Original paper

Mechanism of enamel damage in the grooves of molars during mastication

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Abstract

Background. During mastication, molars are subjected to heavy stress. However, a full explanation of the effects of physiological loads on tooth structures is lacking.

Objectives. The study aimed to determine stress in molars and identify the mechanism of enamel damage in the grooves of the teeth during computer-simulated mastication.

Material and methods. The study was carried out using the finite element method (FEM). A three-dimensional (3D) model of the first mandibular molar and of the crown of the opposing maxillary tooth was created. A food bite was introduced between the antagonistic teeth. The mastication cycle of the bolus was computer-simulated. The equivalent stress in the enamel and dentin of the mandibular molar was calculated according to the modified von Mises (mvM) criterion.

Results. During the simulated chewing activity, the highest equivalent mvM stress and tensile stress concentrated on the molar enamel around the central groove and the foramen cecum. The value of the equivalent mvM stress was close to the tensile strength of the enamel. According to the mvM criterion, the enamel in these areas was exposed to destruction, which coincided with the occurrence of class I caries.

Conclusions. During mastication, significant tensile and mvM stress concentrates on the mandibular molar enamel around the central groove and the foramen cecum. High stress in these areas may cause prism microfractures and facilitate the bacterial penetration of the enamel.

Keywords: finite element analysis, modified von Mises failure criterion, enamel damage, biomechanical causes of caries, simulation of mastication

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Introduction

The enamel is the hardest, mineralized, cell-free form of tissue in the human body. Hydroxyapatite (HA) – calcium fluoridated carbonated apatite crystals – constitutes 96% of the enamel. It is organized in 20-nanometer nanospheres.[1] They form HA crystal nanoparticles. These nanoparticles are long, ribbon-like structures with a hexagonal cross-section, and are approx. 50–70 nm wide, 20–25 nm thick and more than twice as long.[1] The crystals are joined by glycoproteins (2 nm wide) to form enamel prisms, which are mostly arranged perpendicular to the dentin–enamel junction (DEJ). The tissue thickness ranges from 0.01 mm in the cervical region to 2–2.5 mm at the peaks of the molar cusps.[2] The occlusal surfaces of the teeth are anatomically diverse and the cusps are separated by a system of grooves. The depth of the central groove depends on its shape (it can be I-shaped, U-shaped, V-shaped, or inverted Y (IY)-shaped) and ranges from 0.53 mm to 1.15 mm.[3]

The enamel has unique mechanical properties. It is rigid, with an elastic modulus of 84.1 GPa, though the value varies (70 GPa at DEJ and 115 GPa near the occlusal surfaces).[4,5] It is also very hard and has a Vickers microhardness of 4 GPa, which is lower at DEJ (3 GPa) and higher near the occlusal surfaces (6 GPa).[6] Meanwhile, its compressive strength is high (363.0 MPa)[7] and its tensile strength is very low (10.0–11.4 MPa) (Table 1).[8] The stiffness, hardness and compressive strength of the enamel make it resistant to mechanical stimuli within the oral cavity. However, its highly mineralized composition means it is a glass-like biomaterial, prone to breakage (brittleness: 300–900 μm^{-1}; fracture toughness (Kc): 0.67–0.95 $MPa{\cdot}m^{1/2}$).[9,10] The effects of the chewing forces on tooth tissues, as well as stress distribution in the enamel and dentin under occlusal loads, are yet to be fully understood.

The effects of the forces acting on the teeth can be investigated using finite element analysis (FEA). Research in this area has mainly concerned different restorative materials and various shapes of fillings or prosthetic appliances, and has rarely focused on healthy teeth.[11,12] Also, most authors study the von Mises or principal stress in the teeth.[11–13] Here, the modified von Mises (mvM) criterion was used to consider the difference between the compressive and tensile strength of the enamel and dentin. The calculated mvM stress values reflected the actual stress in tooth tissues.

The load used in modeling massively impacts stress distribution. In most finite element method (FEM) studies, static forces are applied directly to the occlusal surfaces.[11,12] However, the current study used a computer model based on the natural interarch relationship. Dynamic three-dimensional (3D) simulations of the bolus mastication cycle were performed using contact elements on the occlusal surfaces, and the molar tooth was loaded with variable chewing forces transmitted by the food bolus to the enamel. Due to this innovative approach, stress in molar structures was investigated under realistic conditions.

