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Cuspal Flexure and Stress in Restored Teeth Caused by Amalgam Expansion

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Clinical Relevance

Although amalgam is being phased out, existing amalgam fillings will still be present for many years. Clinicians should be aware that amalgam expansion may create stress conditions that accelerate tooth cracking.

SUMMARY

Objective: Cracks in amalgam-filled teeth may be related to amalgam expansion. This study measured cuspal flexure and used finite element analysis to assess associated stress levels in amalgam-filled teeth.

Methods and Materials: External surfaces of 18 extracted molars were scanned in three dimensions. Nine molars were restored with mesio-occluso-distal amalgam fillings; the other teeth were left intact as controls. All teeth were stored in saline and scanned after two, four, and eight weeks. Cuspal flexure and restoration expansion were determined by calculating the difference between scanned surfaces. Stresses in a flexed tooth were calculated using finite element analysis.

Results: Cusps of amalgam-filled teeth flexed outward approximately 3 μm, and restoration surfaces expanded 4 to 8 μm during storage. Cuspal flexure was significantly higher in the amalgam group (multivariate tests, $p<0.05$), but storage time had no significant effect (repeated measures, $p>0.05$). Expansion caused stress concentrations at the cavity line angles. These stress concentrations increased stresses due to mastication 44% to 178%.

Conclusions: Amalgam expansion pushed cavity walls outward, which created stress concentrations at the cavity line angles. Expansion stresses can raise stresses in amalgam-filled teeth and contribute to incidentally observed cracks.

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INTRODUCTION

Dental amalgam was introduced in dentistry in the early 1800s and has accumulated an impressive

Figure 1. *Cracks on marginal ridges and triangular ridges next to amalgam restorations.*

record as a tooth-filling material. However, because of environmental, health, and esthetic concerns, amalgam is being replaced by resin-based alternatives as the material of choice for direct restorations. In 2005, an estimated 52 million amalgam fillings were placed in the United States versus approximately 96 million in 1990.[1,2] According to a projection from the United States Food and Drug Administration, more than 30 million amalgam restorations are expected to be placed up to the year 2023.[3] Although the use of amalgam is thus declining, millions of amalgam-restored teeth are still in function today and will be for many years depending on their durability.

Despite the respectable life span of amalgam fillings, often surpassing that of resin-based composite restorations,[4-6] their ultimate failure can have serious consequences for the longevity of a tooth. Common reasons for restoration failures are secondary caries, fracture of the filling, or tooth fracture.[6-8] Secondary caries or fractured fillings can be treated by replacing the filling, but a fractured tooth will require complex or costly indirect restoration or even become unrestorable.

Cracks are a common sight in teeth. Dental practitioners often observe cracks developing at a marginal ridge or radiating from amalgam fillings, as shown in Figure 1. Fractures are the final stage of crack propagation. Teeth restored with nonbonded amalgam were found to be more likely to have cracks or fractured tooth structures than adhesive composite restorations.[6,8,9] Restoration, cavity design, excursive occlusal interference, and age have all been identified as factors that predispose a tooth to cracking.[9-11]

Another factor that may also play a role is expansion of the amalgam restoration, which would introduce stresses in a restored tooth. Amalgam is known to expand due to phase changes and corrosion.[12,13] Expansion of amalgam in a confined cavity coupled with creep and corrosion products has been proposed to close the interfacial gap and cause the amalgam extrusion that can be observed after years of service.[14] The observation of creep implies the presence of continuous pressure imposed on the restoration by the confining tooth structure, which in turn implies the presence of stresses in the tooth structure. It is conceivable that the presence of such stresses has consequences for the longevity of teeth with amalgam fillings if it elevates stress levels in the tooth structure.

