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Influence of Preparation Design and Restorative Material on Fatigue and Fracture Strength of Restored Maxillary Premolars

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W Kerdijk • MMM Gresnigt

Clinical Relevance

The results of this *in vitro* study suggest that a minimally invasive preparation depth design may provide an advantageous adhesive restorative strategy. Upon deeper preparation design, despite the fact that cuspal coverage overall strengthened the tooth, it also led to more catastrophic crown-root fractures. Lithium disilicate is the preferred material of choice for overlay restorations.

SUMMARY

Statement of Problem: Extensive carious lesions and/or large preexisting restorations possibly contribute to crack formation, ultimately resulting in a fracture that may lead to the loss of a tooth cusp. Hence, preparation design strategy in conjunction

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with the restorative material selected could be influential in the occurrence of a cuspal fracture.

Purpose: The purpose of this *in vitro* study was to evaluate the fatigue behavior and fracture strength of maxillary premolars restored with direct composite and indirect ceramic inlays and overlays, with different preparation depths in the presence or absence of cuspal coverage, and analyze their failure types.

Methods and Materials: Sound maxillary premolars (N=90; n=10) were divided into nine groups: group C: control; group DCI3: direct composite inlay 3 mm; group DCI5: direct composite inlay 5 mm; group ICI3: indirect ceramic inlay 3 mm; group ICI5: indirect ceramic inlay 5 mm; group DCO3: direct composite overlay 3 mm; group DCO5: direct composite overlay 5 mm; group ICO3: indirect ceramic overlay 3 mm; group ICO5: indirect ceramic overlay 5 mm. In indirect ceramic, lithium disilicate restoration groups, immediate dentin sealing was applied. After restoration, all specimens were tested in fatigue (1,200,000 cycles, 50 N, 1.7 Hz). Samples were critically appraised, and the specimens without failure were subjected to a load to failure test. Failure types were classified and the data analyzed.

Results: Zero failures were observed in the fatigue testing. The following mean load to failure strengths (N) were recorded: group ICO5: 858 N; group DCI3: 829 N; group ICO3: 816 N; group C: 804 N; group ICI3: 681 N; group DCO5: 635 N; group DCI5: 528 N; group DCO3: 507 N; group ICI5: 482 N. Zero interaction was found between design-depth-material (*p*=0.468). However, significant interactions were found for the design-depth (*p*=0.012) and design-material (*p*=0.006). Within restorations at preparation depth of 3 mm, direct composite overlays obtained a significantly lower fracture strength in comparison to indirect ceramic onlays (*p*=0.013) and direct composite inlays (*p*=0.028). In restorations at depth 5 mm, significantly higher fracture load values were observed in indirect ceramic overlays compared with the inlays (*p*=0.018). Indirect ceramic overlays on 3 mm were significantly stronger than the deep inlays in ceramic (*p*=0.002) and tended to be stronger than the deep direct composite inlays. Severe, nonreparable fractures were observed with preparation depth of 5 mm within ceramic groups.

Conclusions: The preparation depth significantly affected the fracture strength of tooth when restored with either composite or ceramic materials. Upon deep cavity preparations, cuspal coverage proved to be beneficial when a glass ceramic was used as the restorative material. Upon shallow cavity preparations, a minimally invasive approach regarding preparation design used in conjunction with a direct composite material was favorable.

INTRODUCTION

Cracked and fractured teeth are common clinical challenges and presumed to be the third main cause of tooth loss.[1-3] Large restorations and extensive carious lesions can possibly lead to fracture and the loss of a cusp.[4,5] Regarding preparation design, no consensus exists on how to minimize cuspal fracture. Yet, a direct correlation is found between the amount of absent tooth tissue and fracture strength.[5] The width of the isthmus and depth of preparation affect the cuspal deflection, hence, the fracture strength.[6-8] To preserve tooth tissue, defect-oriented preparation should be performed.[9]

Restorations can be distinguished between inlays (no cusps covered), onlays (at least one cusp covered), and overlays (all cusps covered.[10] Placement of cuspal coverage restorations may be considered to prevent cuspal fracture.[11,12] However, recent studies have shown that indirectly restored molars and premolars with and without cuspal coverage have similar fracture resistance and failure types.[13-16] Some studies even conclude that ceramic onlays significantly decrease the fracture resistance of posterior teeth in comparison to inlays.[17,18]