The present study aimed to determine stress in molars and identify the mechanism of enamel damage in the grooves of the teeth during computer-simulated mastication.

Material and methods

Creating tooth models for finite element analysis

The impressions of the maxillary and mandibular teeth were taken from a patient with normal occlusion, using the Express™ polyvinyl siloxane material (3M Espe Dental Products, St. Paul, USA). Based on the impressions, plaster models were cast using class IV Giroform® stone (Amann Girrbach GmbH, Pforzheim, Germany). The scans of the plaster models of the right mandibular first molar and of the opposing maxillary first molar were made using the Ceramill MAP 300 scanner (Amann Girrbach AG, Kolbach, Austria), and then they were processed using the Ceramill Mind software (Amann Girrbach AG). The presentation timestamp (PTS) files containing the coordinates of the tooth surface points were loaded into the Ansys computer program, v. 14 (Ansys, Inc., Canonsburg, USA) for FEA.[14] In the same patient, cone-beam computed tomography (CBCT) of the right mandibular first molar tooth was performed by means of the CS 9300 system (Carestream Dental, Atlanta, USA). The CT scans were used to obtain the points along DEJ and within the chamber of the molar. The selected points were then connected with curves in frontal planes every 0.1 mm, using a preprocessor. Based on these lines, a solid model of the intact molar was created, taking into account the enamel, dentin and tooth chamber. The shape and dimensions of the tooth model corresponded to an average first molar.[15] The scan of the surface of the right maxillary first molar made it possible to generate a model of a fragment of the tooth crown (Fig. 1).

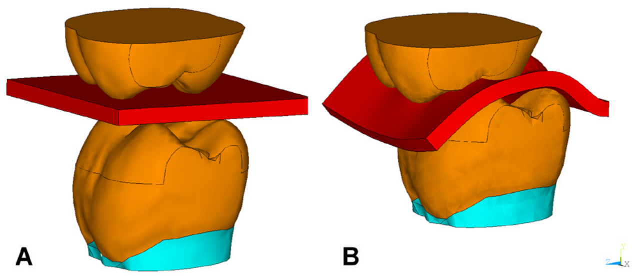

Fig. 1. Models of molars during the simulation of mastication

A – initial closing phase of the mastication cycle (the right mandibular first molar and a fragment of the crown of the opposing tooth in a lateral position, with a morsel between the teeth); B – final closing phase of the mastication cycle (the right mandibular first molar and a fragment of the crown of the opposing tooth in central occlusion, with a morsel between the teeth).

Table 1. Properties of the materials used in the models

Material	Modulus of elasticity	Poisson's ratio	Ultimate compressive strength [MPa]	Ultimate tensile strength [MPa]
Enamel	84.1 GPa	0.33	363.0	10.0–11.4
Dentin	18.6 GPa	0.31	297.0	99.8
Food bolus	21.6 MPa	0.30	–	–

The maxillary crown model was fixed on its upper surface in the nodes, and the opposing tooth model was set in lateral occlusion and vertically spaced apart by 1 mm. A 1-millimeter-thick morsel of food was then inserted between the opposing teeth, creating a 3D computer model of the opposing molars in the initial closing phase of the mastication cycle (Fig. 1A).

Model materials

The values for the modulus of elasticity and Poisson's ratio were entered for the enamel[4] and dentin.[16] The food bolus had the properties of a nut, and its elastic modulus was 21.6 MPa.[17] The tensile strength values were added for the enamel (10.0–11.4 MPa)[8] and dentin (99.8 MPa),[18] as well as the compressive strength values (363.0 MPa[7] and 297.0 MPa,[19] respectively). The materials used in the models were elastic, homogeneous and isotropic, but had different compressive and tensile strength (Table 1).

