Crown Material and Occlusal Thickness Affect the Load Stress Dissipation on 3D Molar Crowns: Finite Element Analysis

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Purpose: To compare the mechanical behavior (stress load dissipation and/or concentration) of posterior crowns made from Lava Ultimate (LU; 3M ESPE) and IPS e.max CAD (LD; Ivoclar Vivadent) using finite element analysis (FEA). Materials and Methods: A 3D model of a mandibular first molar was prepared by reducing the occlusal surface by 1 or 2 mm (according to group), the axial walls by 1.5 mm, and with a 0.8-mm–deep shoulder margin as a finish line. A convergence of 6 degrees between opposing walls was set. Subsequently, four 3D crown models were created according to two test groups with two different occlusal thicknesses: (1) LD with 1.0 mm (LD1); (2) LD with 2.0 mm (LD2); (3) LU with 1.0 mm (LU1); and (4) LU with 2.0 mm (LU2). FEA models were constructed using Femap software (Siemens). A load of 200 N was applied in the axial and oblique (20 degrees) directions for each group, and stress dissipation was viewed using NEi Nastran software. Results: FEA results demonstrated that the LU crowns dissipated the occlusal load to the tooth structure, whereas the LD material concentrated the load inside the crowns. For LU material, the lower the occlusal thickness, the higher the stress concentration inside the crown, and the 2.0-mm occlusal thickness transferred lower stress to the tooth structure. The oblique rather than the vertical load caused an increase in the maximum stress concentration at the shoulder margin and axial walls. Conclusion: The higher the Young modulus mismatch between the crown material and substrate, the higher the load stress concentration inside the material. The 2-mm occlusal thickness acted by decreasing the load stress to the tooth substrate. Finally, the axial load delivered more favorable stress transmission to the tooth substrate. Crown material and occlusal thickness both affect the mechanical behavior of stress dissipation to the tooth structure. Int J Prosthodont 2023;36:301–307. doi: 10.11607/ijp.6974

Nowadays, dentists and patients are more focused on metal-free restorations because of the favorable esthetic appearances of these materials in contrast to metal-ceramic crowns. However, the main objective when restoring loss of tooth structure is to replace it with a material that presents mechanical characteristics that emulate the tooth structure. More recently, restorative materials have been classified into three categories: (1) glass-matrix, (2) polycrystalline, and (3) resin-matrix. However, one of these three categories presents subcategories that more accurately describe the distribution of restorative materials based on chemical composition and microstructure. Although there is a plethora of materials to replace tooth structure loss, none of them present mechanical characteristics similar to tooth structure while concurrently presenting higher fracture strength.
IPS e.max CAD (Ivoclar Vivadent) is a lithium disilicate (LD) glass-matrix ceramic that has been used for a large range of clinical situations, such as single crowns, thin veneers, inlays, onlays, and anterior or posterior three-unit fixed dental prostheses, as well as implant-supported crowns. Moreover, LD can be manufactured as a monolithic or bilayer structure through the lost-wax and heat-pressed techniques or by CAD/CAM processes. Monolithic crowns made of LD present better results than bilayer LD crowns when cemented to dentin or composite resin tooth abutments. However, regardless of its manufacturing process, the use of LD over implant abutments seems to be more promising than when cemented on tooth abutments. The use of monolithic LD seems more reliable due to the absence of a porcelain veneer—a 2-year follow-up study that analyzed 62 posterior monolithic LD crowns described 100% survival (without chipping or catastrophic fractures). Moreover, monolithic LD single crowns cemented to implant abutments presented a 100% survival in a 5-year prospective cohort follow-up study. However, LD ceramics have physical characteristics that are very different from the dentin substrate and that cannot emulate the tooth structure, which has been regarded as an important factor for restoring tooth loss.

Lava Ultimate (LU; 3M ESPE) is termed a nanofill composite because it includes 79 wt% zirconium silicate nanofillers (silica 20 nm + zirconia 4 to 11 nm + zirconium silicate clusters 0.6 to 10 µm) dispersed in a urethane dimethacrylate (UDMA) matrix. This matrix is completely heat processed and presents a higher degree of conversion due to its completely controlled manufacturing process. LU materials present an elastic modulus of 12.8 MPa, which is very close to the modulus of the tooth structure (18 MPa). For this reason, it was initially indicated as an indirect material to build up single crowns. Recently, however, its indication has been altered for use only in inlays, onlays, and veneers due to unexpected full crown debonding when bonded to an implant zirconium abutment. In fact, there is no doubt about the huge mismatch between the elasticity modulus of LU (12.77 MPa) and zirconia abutments (210 MPa). Assuming this fact, higher stress concentration was identified by means of finite element analysis (FEA) at the interface between the LU crown and zirconium or titanium implant abutments and has been suggested as a factor that may cause deterioration of the bonding interface.

