<tr>
<td>Morsel III</td>
<td>10000</td>
<td>0.28</td>
</tr>
<tr>
<td>Morsel IV—non-homogenous containing fragment of bone</td>
<td>2000</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table II. Maximum values of equivalent stresses in models of first mandibular molars and maximum pressure on their occlusal surface during clenching and masticating various morsels [MPa]

<table>
<thead>
<tr>
<th>Occlusal situation</th>
<th>Equivalent stresses in enamel [MPa]</th>
<th>Equivalent stresses in dentin [MPa]</th>
<th>Maximum pressure on teeth [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clenching of molar teeth</td>
<td>65.6</td>
<td>13.0</td>
<td>54.9</td>
</tr>
<tr>
<td>Mastication of morsel I</td>
<td>24.1</td>
<td>19.0</td>
<td>8.1</td>
</tr>
<tr>
<td>Mastication of morsel II</td>
<td>32.0</td>
<td>15.3</td>
<td>33.0</td>
</tr>
<tr>
<td>Mastication of morsel III</td>
<td>31.4</td>
<td>10.9</td>
<td>40.4</td>
</tr>
<tr>
<td>Mastication of morsel IV</td>
<td>70.1</td>
<td>42.5</td>
<td>86.1</td>
</tr>
<tr>
<td>Static loading of 3 forces of 66.6 N each</td>
<td>45.9</td>
<td>10.4</td>
<td>—</td>
</tr>
</tbody>
</table>

Normal masticatory cycles are generally bilateral. Mastication of a morsel occurs on the working side. During cyclic closure of the mandible, the opposing teeth initially contact with the mandible laterally positioned. The mandibular molars glide along the opposing occlusal surfaces of the maxillary teeth, crushing the morsel of food until the teeth reach maximum intercuspal position. The masticatory forces acting on the morsel during mastication are constantly changing in direction, quantity, and location of force application, depending on the contact relationship of the opposing tooth surfaces. Only static loading of constant direction and point of application have been investigated.

The purpose of this study was to examine the stresses induced in the first mandibular molar during clenching and masticating morsels of various elastic moduli.

**MATERIAL AND METHODS**

The study of stresses in mandibular first molars during articulation was conducted by means of a finite element analysis (FEA), using software (ANSYS version 5.6.2.; ANSYS Inc, Canonsburg, Pa). On the basis of anatomical data from the literature, a computerized 2-dimensional model of the mandibular first molar in frontal section was created. The periodontal ligament of 0.1 mm width was modeled around the root, as it significantly affects the distribution of stresses. A model of the opposing maxillary first molar crown was created for analysis.

In order to perform calculations, the tooth model was divided into 4654 triangular 6-node elements (PLANE 2) jointed in 9814 nodes. It was assumed that the model was in a plane stress state. Thus, stresses directed perpendicularly towards the analyzed cross-section equalled zero. The computerized model of the mandibular molar was fixed at the periodontal bone interface.

Each of the tissues in the tooth model was defined in terms of the mechanical properties. The values of elastic modulus and Poisson’s ratio for enamel, dentin, periodontium, and exemplary morsels are shown in Table I. The morsels used in the study were of the same shape and size (1×8.5 mm), but had different elastic moduli. Morsel I had elastic modulus similar to hard gum, morsel II, similar to tough meat, and morsel III, similar to bone. Morsel IV was composed of the same material as morsel I, and included a 1×1-mm fragment of simulated bone. The embedded fragment was located inside the morsel 1.5 mm from its margin. The materials used in models were homogeneous, isotropic, and linear-elastic.

A computer simulation of the relationship between the first mandibular and maxillary molars during clenching and mastication was conducted. The movements of the teeth were reconstructed in the frontal plane. For clenching, the models of the opposing molars were placed in the maximal intercuspal contacts. The teeth occluded against each other with a maximal force of 200 N. It was assumed that the forces applied to the tooth during clenching and mastication of various morsels were the same in order to compare the stresses in the tooth subjected to the varying loads.