Considering the large pool of aging amalgam restorations present in the population, understanding how they may affect stresses in a tooth will remain a clinical concern for many years. The objective of this study was to investigate whether amalgam fillings could add stresses in the tooth-restoration complex and, if so, how significant those stresses could be. To verify that an amalgam restoration can stress a tooth, we measured cuspal flexure of teeth with an amalgam filling. The significance of expansion on stress levels was assessed by evaluating restored teeth with similar cuspal flexure in a finite element analysis.

METHODS AND MATERIALS

Cuspal Flexure and Restoration Expansion

Eighteen extracted human maxillary and mandibular molars (approved by the Institutional Review Board) were mounted in stainless steel rings with embedded reference spheres (Figure 2). The mean and standard deviation of the buccal-lingual widths, measured at the height of contour, were 10.0 ± 0.6 mm. Nine teeth were filled with amalgam, and the other nine teeth were left intact (no preparation). A sample size of nine had 95% confidence to detect a difference of 0.65 standard deviation between groups. The external enamel surfaces were etched with 37% phosphoric acid solution to obtain dull surfaces. A mesio-occluso-distal (MOD) cavity (4-mm deep, 4-mm wide) was prepared in nine teeth and was restored with zinc-containing amalgam (Permite, SDI, Bayswater, Victoria, Australia). The external tooth surfaces and reference spheres were scanned from eight directions following restoration using a three-dimensional optical scanner (COMET xS, Steinbichler Optotechnik GmbH, Neubeuern, Germany). This scan was used as a baseline. After scanning, the restored teeth were immersed in normal saline solution (0.9% sodium chloride irrigation USP; B. Braun Medical Inc, Bethlehem, PA, USA) for eight weeks and rescanned at two, four, and eight weeks. Nine unprepared teeth were used

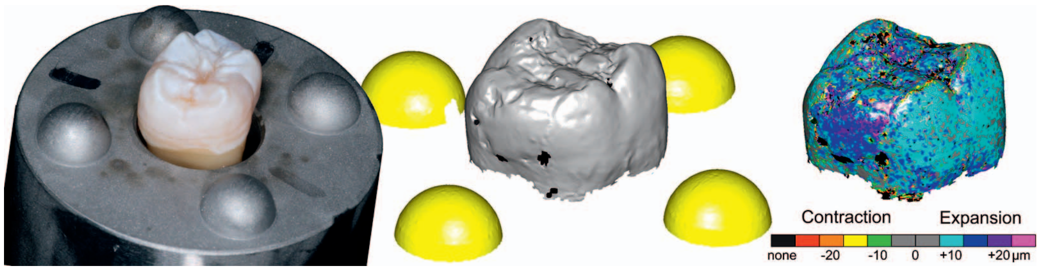

Figure 2. *Teeth were secured in stainless steel rings with embedded reference spheres. The scans were aligned with their baseline using the reference spheres (yellow). Cuspal flexure and expansion of the amalgam restoration on the occlusal, mesial, and distal surfaces are shown according to the color scale.*

as a control. They were scanned and stored using the same procedure as the restored teeth. Scanned surfaces were aligned with the baseline scans by means of the reference spheres on the mounting rings using Cumulus software (Regents of the University of Minnesota; Figure 2). Buccal and lingual tooth surface areas (from height of cavity floor to just below the cuspal ridges) as well as occlusal and proximal amalgam filling surfaces were separately selected on the baseline scans. Custom-developed software compared each of the selected baseline surface areas with the follow-up surface scans. Differences between the baseline and follow-up surfaces, which geometrically constitute a volume, were calculated and divided by the selected surface areas to obtain the buccal and lingual cusp flexure and the occlusal and proximal amalgam filling expansion. Total cuspal flexure was the sum of the buccal and lingual flexure; proximal expansion was the average of the mesial and distal amalgam filling expansion. Effects of amalgam restoration on cuspal flexure were compared with the control group at each time interval with multivariate tests and post hoc multiple comparisons using the Games-Howell test (equal variances not assumed; IBM SPSS Statistics, version 25.0, Armonk, NY, USA). Effects of storage time on cuspal flexure of the amalgam-restored teeth and control teeth were analyzed using general linear model repeated measures (IBM SPSS Statistics).