FEA has been frequently employed in order to both evaluate and anticipate the mechanical behavior of a number of clinical and mechanical characteristics that are of concern to dental subjects because the cement thickness influences stress distribution over CAD/CAM machined crowns. The impact of many clinical aspects at maximum tension develops at the tooth/restoration interface. Moreover, FEA has been used to assess the design modification of zirconia infrastructures and also to predict the biomechanical comportment of fiberglass posts on tooth structures with different coronal remnants. As such, FEA has the capacity to predict the mechanical behavior of different structures without destroying many specimens.

Since 3M ESPE withdrew the crown indication for LU material, as well as its use relating to physical properties of the subjacent structure (e.g., tooth, metal posts, and/or zirconia or titanium abutments), the present study sought to evaluate two parameters (material and occlusal thickness) by means of FEA with respect to the maximum stress of monolithic LD and LU crowns. Specimens in both groups had different occlusal thicknesses (1 and 2 mm) and were subject to distinct load directions (axial vs oblique) cemented to a tooth prepared for a full crown. Three null hypotheses were tested: (1) there would be no mechanical behavior differences between the assessed crown materials; (2) there would be no differences between occlusal thicknesses regarding maximum load distribution over the tooth/crown complex; and (3) there would be no differences between forces applied to the occlusal surface (axial vs oblique) with respect to maximum load distribution over the tooth/crown complex.

MATERIALS AND METHODS

An FEA analysis was performed with the software packages Femap (10.2, Siemens) and NEi Nastran (10.0.3.7). The anatomical features of the mandibular first molar crown were acquired through scanning of an artificial mandibular first molar. After that, a 3D model was acquired, and the root was kept fully constrained. A full crown preparation was simulated by reducing the occlusal surface by 1 or 2 mm (according to group) and reducing the axial walls by 1.5 mm. A convergence of 6 degrees was created between opposing walls (buccal and lingual, in addition to mesial and distal). A 0.8-mm–deep shoulder margin was then designed (Fig 1). Subsequently, four 3D crown models with different occlusal thicknesses were created according to the four test groups: (1) LD with 1 mm (LD1); (2) LD with 2 mm (LD2); (3) LU with 1 mm (LU1); and (4) LU with 2 mm (LU2). In each group, the crown was designed to occupy the space between the original tooth form and the prepared tooth.

The material properties were assumed to be homogeneous and isotropic and to have linear elasticity. The elasticity modulus and the Poisson coefficient were kept constant according to relevant literature (Table 1). Adhesion was simulated as perfect (without voids), no split was permitted between components, and there were no flaws in any of the components. Features from the periodontal ligament, pulp tissue, and cement thickness layer were not taken into account. A 200-N load, which has been regarded as...
a physiologically relevant occlusal load, was axially applied toward the central fossa. The same load was also applied 20 degrees off the long axis at the mesiovestibular cups (Fig 2). The load direction was chosen based on the fact that, clinically, the occlusal contacts occur between the centric cusps and the central fossae or marginal ridges. Additionally, the 20-degree off-axis load direction was chosen because the masticatory cycle can change the load direction on teeth. Data analysis was based on a qualitative description of images created from a color map of tension/deformation and from maximum tension values acquired after the simulation.

RESULTS

Apart from occlusal thickness and load direction, FEA showed that the LU crowns acted to transmit occlusal load to the tooth, whereas the LD material concentrated the load inside the crowns. Also, it was possible to note that the oblique load created traction areas around the cervical shoulder margin for both the LD and LU materials.

