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RESEARCH AND EDUCATION

Effect of preparation design on fracture strength of compromised molars restored with direct composite resin restorations: An in vitro and finite element analysis study

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ABSTRACT

Statement of problem. More data are needed on the influence of preparation design on the fracture strength, failure type, repairability, and polymerization-induced cracks of molar teeth restored with direct composite resin restorations.

Purpose. This in vitro and finite element analysis study investigated the effect of different preparation designs on fracture strength, failure type, repairability, tooth deformation, and the formation of polymerization-induced cracks of compromised molars restored with direct composite resin restorations.

Material and methods. Human molars (n=64) were randomly assigned to 4 different preparation designs: undermined inlay (UI), extended inlay (EI), restricted overlay (RO), and extended overlay (EO). The teeth were restored using direct composite resin and subjected to artificial thermomechanical aging in a mastication simulator, followed by load-to-failure testing. Three-dimensional (3D) finite element analysis was conducted to assess tooth deformation. Polymerization-induced cracks were evaluated using optical microscopy and transillumination. The fracture strength data were analyzed using a Kruskal-Wallis test, while the failure mode, repairability, and polymerization cracks were analyzed using the Fisher exact test (α=.05).

Results. All specimens withstood thermomechanical aging, and no statistically significant difference in fracture strength was observed among the 4 preparation designs (P>.05). The finite element analysis showed differences in tooth deformation, but no correlation was observed with in vitro fracture resistance. The RO and EO groups presented significantly more destructive failures compared with the UI and EI groups (P<.01). The RO group had significantly fewer repairable failures than the UI and EI groups (P=.024). A correlation was found between higher frequencies of repairability and higher tooth deformation. A significant correlation between the increase in microfractures and preparation design was observed (P<.01), with the UI group exhibiting a higher increase in microfracture size compared with the EO group (P<.05).

Conclusions. No influence of preparation design on the fracture strength of compromised molars restored with direct composite resin restorations was evident in this study, but the failure mode of cusp coverage restorations was more destructive and often less repairable. The finite element analysis showed more tooth deformation in inlay preparations, with lower stresses within the root, leading to more reparable fractures. Since cusp coverage direct composite resin restorations fractured in a more destructive manner, this study suggests that even a tooth with undermined cusps should be restored without cusp coverage. (J Prosthet Dent xxxx;xxx:xxx-xxx)

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Clinical Implications

Cusp coverage direct composite resin restorations are more prone to destructive failure modes and demonstrate reduced repairability compared with other designs. As cusp coverage restorations have a higher likelihood of destructive fractures, restoring teeth with direct composite resin restorations without cusp coverage may be preferable.

Replacing defective restorations has been reported to constitute 60% of treatment in a dental practice.[1,2] Frequently, removing existing restorations, especially defective amalgam restorations, can leave undermined tooth structure vulnerable under functional loads. However, consensus on the optimal restorative treatment for molars with compromised, undermined cusps is lacking.

Structurally compromised teeth can be restored directly or indirectly. Direct composite resin restorations have a more flexible preparation design, and the procedure can be completed in a single visit at relatively low cost. The clinical outcomes in posterior teeth have been reported to be good, with a survival rate of 91.7% after 5 years, 82.2% after 10 years,[3] and 74.7% after 15 years.[4] Structurally affected posterior teeth have been reported to perform similarly to direct or indirect composite resin restorations as reported in recent systematic reviews.[5,6]

The preparation design, especially the preparation width, might affect the clinical performance of direct composite resin restorations. However, studies on the influence of the preparation width have reported inconsistent results, and the minimum thickness required to safely maintain thin cusps in direct composite resin restorations is unclear.[7–10] In vitro and finite element analysis studies with posterior teeth did not find a significant influence of preparation width on the fracture resistance of molars restored with direct composite resin with a mesio-occluso-distal restoration.[7,8,10]

Cuspal coverage has been advocated to prevent the fracture of thin remaining walls and improve restoration survival, although the degree of occlusal reduction may be important.[11] Inadequate composite resin thickness creates the risk of fracture of the restoration itself.[11] In addition, an extended cusp coverage restoration has a flatter surface with a lower configuration factor, which could influence the effect of polymerization shrinkage.[12] Preparation design could also influence the mode of failure of restored posterior teeth, and cuspal coverage has been reported to lead to more catastrophic failures in vitro.[13] This type of failure, however, is rarely seen in fractures of vital teeth, with 91% of fractures being supragingival.[14]

Overall, evidence and consensus on the influence of different preparation designs on the fracture strength of extended direct composite resin restorations in weakened molars are lacking. Moreover, the influence of preparation design on the formation of polymerization stress-induced cracks remains unclear. Therefore, this in vitro study tested the null hypotheses that preparation design would have no effect on fracture strength and that no difference in the failure mode, repairability, propagation of microcracks, and tooth deformation would be found among the preparation designs.