Finite Element Analysis

Volumetric expansion was applied in a finite element model of an MOD-restored tooth to evaluate the stress distribution associated with experimentally measured cuspal flexure. The finite element model was based on an image of a cross-sectioned tooth. The outlines of the dentin and enamel were traced and imported into a finite element program (Marc/Mentat, MSC Software, Palo Alto, CA, USA). Three cavity shapes were created using the Mentat preprocessor software, with 0°, 5°, or 10° of wall convergence. Each cavity was 4-mm deep and 4-mm wide, as shown in Figure 3. The outlined dentin, enamel, and restoration were meshed manually using quadrilateral elements, using an element relaxation option that maintained optimal element shapes. The root was not modeled because restoration expansion affected only the tooth crown. The tooth models were therefore fixed below the cemento-enamel junction. Amalgam restoration surfaces were free to separate or slide along the surrounding cavity surfaces with an arbitrary 0.5 coefficient of friction.

Material properties were assigned to the dentin, enamel, and restoration elements. The applied elastic moduli (84 GPa for enamel, 18 GPa for dentin, and 28 GPa for amalgam) as well as the Poisson's ratios (0.30 for enamel, 0.24 for dentin, and 0.35 for amalgam) were obtained from the literature.[15] Transverse isotropic conditions were prescribed for the enamel, assuming the 84 GPa elastic modulus value along the principal enamel axis, perpendicular to the enamel-dentin junction, whereas the value was 42 GPa in lateral directions. Since the objective of this analysis was stress in the tooth structure for a specific experimentally measured cuspal deflection value, creep of the amalgam did not need to be modeled.

To produce the specific cuspal deflection, volumetric expansion was prescribed for the modeled amalgam restoration using thermal analogy. This involved increasing notional temperature in the amalgam to induce expansion. The resulting volume change pressed the amalgam restoration against the surrounding cavity floor and walls, generating deformation and stress in the tooth, outward flexure of the cusps, and an elevation of the occlusal surface as it was extruded. In addition, occlusal forces were applied on the lingual or buccal cuspal inclines to simulate a chewing load of 20 N distributed over a 1.5-mm^2 surface area.

Figure 3. *Calculated displacements and stresses in the cross section of an amalgam-filled tooth with 3-μm cuspal flexure due to amalgam expansion. Stress concentrations are seen at the cavity line angles. Stress concentrations intensified when a masticatory load was added on the lingual or buccal cusp (20 N over 1.5 mm^2 area, indicated with arrows).*

Stresses in three directions (cross-sectional plane and perpendicular to the cross section according to plane strain conditions) were collected in the dentin and enamel elements during the simulation of amalgam expansion and cuspal flexure. The combination of these three stress components was expressed in an equivalent stress value according to the modified von Mises criterion. This criterion is based on the common von Mises criterion but modified such that it can account for the higher compressive and lower tensile strengths of enamel, dentin, and amalgam. The modification assigns tensile stresses higher "weight" in the equivalent stress expression than compressive stresses.[16] The compressive/tensile strength ratios used were 384/10 for enamel, 297/99 for dentin, and 388/66 for amalgam.[15]

RESULTS

Displacements were measured across all external surfaces (Figure 2) after two-, four-, and eight-week storage. Mean cuspal flexure and expansion values of the occlusal, mesial, and distal amalgam surfaces were calculated over each affected surface (Table 1). Positive values indicate outward movement (expansion). Multivariate tests showed that the amalgam restoration caused significant cuspal flexure at each time interval. The repeated-measures tests indicated that the storage time had no significant effect on either the amalgam (p=0.202) or control groups (p=0.069). Amalgam on proximal surfaces expanded more than those on the occlusal surface.