For the LU material, a thicker occlusal thickness compared to a lower load transmission to tooth dentin (Figs 3a and 3b) was observed. The oblique load generated a traction area on the side opposite the load application site (at the shoulder margin), but the stress was also dissipated to the tooth (Figs 3c and 3d). However, it was possible to notice that the central fossae represented a geometric factor that concentrated the load stress. On the other hand, the LD1 group concentrated more tension inside the crown, whereas the stress seemed to spread more over the crown surface in the LD2 group. Different from the LU material, it was possible to observe that there was

<table>
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<th>Table 1 Mechanical Properties of Isotropic Materials</th>
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<td>Materials</td>
</tr>
<tr>
<td>LD</td>
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<tr>
<td>LU</td>
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<tr>
<td>Epoxy resin</td>
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<tr>
<td>Dentin</td>
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\(^a\)Manufacturer information.  
\(^b\)Rees et al., 1994.  
\(^c\)Chen et al., 2014.
a huge concentration of stress at the cementation interface of the LD crowns that was not dissipated to the tooth substrate (Figs 4a and 4b). The oblique load also generated a traction area on the opposite side (at the shoulder margin) of the load application; in this case, the traction force was dissipated to the tooth structure (Figs 4c and 4d).

The maximum stress for axial loading ranged from 128.8 to 151.5 MPa. When the occlusal surface was thicker, the maximum generated stress load was higher.

For oblique loading, the maximum stress that was recorded ranged from 60.7 to 68.4 MPa (Table 2). Overall, the LU crowns, rather than the LD material, presented the maximum stress load. The oblique rather than the vertical load caused an increase in the maximum stress concentration at the shoulder margin and axial walls, and the central sulcus acted as a factor that concentrated stress tension (Table 3).
DISCUSSION

The posterior teeth present a complex geometry and receive higher occlusal loads (axial and oblique) than the anterior teeth, which represents a challenging scenario for reproduction by in vitro or FEA testing. Based on such factors, the present study assessed two different crown materials (LD vs LU), occlusal thicknesses (1 vs 2 mm), and load directions (axial vs oblique) in order to predict the mechanical behavior of such materials under clinical conditions. The first null hypothesis was rejected because LU transferred the load to subjacent structures, whereas LD did not dissipate it through the subjacent tooth structure. The second null hypothesis was also rejected because occlusal thickness played an important role in the load distribution to subjacent structures. Finally, the third null hypothesis was also rejected because the shoulder and axial walls received higher loads when the force was applied obliquely.

The use of resin-matrix ceramic materials has gained attention because such materials use a monolithic partial or full crown restoration concept due to their mechanical properties, which are closer to those found in tooth hard tissues (especially dentin). LU was developed to cause a decrease in elastic modulus mismatches between restorative materials and dentin. Its composition consists of aggregate of an organic phase UDMA matrix, which is full of nanoceramic particles (as described previously) that reduce the number of interstitial spaces. Also, LU presents a higher degree of conversion, which facilitates better mechanical characteristics than traditional composite resin materials. Moreover, LU shows important features because it is easily milled (very different from ceramic materials) and can be easily adjusted by the dentist in the office (for occlusal and proximal contacts). The present results indicate that LU material is more capable of absorbing shock from occlusal forces than LD material in addition to transmitting occlusal loads to subjacent tooth structures by acting as a monobloc structure, which is in agreement with another FEA study. This finding may be explained by the similarity of the elastic modulus of LU and dentin. In a step-stress in vitro test, LU crowns cemented over titanium implant abutments presented a probability of survival similar to metal-ceramic crowns. In this scenario, the main failure mode for metal-ceramic crowns was related to cohesive ceramic fracture (frequently exposing the metal substructure), whereas the main failure mode for LU crowns was related to cohesive fracture. Besides that, the LU material did not display subsurface damage as observed in the LD specimens after an off-axis mouth-motion cycling fatigue test (up to 10^6 cycles). This finding could have been due to higher LU compliance, which helped the stress from mechanical loading dissipate, therefore causing a reduction in the stress intensity at the critical defects. When LU ultrathin occlusal veneers (0.3 to 0.5 mm) that were cemented on the tooth substrate were evaluated with the fatigue test, higher survival probability in comparison to LD ultrathin occlusal veneers was found. However, LU seems unsuitable for full crown restorations over zirconia implant abutments since an unacceptable debonding failure rate (80%) occurred within the 1-year follow-up period, and such drawbacks were attributed to elastic deformation of the restoration during chewing. Moreover, an FEA study identified that LU material cemented to zirconia or titanium abutments presented a higher stress concentration at the cement interface, which might cause deterioration of the cement layer and contribute to adhesion failure.