MATERIAL AND METHODS

The details of the materials used in this study are listed in Table 1. Sound human molar teeth (N=64) of similar size were selected from a pool of recently extracted teeth (< 6 months, stored in water). Approval by an ethical committee was not required. To detect differences in fracture strength, sample size was calculated using a statistical software program (G*Power 3.1; Heinrich-Heine-Universität Düsseldorf) based on the following parameters

Table 1. Brands, types, chemical compositions, manufacturers, and batch numbers of main materials used

Product Name	Type	Chemical Composition	Manufacturer	Batch Number
Gel Etchant 35%	Etch gel	35% phosphoric acid	Ultradent Products, Inc	BKRHZ
Optibond FL Prime	One component primer	2-hydroxyethyl methacrylate ethanol, 2-[2- (methacryloyloxy) ethoxycarbonyl] benzoic acid, glycerol phosphate dimethacrylate	Kerr Corp	8272741
Optibond FL Adhesive	Bonding agent	2-hydroxyethyl methacrylate, 3- trimethoxysilylpropyl methacrylate, 2- hydroxy-1,3-propanediol bismethacrylate, alkali fluorosilicates (Na)	Kerr Corp	7748946
Clearfil AP-X PLT	Light-polymerizing composite resin	bisphenol A-glycidyl methacrylate, triethyleneglycol dimethacrylate, silanated barium glass filler, silanated silica filler and colloidal silica, dl-camphorquinone, catalysts, accelerators, pigments	Kuraray Noritake	5Q0263
K-Y Lubricating Jelly	Glycerin gel	Water, glycerin, propylene glycol, hydroxyethylcellulose, methylparaben, sodium phosphate, disodium phosphate, propylparaben, tetrasodium ethylenediaminetetraacetic acid	Johnson & Johnson	B213520

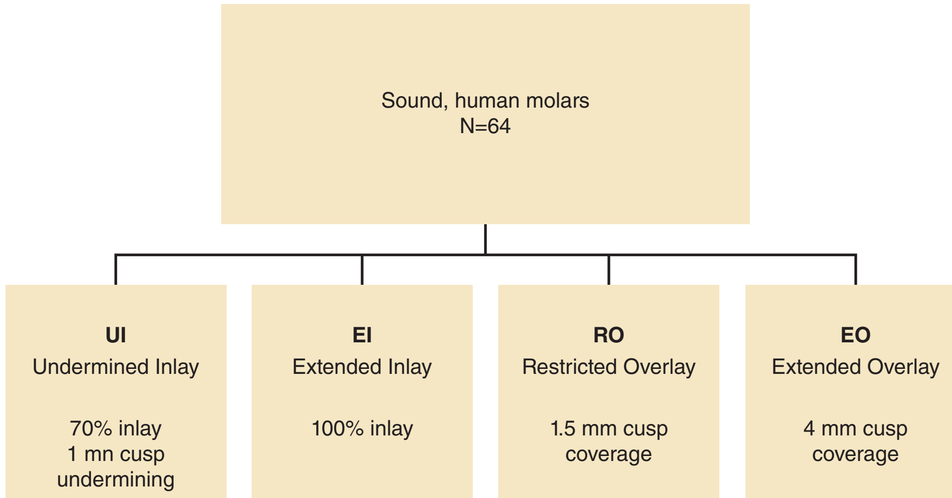

Figure 1. Experimental sequence, allocation, and abbreviation of groups. EI, extended inlay; EO, extended overlay; RO, restricted overlay; UI, undermined inlay.

and assumptions: effect size=0.45, α=.05, power=.8, and number of groups=4.[15] The set effect size was based on previous studies.[16,17] Polymethylmethacrylate (ProBase Cold; Ivoclar AG) was used to embed the teeth up to 1 mm apical to the cement-enamel junction (CEJ); these were stored in water during the study. Digital photographs were made from all sides of each specimen. The teeth were then randomly assigned to 1 of 4 groups using the RAND function in a spreadsheet (Excel; Microsoft Corp). The experimental sequence, allocation, and abbreviations of the groups is presented in Figure 1.

Four experimental preparation designs were made on the teeth (Fig. 2). The undermined inlay (UI) preparation had a preparation width of 70% of the intercuspal width and a depth of 5 mm relative to the highest cusp. Additionally, the width of the approximal box was 5 mm, and the walls were prepared with 0-degree divergence. After that, an undercut was made in the dentin using a round diamond rotary instrument (6801; Komet Dental GmbH). To do this, the thickness of the cusps was first measured with a thickness gauge, and the cusps were then undermined by 1 mm. The measured cusps were