To match the experimentally determined cuspal flexure of about 3 μm, a 0.3% volumetric (=0.1% linear) expansion was applied in the finite element analysis. The simulated amalgam expansion caused stresses in the tooth structure, with stress concentrations at the cavity floor and line angles (Figure 3). The occlusal surface extruded 3.5 to 4 μm due to the amalgam expansion. The 5° of wall convergence increased cuspal flexure by 26% compared with a cavity with straight walls and 29% when the wall convergence was 10°. Stress concentrations in dentin

Table 1: *Cuspal Flexure and Amalgam Expansion on Occlusal and Proximal (Averaged From Mesial and Distal) Surfaces (Mean ± Standard Deviation; μm)*[a]

	2 wk	4 wk	8 wk
Cuspal flexure, amalgam	3.18 ± 2.72*	3.55 ± 2.14*	3.70 ± 2.42*
Cuspal flexure, control	−0.40 ± 0.77§	−0.53 ± 1.00§	−0.41 ± 0.49§
Amalgam expansion, occlusal	4.69 ± 1.38	5.05 ± 1.37	5.02 ± 1.35
Amalgam expansion, proximal	8.66 ± 1.40	8.36 ± 1.43	8.40 ± 1.51

[a] *Positive values indicate outward flexure (expansion). The symbols * and § indicate significantly different mean cuspal flexure values between the control and amalgam-restored teeth (multivariate tests,* $p=0.002$*,* $p=0.001$*,* $p<0.001$ *for the two-week, four-week, and eight-week time intervals, respectively).*

due to amalgam expansion were 3% to 14% higher with convergent cavity walls. The expansion of the amalgam filling caused an increase in stress values in dentin at the lingual line angle by 131% to 178% when a 20-N masticatory load was simulated on the lingual cusp and 44% to 45% in the buccal line angle when the load was applied on the buccal cusp. These percentages corresponded with an average stress increase at the cavity line angles of 10 to 15 MPa. Stresses at the opposite cavity line angle decreased during cuspal loading.

DISCUSSION

A study about amalgam fillings may seem obsolete in the 21st century. However, considering the longevity of amalgam fillings, which can be 30 to 40 years, hundreds of millions are currently in function all over the world. In 2009, a meeting convened at World Health Organization headquarters in Geneva, Switzerland, encouraged a global "phase down" of the use of amalgam due to environmental health concerns and in response to global initiatives on mercury reduction from the United Nations Environment Programme.[17] However, complete phase out of amalgam has not yet happened, as it is still the most affordable restorative option.[2,17] Amalgam restorations will therefore have a presence in dentistry for many years to come.

Although it is well-known that amalgam expands and amalgam extrusion is observed at the margins,[12-14] the mechanism of crack initiation by such expansion has not been studied directly. In this study, we explored expansion as one of the mechanisms contributing to the cracks and fractures that are often observed in aging amalgam-filled teeth. Cracks that could be detected with an explorer were found to be twice as likely in teeth restored with amalgam compared with resin-based composites.[9] In 370 patients with cracked tooth syndrome, 82% of those were found in amalgam-filled teeth.[18] In addition, a 12-year survival study reported more than 10% of 1200 amalgam fillings failed because of tooth fracture or cracked tooth.[8] Cracks in the tooth structure are in response to stresses, which can originate from masticatory forces, environmental effects, or pressure exerted by an expanding restoration. Amalgam expansion due to phase changes or corrosion is well documented,[12,13] and cuspal flexure of amalgam-filled teeth has been observed *in vitro*.[19] Under clinical conditions, amalgam expansion is also confirmed by the observation of occlusal extrusion of aging fillings.[14,20,21] Nevertheless, stresses in the tooth structure due to amalgam expansion have been largely dismissed with reference to creep as an alleviating mechanism.[14] Although amalgam creep would lessen stress levels, creep does not occur without the presence of continuous stress.

