Finite element analysis of mechanism of cervical lesion formation in simulated molars during mastication and parafunction

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Statement of problem. The mechanical theory of cervical lesion formation is popular; however, the mechanism of formation of these lesions is not fully explained.

Purpose. The aim of this study was calculation of the stresses and Tsai-Wu strength ratio in the cervical area of the mandibular molar during grinding, clenching, and mastication, as well as theoretical investigation of the mechanism of cervical lesion formation in teeth.

Material and methods. A 2-dimensional finite element model of the mandibular first molar and crown of the opposing maxillary molar in the frontal section was developed. Computational simulation of mastication of a bolus with high elastic modulus, including grinding and clenching, was performed. Pairs of contact elements were used between the bolus and occlusal surfaces of the teeth. The analysis was nonlinear. During these simulations, the pressure exerted on the occlusal surface and the state of stresses in the mandibular molar were calculated. To evaluate the strength of anisotropic tooth tissues, the Tsai-Wu failure criterion was applied. This criterion considers the difference in strength of materials due to tensile, compressive, and shear stresses.

Results. Significant pressures were exerted on lingual cusps of the mandibular molar model during computer simulations of physiological and pathological load. In enamel elements close to the buccal cemento-enamel junction (CEJ) of the studied tooth, tensile stresses were observed which exceeded the strength of the enamel. In this area, the Tsai-Wu strength ratio reached values higher than 1. According to the Tsai-Wu criterion, these elements were damaged and, thus, were removed from the computer tooth model. During subsequent modeling of the tooth with the initiated cervical lesion, the Tsai-Wu ratio exceeded 1 along the dentino-enamel junction (DEJ), creating an overhang of enamel in the cervical area. Application of minimal horizontal force caused a fracture of this fragile, unsupported enamel fragment.

Conclusions. Overloading of theoretical teeth by computer simulation resulted in enamel damage at the CEJ and led to initiation of a cervical lesion. Subsequent overloading resulted in enamel destruction along the DEJ. The overhanging enamel fragment may easily be chipped. This process was repeated during subsequent tooth overloading and caused enlarging of the lesion. (J Prosthet Dent 2005;94:520-9.)

CLINICAL IMPLICATIONS

This finite element study suggests a mechanism for developing cervical lesions due to high levels of assumed tooth loads. Explanation and understanding of this mechanism may allow for the prevention of cervical lesion formation.

Cervical, noncarious lesions of dental hard tissue may form on the buccal teeth surfaces.1 The lesions are wedge-shaped, with walls converging at an angle from 45 to 135 degrees, with an average depth of 1 to 2 mm toward the pulp chamber.2 These lesions usually form in posterior teeth,2 especially in mandibular molars (21.3%).3 According to other authors, they occur primarily in mandibular premolars.1 The size and frequency of the occurrence of these lesions increase with age.1

Originally, these lesions in teeth were thought to be caused by abrasion4 and erosion.5 Currently, these factors are considered to play a secondary role.6 The most important cause of formation of wedge-shaped lesions is stress occurring in the cervical area of the tooth during oral physiological and pathological loads.7,8 Lee and Eakle9 have proposed the mechanical theory of cervical lesion formation. The authors compared a tooth with a beam, which is subjected to bending in buccal and lingual directions due to forces applied to the tooth. As a result, alternate tensile and compressive stresses are generated in the cervical region. The resulting stresses cause theoretical disruption of the bonds between enamel rods and increase the enamel susceptibility to dissolution and abrasion. Grippo10 defined pathological loss of hard tissues at the cemento-enamel junction (CEJ) caused by
“flexure and ultimate fatigue of enamel at a location away from the point of loading” as abfraction.

Further studies revealed a presence of significant tensile and principal stresses in the buccal cervical region of teeth, resulting in damage to enamel prisms.\textsuperscript{1,12} According to Rees and Hammadeh,\textsuperscript{13} the mechanism of cervical lesion formation is based on undermining of the enamel at the dentino-enamel junction (DEJ). The discontinuity of the enamel and dentin may cause increased stress in the enamel and damage to it. Once the lesion has been formed, the highest stress concentration was observed around the apex of the wedge-shaped lesion.\textsuperscript{14}

The relationship between the formation of cervical lesions and loading conditions of teeth has been confirmed clinically. Pintado et al\textsuperscript{15} and Telles et al\textsuperscript{3} demonstrated direct correlation between the presence of occlusal wear and the growth of cervical lesions. The greater the overload of the tooth during occlusion and articulation, the larger the cervical lesions. In patients with bruxism, in whom occlusal forces were significant,\textsuperscript{16,17} more frequent occurrences of these lesions were seen.\textsuperscript{6} Oblique occlusal forces causing asymmetrical stress are responsible for the formation of cervical lesions of various shape and location.\textsuperscript{7}

In the oral cavity, teeth are exposed to various overloads that cause variable patterns of stress in dental tissues.\textsuperscript{18} The aim of this study was to calculate stresses and Tsai-Wu strength ratio in the cervical area of the mandibular molar during grinding, clenching, and mastication, as well as theoretical investigation of the mechanism of cervical lesion formation in teeth.