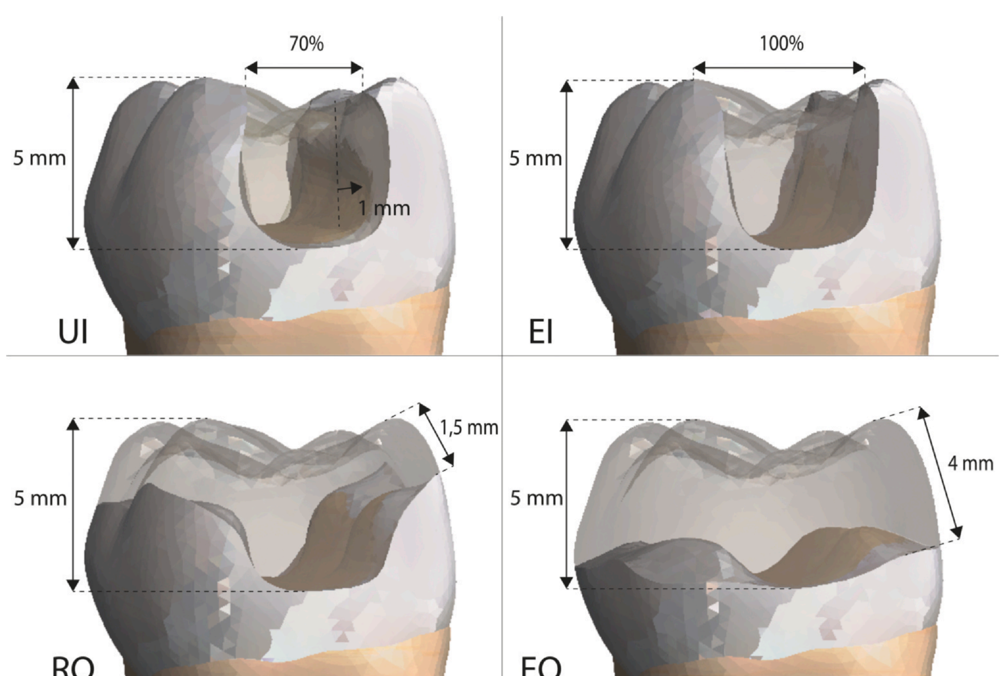

Figure 2. Experimental preparation groups. EI, extended inlay; EO, extended overlay; RO, restricted overlay; UI, undermined inlay.

approximately 3 mm at the base before undermining. The preparation width of the extended inlay (EI) was 100% of the intercuspal width. The walls were prepared with a 6-degree divergence. The depth was 5 mm relative to the highest cusp, and the width of the approximal box was 5 mm. For the restricted overlay (RO), the preparation of the extended inlay was made first. Then, the cusps were lowered by 1.5 mm, and the preparation on the reduced cusps ended obliquely upward at an angle of 20 degrees. For the extended overlay (EO), the preparation of the extended inlay was done initially. Thereafter, the cusps were lowered by 4 mm, and the preparation ended obliquely downward at an angle of 10 degrees.

The preparations were performed under ×10 magnification (OPMI pico; Carl Zeiss AG). Preparations were made with coarse and fine diamond chamfer rotary instruments (6847KR, 8847KR, and 8856; Komet Dental GmbH). The entire preparation was finished smoothly with point polishers (Brownie 9609, Greenie 9620; Komet Dental GmbH) to remove irregularities. Water cooling was used during preparation. A 0.5-mm-wide bevel was placed on all proximal boxes using a sonic handpiece (Sonicflex; KaVo Dental GmbH).

The preparations were etched with 35% phosphoric acid (Ultra-Etch; Ultradent Products, Inc.), the enamel for 30 seconds and the dentin for 15 seconds, rinsed with water for 20 seconds, and dried for 3 seconds. Primer (Optibond FL; Kerr Corp) was actively applied for 20 seconds and gently air dried for 5 seconds. Adhesive resin (Optibond FL; Kerr Corp) was applied for 15 seconds, air thinned, and then photopolymerized for 20 seconds with a polymerization lamp (Bluephase 20i; Ivoclar AG) at an intensity of 1000 mW/cm^2. Composite resin (Clearfill APX PLT; Kuraray Noritake Dental Inc) was applied in layers less than 2 mm thick, followed by 10 seconds of polymerization of each layer. The final layer was shaped using the stamp technique by placing a relined putty index (Provil Novo; Kulzer GmbH, Fit Checker Advanced; GC Corp) over the soft composite resin to reproduce the original morphology. After polymerizing the final layer, glycerin gel (K-Y lubricating jelly; Johnson Johnson) was applied, and the restoration was photopolymerized for another 40 seconds. Glycerin was rinsed away, and the restoration was finished with fine diamond rotary instruments (Komet Dental GmbH), point polishers (Brownies 9609; Komet Dental GmbH), and composite resin polishers (DiaComp Plus, EVE Ernst Vetter GmbH).