Dividing the models into finite elements

For calculations, each tooth model was divided into 10-node structural elements (Solid 187). In total, 61,801 elements joined by 84,215 nodes were used. Pairs of contact elements, Targe 170 and Conta 174, were used on the occlusal surfaces of the teeth and the bolus. The coefficient of friction on the contact surfaces was assumed to be 0.2.[20]

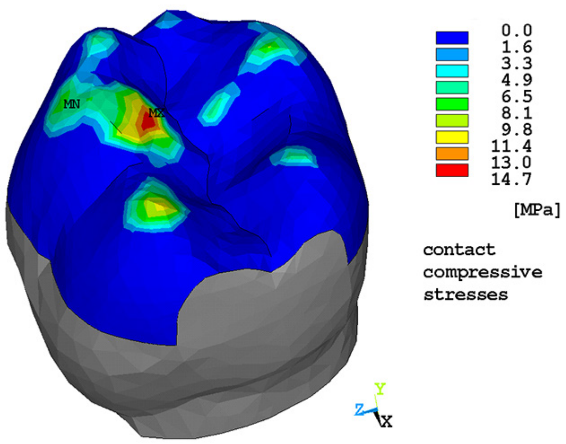

Fig. 2. Pressure exerted on the occlusal surface of the mandibular molar at the end of the closing phase of the mastication cycle

MN – minimum; MX – maximum.

Model loading

A computer simulation of the closing phase of the mastication cycle was performed. The mandibular molar was moved vertically upward, and simultaneously medially and mesially toward the maxillary tooth until maximum intercuspation was achieved. The nodes on the lower surface of the mandibular crown were then displaced, with the vertical displacements chosen so that the maximum reaction force toward the Y-axis in each model was 100 N.[21] The buccal cusps of the lower tooth glided down the bolus and along the occlusal surface of the upper tooth, thereby crushing the bolus (Fig. 1B).[22] In this way, the natural load on the molar during mastication was computer-simulated.

Calculations

The contact simulation performed with the use of FEM is a non-linear analysis. During the masticatory simulation, the pressure exerted on the occlusal surface of the mandibular first molar was investigated and the stress components in the tooth were calculated. The enamel and dentin have different compressive and tensile strength. Therefore, the mvM criterion was used to evaluate the enamel and dentine strain in complex stress states.[23] According to this criterion, the material will fail when the value of the equivalent mvM stress exceeds the tensile strength of the material.

Results

The highest, unevenly distributed pressure was exerted on the occlusal surface of the mandibular molar by the crushed bolus during the final closing phase of the mastication cycle. A maximum pressure of 14.7 MPa was exerted on the tops and slopes of the working cusps (Fig. 2). The buccal and lingual cusps were pushed apart during loading, and the equivalent mvM stress reached around the central groove in the enamel of the intact tooth was 9.75 MPa (Fig. 3), which is very close to the tensile strength of the enamel.[8] Meanwhile, the tensile stress in the grooves was 6.34 MPa (Fig. 4). The equivalent mvM stress of 4.86 MPa occurred around the foramen cecum (Fig. 3). In the dentin, a maximum mvM stress of 21 MPa concentrated at the tooth cervix on the buccal side (Fig. 5). However, this stress value was 5 times lower than the tensile strength of the dentine (99.8 MPa).[18]

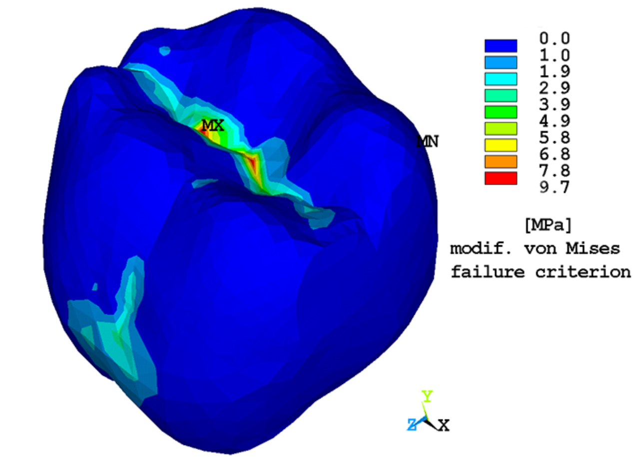

Fig. 3. Distribution and values of the equivalent stress according to the modified von Mises (mvM) criterion in the enamel of the mandibular molar at the end of the closing phase of the mastication cycle