<table>
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<tr>
<th>Group</th>
<th>Axial load</th>
<th>Oblique load</th>
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<tr>
<td>LD1</td>
<td>128.8</td>
<td>60.7</td>
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<tr>
<td>LD2</td>
<td>136.7</td>
<td>62.4</td>
</tr>
<tr>
<td>LU1</td>
<td>129.6</td>
<td>68.4</td>
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<td>LU2</td>
<td>151.5</td>
<td>61.7</td>
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<th>Table 3 Maximum Principal Stress (MPa) Values in Central Sulcus, Axial Walls, and Shoulder Margin According to Test Group</th>
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<td>Axial load</td>
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<tr>
<td>-----------</td>
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<tr>
<td>LD1</td>
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<td>LD2</td>
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<td>LU1</td>
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<td>LU2</td>
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as pointed out by the present study, the LU material transferred the load to the tooth structure, and the mismatch between the LU material and abutment should be taken into account because it seems to be an important subject regarding adhesion integrity. Even though 3M ESPE has withdrawn the crown indication for LU, this issue warrants further clinical and in vitro fatigue testing after taking into account the physical characteristics of the subjacent abutment (dentin vs composite resin vs zirconia vs titanium).

On the other hand, the LD crowns did not dissipate the occlusal loads to the tooth substrate, but rather acted as a stress concentrator. FEA tests revealed a higher mismatch between the material crown and substrate compared to the maximum stress located inside the material and at the margin of restoration. In spite of the present FEA results showing that there was a higher stress concentration within the LD material crown, clinical results have pointed out higher survival rates (100% survival regarding absence of mechanical failures) for LD monolithic crowns during a 2-year follow-up. Moreover, a long-term prospective study showed survival rates of 97.4% and 94.8% after 5 and 8 years, respectively, for LD bilayer single crowns (most of the crowns were located in the anterior region). Recently, a prospective cohort study demonstrated that LD monolithic crowns that were adhesively cemented over implant abutments presented a 100% cumulative survival rate (no mechanical failures were observed). It can be speculated that the fine microstructure of LD glass-ceramic plays an important role in explaining the higher clinical cumulative survival results found in clinical investigations because LD impairs crack propagation, and the physical property mismatch between the LD glass-ceramic and dentin may be a secondary factor involved in long-term survival of LD crowns. Moreover, in all proposed simulations, the maximum principal stress values (see Table 3) did not exceed the flexural strength of the materials given by the manufacturers (360 and 204 MPa for LD and LU, respectively).

Finally, the results of the present study should be interpreted with caution, as FEA simulations present some limitations, such as the fact that CAD models may differ from those existing in a clinical context and teeth are intraorally subjected to a high range of complex loading conditions. Therefore, some simplifications were used in the present study, and concerns might arise from the fact that the effects of cement, pulp, and the periodontal ligament on the load stress analysis were not considered. However, the mechanical conditions were similar and completely comparable between the simulated conditions. It is noteworthy that biologic tissues are anisotropic, but the conditions in the present study were assumed as isotropic; thus, an improper adjustment between FEA and real biologic conditions exists. Therefore, these results can only be used to understand the initial behavior of the restoration, since cyclic masticatory loads were not applied. The accuracy of probable clinical application must be confirmed by laboratory studies and controlled clinical trials.

CONCLUSIONS

The three null hypotheses of the study were rejected because the mechanical behavior of posterior crown models differed when certain parameters, such as thickness of the restorative material in addition to the direction of load, were applied. The most favorable stress distribution was obtained with the 2-mm-thick occlusal crowns with an axial load application, mainly for LU material.

ACKNOWLEDGMENTS

The authors report no conflicts of interest.

REFERENCES

Computer-assisted implant surgery (CAIS), either static or dynamic, is well documented to significantly improve the accuracy of implant placement. Whether the increased accuracy leads to a corresponding improvement in clinical outcomes has not yet been systematically investigated. The aim of this critical review was to investigate whether the use of CAIS can lead to reduction of complications as well as improved clinical and patient-reported outcomes (PROs) when compared with conventional freehand implant surgery. A comprehensive online search was conducted to identify studies where implants were installed with static computer-assisted implant surgery (s-CAIS) or dynamic computer-assisted implant surgery (d-CAIS) or combinations of the two, either compared with conventional free-hand implant placement or not. Seventy-seven studies were finally included in qualitative analysis, while data from three studies assessing postsurgical complications were available in the form of systematic reviews. Seventy-seven studies were finally included in qualitative analysis, while data from three studies assessing postsurgical complications were available in the form of systematic reviews. Whether the increased accuracy leads to a corresponding improvement in clinical outcomes has not yet been systematically investigated.


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Literature Abstract


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