In order to detect stress-induced polymerization cracks, the specimens were evaluated before specimen preparation and 1 week after restoration at ×1.5 magnification using digital photography (EOS 70D 100 mm macro lens with Macro Ring Lite flash; Canon Inc) under standardized conditions and with transillumination (Microlux; Addent, Inc). Transillumination before preparation excluded pre-existing cracks. Cracks were categorized on 3 levels: no cracks visible, visible cracks smaller than 3 mm, and visible cracks larger than 3 mm. The size of the cracks after restoration was compared among the groups.

The specimens were subjected to artificial aging using a mastication simulator (Chewing Simulator CS-4.8; SD Mechatronik GmbH). A zirconia ceramic antagonist sphere was loaded perpendicular to the occlusal plane in the central fossa, and the specimens were subjected to 1.2×10^6 cycles at a frequency of 1.7 Hz and a load of 50 N. The specimens were subjected to simultaneous thermocyclic aging for 8000 cycles between 5 °C and 55 °C. Subsequently, the specimens were evaluated in terms of failures, cracks, and fractures under ×40 magnification (M3; Wild Heerbrugg AG), and digital photographs were made. Load-to-failure was applied using a universal testing machine (810 Material Test System; MTS Systems Corp). The specimens were loaded with an 8-mm steel ball, at an angle of 30 degrees to the tooth axis on the inner surface of the buccal cusp at a crosshead speed of 1 mm/minute. The maximum forces to failure (Newton) were recorded. Failure sites were observed using an optical microscope (M3; Wild Heerbrugg AG) at a maximum of ×40 magnification and classified according to the following criteria: fracture of enamel and dentin, fracture of the restoration, fracture of the restoration and enamel, fracture of the restoration, enamel, and dentin, or root fracture. Fractures occlusal to the CEJ were classified as repairable, and those apical to the CEJ extending in the root as nonrepairable.

The data were analyzed using a statistical software package (IBM SPSS Statistics, v28; IBM Corp). A Kolmogorov-Smirnov test was used to test normal distribution of the fracture strength data. As these data were not normally distributed ($P<.05$), a Kruskal-Wallis test was applied to analyze the effect of the preparation design on the fracture strength. After that, post hoc comparisons (with Bonferroni correction to correct for type I errors) were applied to analyze pairwise comparisons. The correlation of the groups with failure mode, repairability, and the formation of polymerization-induced cracks was analyzed using the Fisher exact test, followed by a post hoc test with Bonferroni correction, as the assumptions for chi-squared were violated. Finite element analysis results were visually analyzed for correlations with repairability.

A 3-dimensional (3D) finite element analysis was performed by considering the same study factors and specimen designs used in the in vitro test to better understand the biomechanical behavior of different models. The intact molar was first used to obtain the separated surfaces of enamel, dentin, and pulp chamber

Table 2. Material properties used

Material	Elastic Modulus (GPa)	Poisson Ratio
Dentin[19]	18.6	3.1×10^{-1}
Enamel[19]	84.1	3.0×10^{-1}
Pulp[19]	2×10^{-3}	4.5×10^{-1}
Kuraray Clearfil APX[20]	16.8	2.6×10^{-1}
Acrylic Resin[20]	3.2	3.0×10^{-1}

Superscript numbers refer to references.

from a cone beam computed tomography (CBCT) scan and exported as standard tessellation language (STL) files according to a previously described process[18] in a specific software program (InVesalius; Renato Archer Information and Technology Center). The intact tooth surface and the preparations were scanned with an intraoral scanner (CEREC Omnicam, software CEREC SW 5.2.1; Dentsply Sirona). The STL files obtained from the CBCT scan and intraoral scans were combined in an open-source software program (Meshmixer; Autodesk Inc) for mesh refinement before being exported to a computer-aided design (CAD) software program (SolidWorks 2018; Dassault Systèmes; SolidWorks Corp), where the final 4 models were generated in accordance with the in vitro groups.

The 4 CAD models were exported to a software program (ANSYS Workbench 14; Ansys Inc) for numeric analysis. The properties of the material used in the models were obtained from the literature and are presented in Table 2.[19,20] All the materials were considered linearly elastic, homogenous, and isotropic. After the 5% convergence analysis,[21] a 0.3-mm element size was set. Contacts between parts of the model were defined as being bonded. The boundary conditions were defined by fixing the lateral and lower surfaces of the acrylic base in all directions. In order to simulate the loading condition performed in the in vitro test, a 30-degree-oblique load was applied to the buccal cusps. A 131.9-N load was chosen to simulate the clinical condition of mean occlusal force.[22] The deformation values were obtained in a $\times10^{-4}$ -mm quantitative analysis.