The most obvious source for continuous stress is pressure imposed on the amalgam filling by the confining tooth structure if amalgam would expand. If amalgam is under pressure from the tooth structure, the tooth must also be under stress. To evaluate the hypothesis that a tooth structure can be stressed by an amalgam filling, we measured cuspal flexure. The experimental method for measuring tooth cusps bending in- or outward is well established for determining the effects of polymerization shrinkage or hygroscopic expansion stresses in restored teeth.[22-24] We used saline storage in an attempt to accelerate the aging of our amalgam fillings because reference surfaces necessary for accurately determining tooth surface changes cannot be kept stable for long. We measured significant cuspal flexure for the amalgam-filled teeth of more than 3 μm after two weeks of storage. This value is comparable to the 2.7 μm previously reported for teeth with 4-mm-wide amalgam MOD fillings after one week.[19] Since unsupported cusps after cavity preparation have been shown to flex in random directions,[25] the consistently outward cuspal flexure supports the hypothesis that the amalgam fillings expanded and stressed the tooth structure. Moreover, we measured 4- μm to 8-μm expansion on the occlusal and proximal amalgam surfaces, which confirmed an expanding amalgam filling and indicated that the reason for the cuspal flexure was likely expansion of the filling.

Amalgam expansion and creep are generally considered positive effects because they close the interfacial gap,[14] thereby tacitly assuming that expansion is an insignificant factor in tooth fractures. In a photoelastic study, cylindrical amalgam fillings caused only minimal stresses in a block of photoelastic material.[26] To test the significance of the measured flexure values, we calculated the stress level associated with 3-μm cuspal flexure of a tooth with MOD filling using finite element analysis. The analysis showed stress concentrations at the cavity line angles. Stress concentrations are areas where stresses are higher compared with surrounding areas (indicated by orange and yellow colors in Figure 3) and therefore identify locations where maximum stress will be exceeded first and crack initiation is thus most likely. The analysis thus confirmed clinical observations that line angles are usually involved in cuspal fractures. Nevertheless, there is no clinical or experimental evidence that amalgam expansion stress is sufficient to cause cusp fracture.[21] In our finite element analysis, the highest (principal) stresses at the cavity line angles were in the range of 10 to 25 MPa, which is well below the tensile strength of dentin and thus supports the notion that amalgam expansion alone is not sufficient to cause tooth fracture.

Cuspal fracture usually occurs during functional or parafunctional loading, often when no excessive forces are applied. Anecdotes of cuspal or tooth fractures when chewing on soft food are very familiar. Such fracture behavior has all the characteristics of fatigue failure, which is a process of crack propagation under repetitive loading that is lower than the original structural strength. Amalgam expansion stresses may not be sufficient to fracture a cusp, but they may accelerate fatigue crack initiation and propagation by raising stress levels in a tooth. We used the finite element analysis to test this hypothesis and found that amalgam expansion stresses associated with a 3-μm cuspal flexure increased stress concentrations at the cavity line angles 44% to 178% compared with a nonexpanding amalgam filling. According to the classic crack growth equation known as Paris' law, the fatigue crack rate is essentially a power function of the stress amplitude.[27] Increases in the level of repetitive stress values could thus result in significant acceleration of crack propagation and in higher incidence of fatigue fractures. The clinical significance of amalgam expansion is therefore not its inability to break a cusp but rather the effect it has on increasing the stress levels.

Stress levels in restored teeth depend on many factors, where each combination of amalgam alloy, cavity configuration, and tooth will affect the stress development and distribution. Not all variations could be covered in this study. The amalgam we used is a high-copper, non-gamma-2 admixed alloy containing 0.2% zinc.[28] High-copper amalgam associated with expansion and low creep is thought to have contributed to an increased incidence and severity of cusp fracture of endodontically treated posterior teeth.[29] Other amalgams, for example, zinc-containing low-copper alloys, could have caused more expansion if contaminated with moisture,[30] or amalgams exhibiting more creep could have resulted in lower cuspal flexure values.[14] We chose the zinc-containing high-copper alloy because it allowed us to accelerate the aging process needed to assess cuspal flexure before reference surfaces became unstable. The controls showed that after eight weeks in saline, the stability of the reference surfaces became unreliable. Note that moisture contamination was not an issue because the fillings were placed in a dry *in vitro* environment.