![Fig. 1. A, Model of mandibular first molar with fragment of mandible and crown of maxillary molar in frontal plane. Opposing teeth are in lateral contact position. Bolus is placed between opposing teeth. B, Closing phase of masticatory cycle. C, Last step of closing phase of 1 masticatory cycle (maximum intercuspation position of opposing teeth).](image)

Table I. Mechanical properties of materials used in model of mandibular molar

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus E (MPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel along prisms</td>
<td>87,500\textsuperscript{21}</td>
<td>0.33</td>
</tr>
<tr>
<td>Enamel perpendicular to prisms</td>
<td>72,700\textsuperscript{21}</td>
<td>0.33</td>
</tr>
<tr>
<td>Dentin</td>
<td>18,600\textsuperscript{27}</td>
<td>0.31</td>
</tr>
<tr>
<td>Periodontium</td>
<td>50\textsuperscript{28}</td>
<td>0.45</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>11,500\textsuperscript{29}</td>
<td>0.33</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>431\textsuperscript{30}</td>
<td>0.30</td>
</tr>
</tbody>
</table>

**MATERIAL AND METHODS**

The study of stresses in mandibular first molars during grinding, clenching, and mastication was conducted with finite element analysis (FEA)\textsuperscript{19} using software (ANSYS version 7.1; ANSYS Inc, Canonsburg, Pa). On the basis of anatomic data from the literature,\textsuperscript{20} a computerized 2-dimensional (2D) model of a mandibular first molar in the frontal section was created (Fig. 1). A periodontal ligament, 0.1 mm wide, was modeled around the root.\textsuperscript{21} The periodontium reached to the CEJ with the tooth fixed in the mandible bone. A model of the opposing maxillary first molar crown was also created for analysis.\textsuperscript{20} To perform calculations, the tooth model was divided into 8489 triangular 6-node elements, jointed in 16,865 nodes.

Prismatic composition of the enamel was considered in the study\textsuperscript{21,22} by spatial orientation of the elements in local coordinate systems. The values of elastic modulus for the enamel (Table I),\textsuperscript{23} its tensile strength (42.2
There are various failure criteria for materials. For isotropic materials, the most commonly used is the von Mises criterion. However, dental tissues and, in particular, enamel have anisotropic properties. The Tsai-Wu criterion used for the evaluation of the strength of tissues was created for orthotropic composite resin materials. This criterion allows consideration of the anisotropic properties of the enamel (different elastic moduli and various tensile, compressive strengths of this tissue in 3 directions: x, y, z) in the calculations. This is why the correlation between experimental and theoretical results of failure of tooth tissue was improved. This criterion can be described by the formula:

\[
f = F_i \sigma_i + F_{ij} \sigma_j \sigma_i = 1
\]

where \(i, j = 1, \ldots, 6\); \(F_i\) and \(F_{ij}\) are coefficients dependent on the strength properties of materials to tension, compression, and shear in \(x, y, z\) direction, where these coordinate axes are directed according to main directions of material orthotropy; and \(\sigma_i\) and \(\sigma_j\) are stresses corresponding to principal directions in material.

The result of these calculations is the Tsai-Wu ratio. If the value of formula \(f\leq1\), then according to the Tsai-Wu criterion, the material will not fracture; however, if this value is \(f>1\), then damage of material may occur. This value was calculated for all elements of the studied model. Elements with the value exceeding 1 were excluded from the model, and then calculations were performed on the model without these elements. The results of the calculations were presented graphically as maps of stress distribution, evident on the cross-section of molars in the frontal plane.