RESULTS

All specimens withstood thermomechanical aging in the mastication simulator. Descriptive analysis of fracture strength and finite element analysis tooth deformation are shown in Table 3. The mean ±standard deviation fracture strengths for the groups were: UI=1449.46 ±417.93 N, EI=1314.73 ±395.56 N, RO=1425.26 ±406.59 N, EO=1651.82 ±375.95 N. Fracture strengths of the groups were not normally distributed, as shown by the Kolmogorov-Smirnov test for normality (P=.018). The Kruskal-Wallis test was conducted to examine the influence of preparation design on the fracture strength. No statistically significant difference in fracture strength was found among the different preparation designs (P>.05). Considering the finite element analysis, the criterion selected for the finite element analysis comparison was the deformation of the tooth. No correlation between the in vitro fracture resistance and finite element analysis tooth deformation was observed. Tooth deformation in EI was 30% greater than in EO, even though this difference was not observable in the fracture resistance test. Figure 3 visualizes the tooth deformation in the preparation designs.

The Fisher exact test showed a significant correlation between the preparation design and the failure mode (P<.001). The RO group exhibited significantly more destructive failures than the UI group (P<.01) and the EI group (P<.01). Similarly, the EO group showed significantly more destructive failures than the UI group (P<.01) and the EI group (P=.01). In the UI and EI groups, fewer destructive failures, like enamel and dentin fractures, were seen more frequently. Figure 4 shows failure patterns. Figure 5 shows representative examples of the modes of failure. When repairability was considered, a significant correlation was found between the preparation design and the repairability of the specimens (P<.001). The RO group presented significantly more nonreparable failures than the UI group (P=.024) and the EI group (P=.024). A correlation was observed between the frequency of repairability (in vitro) and tooth deformation (finite element analysis). Groups with higher frequencies of repairability (UI and EI) were associated with higher tooth deformation. The higher tooth deformation in the coronal area induced less stress concentration on the root and therefore more favorable failures. Figure 6 shows the distribution of repairability of the fractured specimens in combination with the tooth deformation.

Table 3. Tooth deformation from finite element analysis and fracture strength of experimental groups: mean, minimum, maximum, and 95% confidence interval

		Fracture Strength (N)					Tooth Deformation ($\times10^{-4}$ mm)
	n	Mean ±Standard Deviation	Minimum	Maximum	95% Confidence Interval for Mean		
					Lower Bound	Upper Bound	
UI	16	1449.46 ±417.93	1015.65	2229.47	1226.76	1672.16	99
EI	16	1314.73 ±395.56	810.24	2240.38	1103.95	1525.51	104
RO	16	1425.26 ±406.59	952.27	2383.52	1208.60	1641.91	92
EO	16	1651.82 ±375.95	1048.41	2165.09	1451.49	1852.15	72

EI, extended inlay; EO, extended overlay; RO, restricted overlay; UI, undermined inlay.

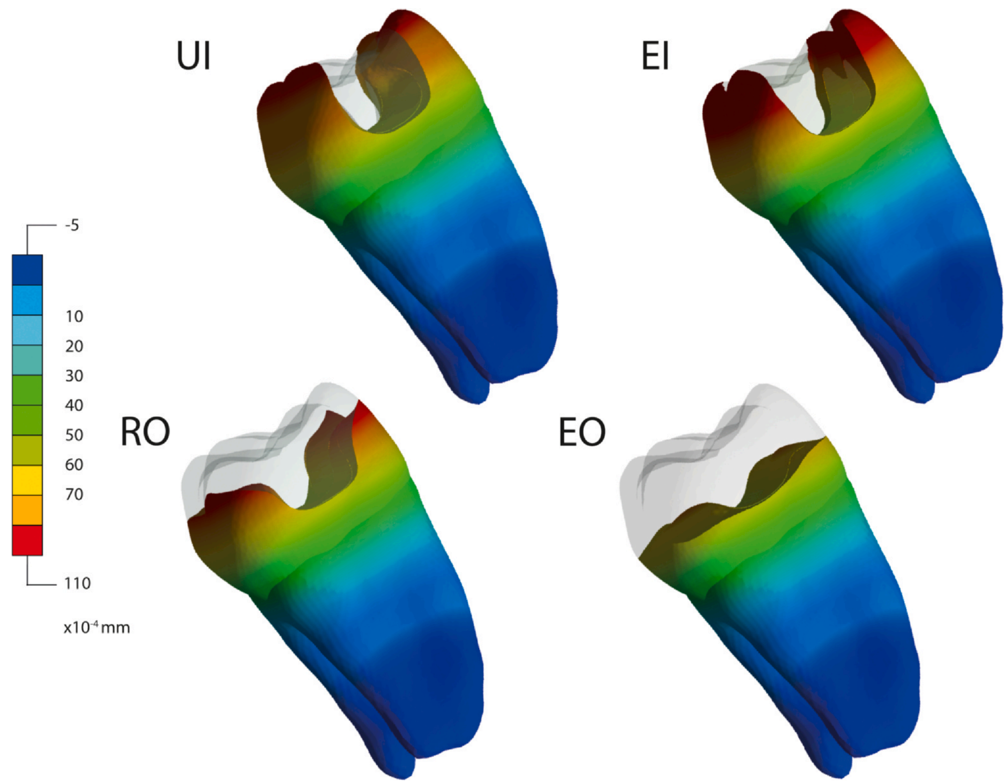

Figure 3. Tooth deformation in experimental preparation groups loaded at 30-degree angle to tooth axis. Tooth deformation in $\times10^{-4}$ mm. EI, extended inlay; EO, extended overlay; RO, restricted overlay; UI, undermined inlay.