Adhesive materials are advocated to reinforce weakened teeth resulting from their adhesive strength to enamel.[19] Adhesive procedures can alleviate the weakening effect of cavity preparation and minimize the harmful effect of cuspal deflection.[20,21] Fennis and others[22] published a randomized controlled trial considering the clinical success of cusp-replacing restorations. Direct composites tend to perform better than indirect composites as restorative material in cusp-replacing restorations.[22] However, direct composite restorations have their disadvantages as they are operator sensitive, subject to polymerization shrinkage, and prone to wear.[22] Recent meta-analyses reveal a promising long-term clinical performance for extensive resin composite restorations.[23,24] However, the differences between direct and indirect composite restorations did not reach statistical significance, and one technique could not be recommended over the other. Ceramic materials are presumably esthetically superior, biocompatible, more abrasion resistant, and more stable in color and have a similar thermal expansion to tooth enamel. However, these materials are brittle, time consuming, and more expensive than direct resin composite restorations.[25,26] Controversy exists on the influence of restorative systems on the fracture strength of teeth in posterior regions. Molars and premolars restored using ceramic restorations have the same fracture resistance as intact teeth under axial loading, whereas molars and premolars restored with composite have a lower fracture strength compared with ceramic inlays and intact teeth.[27-30] Some studies, however, have demonstrated that there was no significant difference in fracture strength between direct and indirect restorations.[31]

Regarding the preparation design, cuspal coverage seems to be the most controversial subject. While a high degree of macrostructural conformity exists between the gross form of the dentin and the overlying enamel, a significant exception is found at the localized enamel thickness on the buccal and lingual middle thirds of the anatomical crown, expressing a transitional sigmoid curve distribution.[32] The sigmoid curve distribution exists on the posterior cusps (maxillary/mandibular), being more extensive on the functional ones. By connecting the buccal and lingual inflection points circumferentially, the inflection plane is drawn (Figure 1).

So, there appears to be inconsistency in the literature when comparing direct and indirect restorations regarding their strength and elastic modulus of the tooth. Besides that, there seems to be no difference in fracture strength and survival of indirect and direct composite restorations. Therefore, the objectives of this study were to 1) compare the fracture strength of direct composite and indirect ceramic restored maxillary premolars, with different preparation depths in the presence and absence of cuspal coverage, and 2) analyze and compare the failure types. The following null hypotheses were tested: 1) the preparation depth has no influence on the fracture strength, 2) cuspal coverage will not affect the fracture strength, 3) the type of restorative material has no influence on the fracture strength, and 4) the preparation design and restorative material will not affect the failure type.

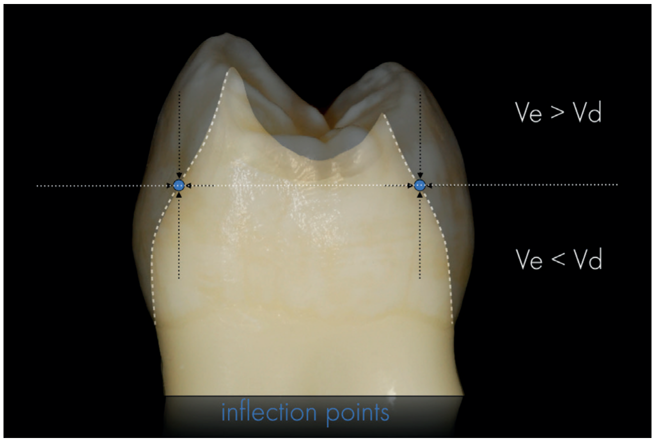

Figure 1. *Sigmoid curve distribution. By connecting the buccal and lingual inflection points circumferentially, one derives the inflection plane. Abbreviations: Ve, volume enamel; Vd, volume dentin.*

METHODS AND MATERIALS

The brands, types, main chemical compositions, manufacturers, and batch numbers of the materials used are listed in Table 1. A schematic description of the experimental design is presented in Figure 2. This study met regulations for institutional review board approval.

Specimen Selection and Randomization

Sound recently extracted human maxillary premolars (N=90), free of endodontic treatments, and cracks, were embedded up to 1 mm below the cementoenamel junction (CEJ) in polyvinylchloride tubes using autopolymerizing acrylic resin (ProBase Cold, Ivoclar Vivadent, Schaan, Liechenstein) and stored in distilled water at 18°C until preparation. The teeth were extracted on clinical indications and never for research purposes. Specimens were randomly divided into nine groups (n=10; see Table 2). Measured from highest cusp, restorations ended 1 mm above (3 mm deep) or 1 mm underneath (5 mm deep) the inflection plane.