Computer simulation was done only for the phases of mastication where crushing of morsels occurred. The teeth initiated movements from the lateral contact position. The morsels were placed between opposing teeth. For the purpose the calculation, the assumption was made that during mastication the maxillary tooth moved. The total vertical forces of 200 N and lateral displacement by 1.5 mm were applied on the upper surface of the crown of the maxillary tooth. The tooth slid along the morsel and crushed it until the maximal intercuspal position was achieved.

On the interface between occlusal surfaces of molars and morsels, pairs of contact elements were used (CONTRA 172 and TARGE 169). It was assumed that the friction coefficient on the contact surface of the tooth models was 0.05. Contact simulation of FEA was a non-linear analysis that required the load and displacement to be applied in a number of steps. Automatic time stepping was applied in this analysis.
Additionally, a first mandibular molar during static loading was studied. Three forces of 66.6 N each, parallel to the longitudinal axis of the tooth, were applied to the expected occlusal contact areas of the molar studied: the buccal slope of the buccal cusp, the lingual slope of the buccal cusp, and the buccal slope of the lingual cusp.

For the mandibular first molar, the pressure exerted on the occlusal surface, stress components (normal stresses \( \sigma_x, \sigma_y \), shear stresses \( \tau_{xy} \), principal stresses \( \sigma_1, \sigma_2 \)) and equivalent stresses were calculated. Equivalent stresses were determined according to Huber-Mises-Hencky's failure criterion of distortional energy. Detailed analyses were performed for stresses in dentin and enamel. The results of these calculations were presented graphically as maps of stress distribution, evident on the cross-sections of molars in the frontal plane.

**RESULTS**

During simulation of tooth clenching in maximal intercuspal position, the maximum pressure was exerted on the middle portion of the occlusal surface of the mandibular molar (Fig.1, A). It caused high equivalent stress concentration in enamel on the lingual slope of the buccal cusp where contact occurred with the maxillary tooth (Fig.1, B). The equivalent stresses in dentin did not exceed 13 MPa (Table II).

During mastication of morsel I, the maximal interocclusal pressure was distributed over the entire occlusal surface of the tooth (Fig. 2, A). The highest equivalent stresses arose before maximal intercuspation in the lingual wall of the mandibular molar (Fig. 2, B). In enamel, the stresses were located near the cemento-enamel junc-
tion (CEJ). In dentin, the equivalent stresses occurred in the cervical area, along the outer root surface below the CEJ, and along the pulp chamber. They were 46% higher compared to those during clenching.

Masticating morsels II and III, with higher elastic moduli, evoked the highest pressures in the mandibular molar cusps (Figs. 3, B and 4, B). During mastication of these morsels, higher equivalent stresses were generated in the occlusal enamel of the molar studied (Figs. 3, B and 4, B). In both situations, mostly compressive stresses appeared in the dentin along the x-axis. The concentration of equivalent stresses occurred in the lingual wall of the mandibular molar, but the dentinal stresses appeared to be lower for the masticating of morsel I by 19% to 43% (Table II).

Masticating a nonhomogeneous morsel containing a bony fragment resulted in the highest pressure on enamel in the area of contact with this element (Fig. 5, A). Location of the bony element on the slope of the lingual cusp yielded very unfavorable stresses in tissues (Fig. 5, B). In enamel, the equivalent stresses were 191% higher than during the crushing of morsel I. In the dentin of the lingual wall, stresses were twice as that for the homogeneous morsel I (Table II). Near the intercuspal fissure tensile stresses of 28 MPa along the x-axis were observed (Fig. 5, C). Along the y-axis, the tensile stresses occurred on the buccal side and compressive stresses on the lingual side of the tooth structure (Fig. 5, D).

Fig. 3. Frontal cross-section of first molars during mastication of morsel II. A, Pressure exerted on occlusal surface. B, Distribution of equivalent stresses (X, Y, Z = signs of coordinate axes).

Fig. 4. Frontal cross-section of first molars during mastication of morsel III. A, Pressure exerted on occlusal surface. B, Distribution of equivalent stresses (X, Y, Z = signs of coordinate axes).
forces caused considerable equivalent stress concentrations in the occlusal enamel and at the dentin-enamel junction. In dentin, the stresses were distributed symmetrically in relation to the pulp chamber (Fig. 6).