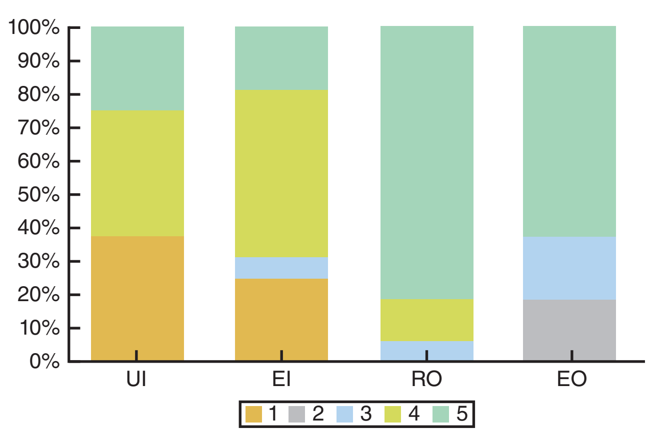

Figure 4. Frequencies of failure modes after load-to-failure test. 1) Fracture of enamel and dentin; 2) Fracture of restoration; 3) Fracture of restoration and enamel; 4) Fracture of restoration, enamel, and dentin; 5) Root fracture. EI, extended inlay; EO, extended overlay; RO, restricted overlay; UI, undermined inlay.

Figure 7 shows the distribution of teeth with different sizes of microcracks for the preparation designs after preparation and 1 week after restoration. From the Fisher exact test, a significant correlation was found between the increase in microfractures and preparation design (*P*<.01). The increase in the size of microfractures was observed significantly more often in the UI group than in the EO group (*P*<.05). Figure 8 shows 2 representative specimens from the UI and EO group before preparation and 1 week after restoration.

DISCUSSION

This in vitro study evaluated the influence of different preparation designs on the fracture strength, failure type, and repairability of compromised molars restored with direct composite resin restorations and determined the influence of polymerization shrinkage on the formation of microcracks after aging. The authors are unaware of a similar previous study.

The first hypothesis, that no statistically significant effect of the preparation design on the fracture strength of compromised molars restored with direct composite resin restorations would be found was not rejected. Previous studies have reported conflicting results. Hofsteenge et al[17] reported no significant difference in the fracture strength of premolars restored with direct composite resin restorations with or without cusp coverage. In addition, Forster et al[8] reported that cusp thickness had no significant effect on the fracture strength of MOD composite resin restorations in molars. However, Fennis et al[13] reported increased fatigue resistance with palatal cusp coverage of Class II composite resin restorations replacing the buccal cusp in premolars.