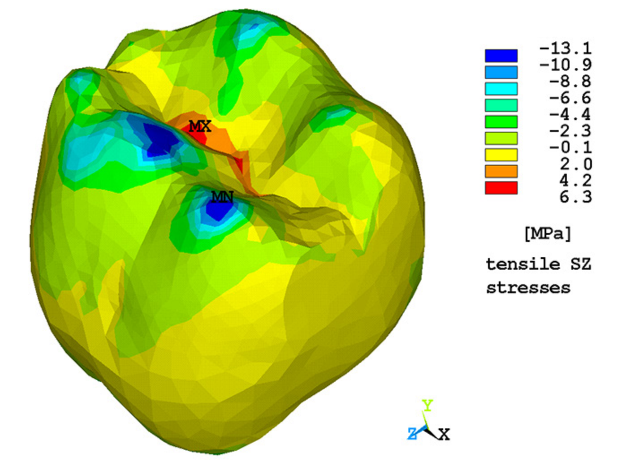

Fig. 4. Distribution and values of the tensile SZ (in the B–L direction) stress in the mandibular molar at the end of the closing phase of the mastication cycle

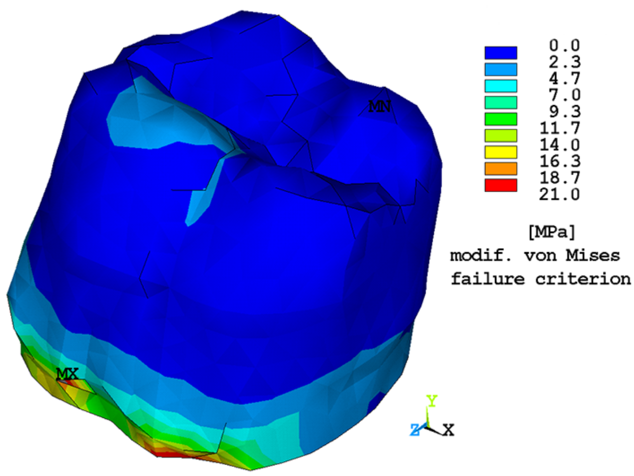

Fig. 5. Distribution and values of the equivalent stress according to the modified von Mises (mvM) criterion in the dentin of the mandibular molar at the end of the closing phase of the mastication cycle

Discussion

The present study demonstrated that the cusps of the molar are subjected to bending and are pushed away from each other during normal mastication, which confirms the findings of other experimental studies.[24] In the enamel, the highest tensile stress and the greatest strain occurred around the central groove of the tooth. Meanwhile, the highest value of the equivalent mvM stress was also observed around the central groove of the molar, and it was close to the tensile strength of the enamel. The enamel has different compressive and tensile strength, and is characterized by a low tensile strength (10.0–11.4 MPa) due to the perpendicularly oriented enamel prisms.[8] According to the mvM criterion, the enamel in this area was exposed to destruction. Indeed, the enamel in the tooth grooves may fail when it is subjected to cyclic forces greater than 100 N. The maximum bite force in the molar region in dentate patients varies between 402.07 N and 686.46 N, and for natural mastication, it varies between 68.64 N and 147.10 N.[25]

The FEM studies by Benazzi et al.[13,26] and Magne and Belser[27] confirm our results. Magne and Belser demonstrated that the pressure exerted on the non-working cusps was particularly dangerous and caused high tensile stress in the teeth.[27] Benazzi et al. found that the greatest tensile stress occurred in the grooves during maximum intercuspation.[26] According to Wan et al., the horizontal component of the masticatory forces opens the spaces between the central grooves.[28] Particularly sharp angles and narrow curves within the fissure system generate concentrated stress. At the bottom of the fissures, especially the I-shaped, V-shaped and IY-shaped ones, enamel cracks initiate and propagate into the enamel to a depth of 1.04–1.25 mm.[28]

The mechanism of enamel failure during loading was presented by Xia et al.[1] Enamel crystals respond to the mastication forces at nanoscales in 3 distinct ways: plucking; plastic deformation; and fragmentation. The plucking of HA nanoparticles occurs when the forces exceed the strength of the protein. In particular, the tensile stress acting perpendicularly to the prisms is dangerous.[1] The present study showed that mastication contributed to an unfavorable distribution of tensile stress in the central groove of the enamel, which can predispose to collagen breakdown and the microfractures of the enamel prisms. The continuous repetition of the process can reduce the integrity of the enamel. To date, it has not been demonstrated that physiological loads on molars contribute to the creation of significant tensile stress in the anatomical cavities of the enamel, which may lead to the microfractures of the enamel prisms in these places.