Specimen Preparation

Prior to preparation, silicone putty impressions were made from each sample to obtain molds for the provisional restoration. Specimens of inlay groups received a MOD preparation (001-029 FG, Horico, Berlin, Germany), with a width of 3 mm. Box outlines were provided with a 0.5-mm bevel (Sonicflex Prep Ceram, KaVo Dental GmbH, Biberach, Germany) for composite restorations and a shoulder outline (Shoulder TPS 2-11, Komet Dental, Lemgo, Germany) for ceramic restorations. All surfaces were smoothed with a fine diamond bur (878EF.314.012, Komet Dental).

Samples of overlay groups first received a MOD preparation, followed by a complete cuspal reduction of both cusps by 2 mm. Preparation outline was finalized with a bevel of 0.5 mm for composite restorations. All internal angles and surfaces were smoothed. For preparation designs, see Figure 3.

Table 1: *Product Name, Type, Manufacturer, Compositions and Batch Numbers of the Materials Used for This Study*

Product Name	Type	Chemical Composition	Manufacturer	Batch Number
OptiBond FL	Adhesive resin	Prime: Hydroxyethyl methacrylate, glycerolphophate dimethacrylate, phathalic acid monoethyl methacrylate, ethanol, water, photo-initiator Adhesive: Triethylene glycol dimethacrylate, urethane dimethacrylate, glycerolphophate dimethacrylate, hydroxyethyl methacrylate, bis-phenol A glycol dimethacrylate, filler, photo initiator	Kerr	5254762 5375858
Filtek Supreme XTE A2 Enamel / A2 Dentin	Photo-polymerized composite resin	Bis-GMA, UDMA, TEGDMA, bis-EMA silica en zirconia particles	3M ESPE	N675829 N462125 N567639
Tetric EvoFlow A3	Photo-polymerized flowable resin	Bis-GMA, UDMA, ethoxylated bis-EMA, 16.8% barium glass filler, ytterbiumtrifluoride, mixed oxide 48.5%, prepolymers 34%, additives 0.4% catalysts and stabilizers 0.3%, pigments <0.1%	Ivoclar Vivadent	U14555
CoJet-Sand	Blasting particles	Aluminium trioxide particles coated with silica, particle size: 30 µm	3M ESPE	506649
IPS Ceramic Etching Gel	Etching agent	4.9% HF acid	Ivoclar Vivadent	T29351
Monobond Plus	One component primer	Ethanol, 3-trimethoxysilsyl propyl methacrylate, methacrylated phosphoric acid ester	Ivoclar Vivadent	T07775
ESPE-Sil	Silane coupling agent	Ethyl alcohol, methacryloxy propyl, trimethoxysilane	3M ESPE	533754
Enamel Plus HFO	Photo-polymerized microhybrid composite resin	Diurethan dimethacrylate, Bis-GMA), butandiol dimethacrylate, glass filler mean particle 0.7 µm; highly dispersed silicone dioxide mean particle 0.04 µm	Micerium	2014008412 2015007203
Shofu Vintage LD Press	Lithium disilicate glass ceramic	Lithium disilicate	Shofu Dental Corporation	021501

Abbreviations: bis-EMA, bisphenol A diglycidyl methacrylate ethoxylated; Bis-GMA, bisphenol-A-diglycidylether dimethacrylate; HF, hydrofluoric acid; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