The choice of cavity configuration also affected our outcomes. A large MOD cavity significantly weakens the tooth structure, which increases the tooth deformation and thus stresses in the tooth. The slot cavity design in this study had a constant 4-mm depth without proximal boxes to achieve maximal cuspal deformation. A small occlusal cavity or conventional Class II cavity is less injurious to the tooth stiffness, which results in less tooth deformation from amalgam expansion and thus lower stresses in the tooth. This may explain the previously mentioned low stresses in a block of photoelastic material with cylindrical cavity.[26] Note, however, that stress concentrations will change depending on the cavity configuration. In occlusal fillings, stress concentrations due to expansion are likely to shift to the occlusal surface where the lower tensile strength and fracture toughness of enamel may predispose occlusal margins to increased risk of crack initiation and propagation. In this study, we considered three levels of convergence for our MOD cavities (0°, 5°, and 10°). Generally, stress concentrations intensified with increasing convergence. However, the value did not only depend on convergence, but also the surrounding, remaining tooth structure. For example, a smaller cavity with higher conversion angle may generate lower stress concentrations than a large cavity with less convergence. Similarly, stress distributions are affected by the location and distribution of occlusal loading. Two load conditions were examined in this study. They showed that loading of unsupported cusps creates significant stress concentrations at the cavity line angles. Those stress concentrations caused by masticatory loading can be avoided by bonding a filling to the cavity walls.[31] However, stress concentrations at cavity line angles that are generated by restoration expansion will not be prevented by bonding. Note also that expansion stresses differ from more familiar polymerization shrinkage stresses because stresses caused by the expansion of Class II restorations tend to concentrate on internal tooth surfaces, whereas stresses caused by shrinkage tend to concentrate on external tooth surfaces.[31] Restoration expansion stress concentrations thus coincided with the location where stresses generated by masticatory loading also concentrated.

Clearly, predicting stresses is complex and should not be generalized because unique factors of each tooth-restoration complex need to be taken into account. The results of this study should therefore not be applied blindly to other alloys or cavity configurations. The significance of our experiment, however, is the demonstration that amalgam has the potential to significantly raise stress levels in filled teeth. Even though the life span of amalgam fillings is respectable,[4,6,8] cracks in the tooth structure can lead to extensive re-restoration or render a tooth unrestorable.

Clinicians should therefore be aware that cracks associated with amalgam restorations are likely to propagate in a fatigue process that eventually leads to catastrophic fracture. Viewing teeth with amalgam filling up close with an intraoral camera helps to verify the presence of microcracks, especially when using a bright light to transilluminate the tooth. Moreover, clinicians should be aware that higher convergent cavity walls as well as sharp cavity line angles intensify the local stress concentrations, which are likely to accelerate crack propagation, and that bonding an amalgam filling may restore structural integrity but will not eliminate the effect of amalgam expansion stresses. Amalgam fillings have a good track record for longevity and technique insensitivity, but if clinicians are concerned about maintaining tooth integrity, amalgam may not be the best choice. Amalgam fillings may create stress conditions that accelerate tooth cracking. Amalgam fills a cavity but does not restore the tooth.[31]

CONCLUSION

During the eight-week storage in normal saline solution, amalgam fillings expanded and pushed cavity walls outward. Finite element analysis showed that the expansion caused stress concentrations in the tooth structure at the lingual and buccal internal line angles. These expansion stresses added to stresses generated by masticatory loads and were hypothesized to contribute to initiation and propagation of tooth cracks incidentally observed around amalgam restorations. Results from the finite element analysis suggested that cavity convergence may be a contributing factor.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the University of Tennessee Health Science Center. The approval code for this study is 15-04302-NHSR.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

Note

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