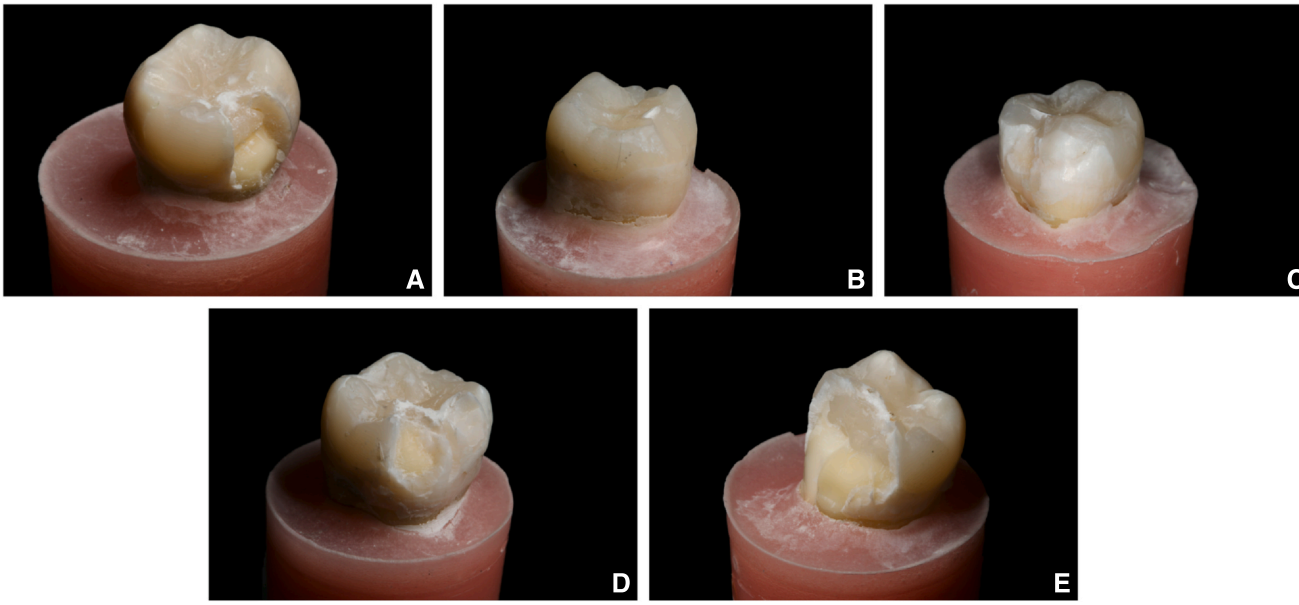

Figure 5. Representative examples of failure modes after fracture test. A, Fracture of enamel and dentin. B, Fracture of restoration. C, Fracture of restoration and enamel; D, Fracture of restoration, enamel and dentin; E, Root fracture.

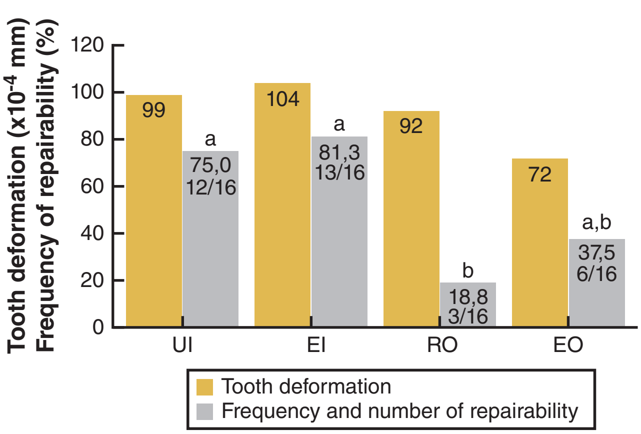

Figure 6. Frequencies of repairability in conjunction with tooth deformation. Different letter indicates statistical differences found among groups for repairability. EI, extended inlay; EO, extended overlay; RO, restricted overlay; UI, undermined inlay. Tooth deformation: UI: 99×10^{-4} mm, EI: 104×10^{-4} mm, RO: 92×10^{-4} mm, EO: 72×10^{-4} mm. Repairability: UI: 75.0% repairable, EI: 81.3% repairable, RO: 18.8% repairable, EO: 37.5% repairable.

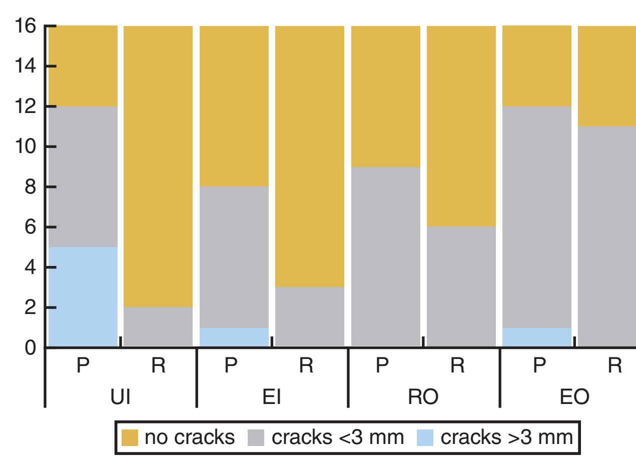

Figure 7. Distribution of teeth with microcracks of different size after preparation (P) and one week after restoration (R). EI, extended inlay; EO, extended overlay; RO, restricted overlay; UI, undermined inlay.

Human mastication forces have been reported to be between 40 and 240 N, depending on the type of food.[23–26] The mean maximum axial occlusal forces range from approximately 600 N for women to 900 N for men.[27] In the present study, the fracture forces, with a 30-degree load angle, were between 810 N and 2384 N and would therefore be expected to withstand clinical mastication.

The second and third hypotheses stating that no difference would be found in the failure mode and repairability were rejected. A significant influence of the preparation design on failure mode and repairability was found. Cusp coverage led to more catastrophic failures, often not repairable. This finding was consistent with that of Fennis et al,[13] who reported more catastrophic failures in restorations with cusp coverage and suggested caution in providing cusp coverage. Interpreting these in vitro failures should be done with caution, since these failures may not be representative of the clinical situation.