## RESULTS

Two-dimensional finite element simulation of the masticatory cycle of a bolus similar to an almond was performed (Fig. 1). During this simulation, pressure exerted on the occlusal surface and stresses occurring in the model of the first mandibular molar were calculated. The highest pressure was exerted on the lingual cusp of the mandibular molar in the closing phase of mastication, preceding the maximal intercuspal position (Fig. 2, A). This phase of mastication was considered. All stress components (normal stress, shear stress, principal stress) for this situation were calculated. The highest values of normal stress were seen along the Y axis. The compressive stress occurred on the lingual surface, and tensile stress occurred on the buccal surface of the mandibular molar (Fig. 2, B). The concentration of the highest tensile stresses, 24.4 MPa, in the direction perpendicular to the prisms, appeared in the enamel near the CEJ at the buccal surface of the tooth (Fig. 2, C). The value of these stresses exceeded the enamel...
tensile strength.\textsuperscript{24} In this area, the theoretical Tsai-Wu ratio reached 3.2 (Fig. 2, D). According to this criterion, elements in which the value exceeded 1 were damaged and, thus, were removed from the model. A small cervical lesion formed near the CEJ (Fig. 3). In subsequent simulations of the mastication cycle, the tensile stresses in the enamel along the DEJ exceeded the strength of this tissue. Enamel elements in which the Tsai-Wu ratio was higher than 1 were eliminated. Thus, an enamel overhanging fragment was created, separated from the dentin by a fissure (Fig. 4). A horizontal force of 2 N was applied to this unsupported enamel structure. On the external surface of the overhanging fragment, the tensile stresses exceeded 17 MPa (Fig. 5) and the Tsai-Wu ratio reached 2. These load scenarios resulted in theoretical chipping of this structure. Enamel undermining at the junction with dentin and chipping of the overhanging fragments recurred during subsequent

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**Fig. 2.** A, Distribution of maximum pressure exerted on occlusal surface of model of mandibular molar during closing phase of initial cycle of mastication of bolus with high elastic modulus (MPa) (highest pressure marked MX, red). B, Distribution of maximal normal stresses along Y axis (SY) in model of mandibular molar during initial cycle of bolus mastication (MPa) (tensile stresses, red and orange; compressive stresses, blue and green). C, SY in cervical area of mandibular molar model during initial cycle of bolus mastication (MPa). Fragment of studied model divided into elements. Tensile stress concentration (marked MX, red) appears in enamel close to CEJ. D, Distribution of Tsai-Wu strength ratio in model of enamel of mandibular molar during initial cycle of bolus mastication (maximum Tsai-Wu strength ratio marked MX, red).
simulation of mastication cycles of hard bolus. This mechanism may be responsible for enlargement of a cervical lesion (Fig. 6).

Similar distribution of stresses in the mandibular molar occurred during simulation of grinding. Buccal displacement of the mandibular molar by 0.1 mm while grinding with a force of 200 N evoked pressure of 287.5 MPa exerted on the lingual cusp of the studied molar (Fig. 7, A). This caused concentration of tensile stresses along the Y axis of 92.6 MPa in the CEJ, at the buccal surface of the tooth. The theoretical Tsai-Wu ratio reached values over 12 in enamel, on the buccal side of the tooth (Fig. 7, B). Grinding with displacement of the mandibular molar to the opposite side evoked a load in the lingual slope of the buccal cusp of the mandibular molar. Compressive stresses of 56 MPa appeared in the enamel near the CEJ on the buccal side. In this situation, the theoretical Tsai-Wu ratio did not exceed 1 for the entire tooth structure.

Clenching teeth with a force of 200 N evoked a pressure of 129 MPa in the functional and nonfunctional cusps simultaneously. This caused concentration of tensile stresses in the central fissure and in the CEJ on the buccal surfaces. The Tsai-Wu ratio reached maximal value of 1.65 in the enamel, in the cervical area of the studied tooth.

DISCUSSION

The computer simulation of particular theoretical stages of the lesion formation caused by tooth overload has been presented. Teeth are exposed to overloading
during mastication of hard bolus and during parafunction, especially in persons with bruxism.\textsuperscript{16,17} During computer simulation of mastication of a bolus with high elastic modulus, grinding, and clenching, considerable pressure was exerted on the lingual cusps of the mandibular molar model. The highest overload of this cusp occurred during grinding with buccal displacement of the mandible. These situations evoked tensile stresses in the enamel, in the buccal cervical area of the studied tooth, which exceeded the strength of this tissue. The enamel is a hard substance of nonhomogenous, prismatic structure and anisotropic properties.\textsuperscript{21,22,23} The compressive strength of this tissue is 33 times larger than its strength in tension.\textsuperscript{24,25} This tissue has particularly low resistance to tension across prisms.\textsuperscript{24} The theoretical Tsai-Wu criterion was used in calculations, considering the anisotropic properties of enamel. During overload of lingual cusps, in enamel elements
in the cervical area of mandibular molars, the value of the Tsai-Wu ratio exceeded 1. In using the criterion assumptions, these elements were removed from the model, simulating the loss of tooth structure in this area. This caused a simulated “crumbling” of the enamel close to the CEJ and development of a cervical lesion.