DISCUSSION

In this study contact elements were used to recreate the loading of the first mandibular molar during mastication of various morsels. Changes of stresses in the tooth during these loading conditions were calculated. For all situations the highest equivalent stresses appeared at the moment preceding maximal intercuspal position (Figs. 2, B and 5, B). These stresses occurred in occlusal enamel and in the cervical region of the lingual wall of the molar. The distribution of principal stress in the tooth studied was similar to that observed in the tooth when the pressure was applied to the lingual slope of the buccal cusp. Application of vertical forces directly to the molar surfaces and application of oblique forces...
forces acting simultaneously on lingual and buccal cusps caused symmetrical stress distribution in the teeth which were different from those generated during simulated mastication. These static load stresses may not reflect the conditions encountered intraorally.

This investigation demonstrates that masticating morsels of various elasticity and consistency affects the stresses in the tooth model. Mastication of morsels with high elastic moduli, that are more easily penetrated and conform to the surface of teeth, caused pressure in the entire occlusal surface of the tooth studied. In this situation, considerable equivalent stresses occurred in the cervical area of the molar lingual wall. The most unfavorable stresses appeared when chewing a nonhomogeneous morsel containing a fragment of bone. In this simulation, the fragment transmitted masticatory forces to the buccal slope of the lingual cusp. Because of the small angular inclination of the cusp, these forces were directed against the cusp lateral to the central intercuspal fissure and caused high tensile stress in enamel near this fissure (Fig. 5, C). At the same time, in the lingual cervical area of the tooth, a high equivalent stress concentration was observed (Fig. 5, B). This unfavorable distribution of stresses may be conducive to lingual cusp fracture.

Intraoral neuromuscular reflexes may prevent fracture of teeth. Due to proactive preventive reflex, mastication of hard food is done with less force than used when masticating softer food. Unanticipated contact of a hard fragment imbedded in a soft morsel causes the jaw-opening reflex, activated by pain stimuli, to rapidly separate the teeth and reduce masticatory forces acting on the tooth. If the force is not reduced, the stress may exceed the strength of tissues and lead to a fracture of the tooth. Clinical practice shows that unexpected crushing of a hard bone fragment or fruit stone in a soft morsel may lead to crown fracture. The mechanism of fracture in teeth is a difficult nonlinear problem that should be analyzed further based on the theory of the fracture mechanics of materials.

In vivo, fracture of the lingual cusps may be observed primarily in teeth weakened by caries, extensive preparation, and the presence of large restorations. This study demonstrated that the tendency to fracture nonfunctional cusps in mandibular molars may result not only from structural weakening, but also from unfavorable distribution of stresses in the teeth occurring during mastication of various types of food. When restoring molars, care must be taken to protect not only the functional cusps, but also the nonfunctional cusps of these teeth.

A natural tooth is a 3-dimensional structure, operating in complex loading conditions. It was not possible to include all factors that occur intraorally in this computer simulation. Therefore, some simplification was used. The extent to which FEA results are clinically relevant depends on various factors, including the accuracy of a model, the application of proper material data, genuine boundary conditions, and loading of a model studied in relation to the real tooth. In this study, a 2-dimensional model of the molar in plane stress condition was created using isotropic materials. For comparison, the same value of masticatory force was applied for all morsels. On the assumption that the computer simulations were simplified, the results of the study might differ from values of stresses encountered by teeth and were therefore considered qualitatively, not quantitatively.

The present study represents an initial stage of research to evaluate the loading in mandibular molars during a single mastication cycle. Further studies should concentrate on anisotropy of tissues, 3-dimensional structure of teeth, and changing parameters of mastication.

CONCLUSIONS

1. Clenching of molars and masticating morsels of high elastic moduli evoke a considerable stress concentrations in occlusal enamel of these teeth.

2. Masticating a morsel of low elastic modulus, that conforms to the occlusal surfaces of teeth, creates considerable stresses in the cervical portion of the lingual wall of the mandibular molar.

3. Mastication of a nonhomogeneous morsel that contains a fragment of bone results in unfavorable stresses in the mandibular molar.

REFERENCES


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