The fourth hypothesis, stating that no difference would be found in the propagation of microcracks among the preparation designs was rejected as a statistically significant difference was found in the increase in microcracks among the groups. The restoration of undermined inlay preparations resulted significantly

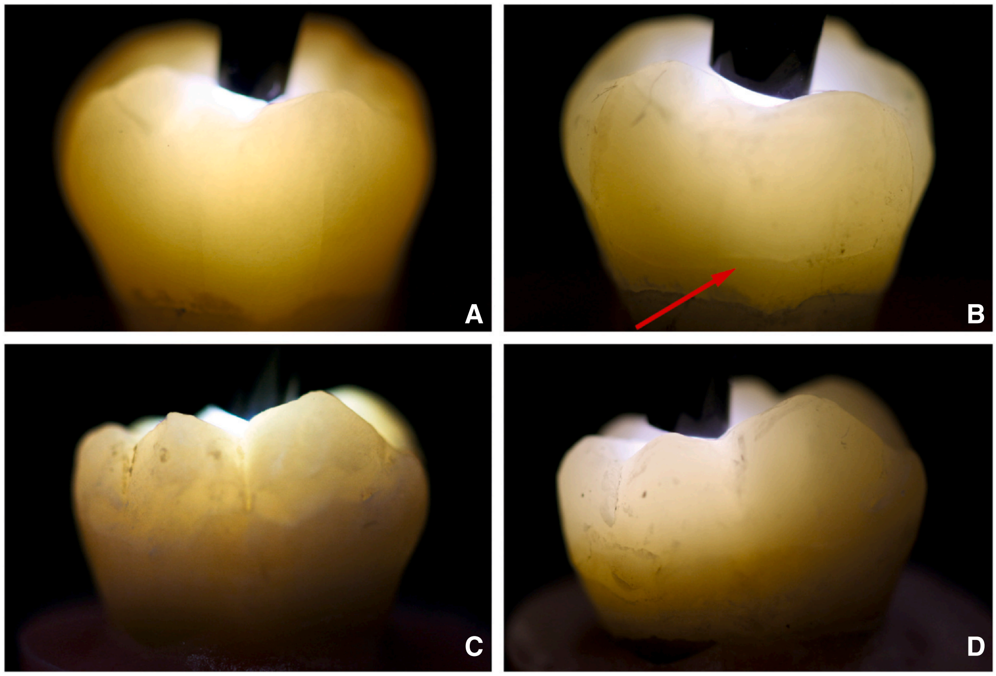

Figure 8. Representative specimen with transillumination before preparation, and one week after restoration. A, Lingual side of molar before preparation. B, Lingual side of same, restored, molar with undermined inlay preparation. Note cracks at base of cusp (*red arrow*). C, Buccal side of molar before preparation. D, Lingual side of same restored molar after extended overlay preparation. Note no cracks visible.

more often in an increase in the size of microfractures than in extended overlay preparations. The influence of polymerization shrinkage on the formation of microcracks has been studied,[28] and an increase in polymerization-induced microcracks after direct composite resin restoration has been reported previously.[29–31] The configuration factor was higher in undermined inlay preparations than for the extended onlay preparations on a relatively flat surface, which could explain the increased influence of polymerization shrinkage.[12] However, little evidence is available for the clinical effect of the formation of polymerization-induced cracks.[28]

The fifth hypothesis was not accepted, as the results from the finite element analysis demonstrated a difference in tooth deformation among the groups, which could be correlated with the repairability of the groups. The higher the tooth deformation in the cusps, the more repairable failures, associated with reduced stress formation in the root. Higher stresses in the root were also observed in a comparable FEA study with direct composite resin inlays and onlays.[32] Kantardžić et al[10] reported an increase in von Mises stress in the dentin when cusps were covered in direct composite resin restorations.

The present in vitro study used load-to-failure to test the strength of the restored specimens. The loading of the teeth in the oral situation is different, with repeated small forces that will eventually lead to the failure of the restoration or teeth.[33] The failures in this in vitro study are consequently more destructive and less often repairable in comparison with the clinical situation, which is a limitation of such studies. Therefore, extrapolating the results of this laboratory-based study to the clinical scenario should be done with caution. The use of survival analyses or cyclic isometric loading, which are more comparable with the clinical situation, could be more suitable.[34] Further research could also be conducted on the influence of fiber-reinforced composite resins on the fracture strength and crack formation in compromised molars, as a recent study reported no difference in crack formation between direct composite resin restorations and fiber-reinforced direct composite resin restorations.[35]

All restorations appeared to sustain forces for clinical application. Further research should investigate patient-related and operator-related factors in greater detail to determine their impact on the survival of extensive direct composite resin restorations.

CONCLUSIONS

Based on the findings of this in vitro and finite element analysis study, the following conclusions were drawn:

1. No influence of preparation design on the fracture strength of compromised molars restored with direct composite resin restorations was evident.
2. The failure mode of cusp coverage restorations was more destructive, and the restorations were less often repairable.

3. The finite element analysis shows more tooth deformation with the inlay preparations, with lower root forces, leading to more repairable fractures.
4. All preparation designs were strong enough to withstand physiological mastication forces.
5. Since cusp coverage restorations can lead to more destructive fractures, the results suggest that compromised vital molars should be restored with direct composite resin without cusp coverage. Clinical studies should be performed to validate this conclusion.

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