During subsequent overloading of the studied tooth, the Tsai-Wu ratio exceeded 1 along the DEJ. This predicted damage of elements along the junction and creation of an enamel overhanging fragment. Rees and Hammadeh,\textsuperscript{13} who support the theory of enamel undermining at the DEJ, suggested that creation of a fissure between the enamel and dentin generates a dramatic increase in principal stress in the enamel. Unsupported enamel is chipped after application of a minimal horizontal force during, for example, tooth brushing. This mechanism is repeated during subsequent overload of

\textbf{Fig. 5.} Distribution of normal stresses along Y axis (SY) in cervical area of model of mandibular molar after application of horizontal forces to overhanging fragment (MPa) (maximum tensile stress marked MX, red).

\textbf{Fig. 6.} Distribution of normal stresses along Y axis (SY) in cervical area of model of mandibular molar with formed cervical lesion during subsequent cycle of bolus mastication (MPa) (maximum tensile stress marked MX, red).
lingual cusps of the mandibular molar and could lead to
enlargement of the lesion.

Understanding the etiology of cervical lesion forma-
tion is important. This simulation demonstrated that
lower loading of the lingual cusp of the mandibular mo-
lar during mastication, as compared to grinding, caused
lower tensile stress and a Tsai-Wu ratio in cervical
enamel. This suggests that decrease of tooth overloads
by adjusting occlusion, elimination of parafunction, or
fabrication of occlusal splints may limit formation of
these lesions. According to Kuroe et al.,14 restoration
of these lesions significantly reduces stresses evoked in
tooth tissues around them, which can prevent further
enlargement. Restoration that bonds the prisms can
protect enamel from further chipping and protect non-
exposed dentin from abrasion.

The study of abfraction by FEA is an attempt to the-
oretically determine the mechanism of cervical lesion
formation. It was impossible to include all of the fac-
tors that occur intraorally in the computer simulation.
Simplified 2D models in plane strain state of the man-
dibular molar were used in the study. Anisotropic prop-
erties of dental tissues were accounted for in the model.
The simulation of mastication of hard food was per-
formed in the frontal section due to the fact that the
working-side first molar has a primarily lateral

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Fig. 7. A, Distribution of maximum pressure exerted on occlusal surface of model of mandibular molar during grinding with buccal movement of mandible (MPa). B, Distribution of Tsai-Wu strength ratio in enamel of model of mandibular molar during grinding with buccal movement of mandible (maximum Tsai-Wu ratio marked MX, red).
CONCLUSIONS

Within the limitations of this study, the following conclusions were drawn:

1. In a simulation model, the mastication of a bolus of high elastic modulus, grinding, and clenching evoked considerable overload of the lingual cusp of the mandibular molar. In the buccal cervical area, tensile stress appeared that theoretically exceeded the strength of the enamel. The Tsai-Wu strength ratio in this area exceeded 1.

2. According to the 2D FEA, overloading of teeth may result in damage of the enamel at the CEJ and initiate a cervical lesion.

REFERENCES


20. Wheeler RC. Wheeler’s atlas of tooth form. 5th ed. Philadelphia: Saun-


Reinforcement of poly(methyl methacrylate) denture base with glass flake

Objectives: Since the introduction of poly(methyl methacrylate) as a denture base material, it has suffered from having relatively poor mechanical properties. Many methods of improving its strength and toughness have been investigated. Most of these have not been adopted due to: increased cost, the need for specialist processing equipment or increased laboratory time due to more complicated procedures. Glass flake has been used as a reinforcing agent in many industrial polymers, but is as yet untested with denture base acrylic materials. The aim of this study is to evaluate the effect of adding glass flake to denture base acrylic powder on the fracture toughness of the set material.

Methods: Glass flake was added in 5, 10 or 20% w/w to Trevalon® denture base powder. The material was mixed, flasked, packed and processed in a manner typical for a denture base material. Fracture toughness was determined using a double torsion test technique.

Results: The addition of glass flake gave up to a 69% increase in fracture toughness compared to plain Trevalon material. The addition of 5% glass flake lead to an improvement in fracture toughness that was statistically significant compared to both plain Trevalon and the 10 and 20% groups.

Significance: The significant improvement in fracture toughness of a denture base acrylic material using glass flake is an extremely promising result. Other mechanical properties will require testing before glass flake can be recommended as a reinforcing agent for denture base acrylic materials.—Reprinted with permission of The Academy of Dental Materials.