According to Ricucci et al., bacterial biofilms colonize cracks in the enamel consistently.[29] Moreover, it was demonstrated by Walker et al. that the cracked enamel was permeable to dyes and cariogenic bacteria.[10] As such, cracks open the way for bacterial invasion and are one of the causes of tooth decay. Furthermore, cyclic mechanical loads increase the penetration of bacteria into narrow tooth gaps.[30,31] In the absence of occlusive pressure, the degree of bacterial penetration into the dental gaps is approx. 30 µm (67%). However, this increases to 100% during the cyclic loading of the tooth.[30] The current study showed the perfect convergence of the location of the maximum equivalent mvM stress in the enamel generated during mastication with the occurrence of class I caries in the fissures and the foramen cecum.

Dental caries is a major oral disease and the most common dental disorder of multifactorial etiology. The modern concept of caries etiology describes an imbalance between the microbial load and lifestyle, the protective role of saliva, and the enamel resistance. The development of caries is accompanied by key components, such as bacterial plaque, carbohydrates and dental susceptibility.[32] The main mass of the biofilm adhering to the surfaces of the teeth consists of spatially organized bacteria surrounded by an extracellular matrix. The consumption of carbohydrates increases the number of carious bacteria and the cariogenicity of the plaque through acidic fermentation products.[33] The carious process begins with changes in the enamel, and the susceptibility of the enamel depends on the degree of hard tissue mineralization and the anatomical structure of the tooth.[34] Bacteria do not colonize all tooth surfaces equally, and caries is most common on the occlusal surfaces of molar teeth.[35] Indeed, narrow fissures on the occlusal surface, such as grooves and anatomical depressions, are particularly prone to biofilm retention.[36] Bacterial colonies were noted in the prismatic structures of the enamel and the interprismatic substance, even within an intact groove-fossa system.[37] Unfortunately, these areas are resistant to natural abrasion, hygiene methods and the protective properties of saliva.

This paper presents the mechanism of enamel destruction in the molar grooves as a result of masticatory mechanical loads. Furthermore, areas in the molar enamel where significant tensile stress occurred corresponded to areas that were affected by class I caries. Two mechanisms may contribute to the formation of class I caries in molars, i.e., the destruction of the enamel prisms in the grooves due to tensile stress that exceeds the enamel strength, and the penetration of bacteria deep into the grooves during cyclic loading. Mechanical damage to the enamel prisms can act as a gateway to bacterial infection and biofilm retention, and tooth biomechanics can be considered one of the factors that contribute to the initiation of dental caries.

Research and treatment in modern dentistry are increasingly based on numerical methods, as they are more accurate and provide more possibilities than the conventional methods. Indeed, computerized kinematic facebows are preferred over mechanical facebows,[38] intraoral scanners have an advantage over traditional impressions,[39] the computer-aided design (CAD) and computer-aided manufacturing (CAM) of prosthetic restorations are now commonly used, and models can be 3D-printed instead of being plaster-cast.[40] The use of FEM in this study made it possible to visualize the distribution of stress in tooth tissues during the simulation of mastication.

Conclusions

Taking into account the limitations of the method, the following conclusions can be drawn:

– during mastication, significant tensile and mvM stress concentrates on the mandibular molar enamel around the central groove and the foramen cecum;
– high stress in these areas may cause prism microfractures and facilitate the bacterial penetration of the enamel; it coincides with the occurrence of class I caries.

Ethics approval and consent to participate

The study was approved by the Bioethics Committee at the Medical University of Lodz, Poland (approval No. RNN/98/09/KE UM). The informed written consent was obtained from the patient.

Data availability

All data generated and/or analyzed during this study is included in this published article.

Consent for publication

Not applicable.

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