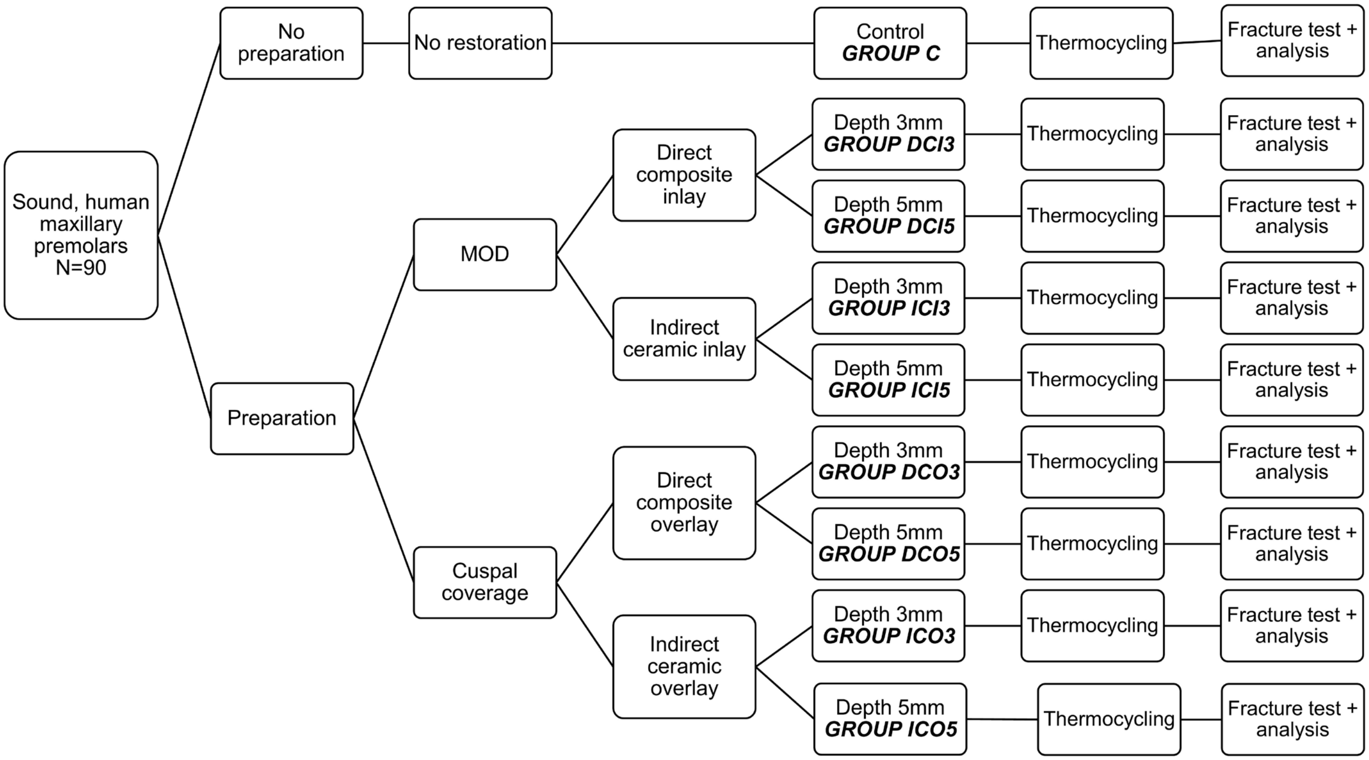

Figure 2. *Flowchart showing experimental sequence and allocation of groups.*

Direct Composite Restorations

After preparation, the restorative procedure involved etching enamel with 38% phosphoric acid (Topdent Etch gel, DAB dental, Sweden) for 30 seconds and dentin for 10 seconds, rinsing for 20 seconds and subsequent air-drying. Primer (OptiBond FL, Kerr, Orange, CA, USA) was actively applied for 20 seconds, followed by five seconds of air-drying. Adhesive resin (OptiBond FL, Kerr) was applied for 15 seconds, followed by 20 seconds of polymerization using a light emitting diode (LED) polymerization device (>1000 mW/cm^2, Bluephase, Ivoclar Vivadent). Composite (Filtek Supreme XTE, 3M ESPE, Seefeld, Germany) was applied in 3-4 layers (<2-mm thick), followed by 20 seconds of polymerization of each layer. After application of glycerin gel (K-Y, Johnson & Johnson, Sezanne, France), the surface was again polymerized for 40 seconds from three sides. Excess resin was removed, and margins were finished and polished using diamond burs (878EF.314.012, Komet Dental) and rubbers (Brownie, Shofu Dental Corporation, San Marcos, CA, USA).

Table 2: Description and Abbreviations of the Study Groups

Group	Abbreviation	Full Names
1	C	Control (no preparation or restoration)
2	DCI3	MOD preparation, direct composite inlay, 3 mm
3	DCI5	MOD preparation, direct composite inlay, 5 mm
4	ICI3	MOD preparation, indirect ceramic inlay, 3 mm
5	ICI5	MOD preparation, indirect ceramic inlay 5 mm
6	DCO3	Cuspal coverage preparation, direct composite overlay, 3 mm
7	DCO5	Cuspal coverage preparation, direct composite overlay, 5 mm
8	ICO3	Cuspal coverage preparation, indirect ceramic overlay, 3 mm
9	ICO5	Cuspal coverage preparation, indirect ceramic overlay, 5 mm

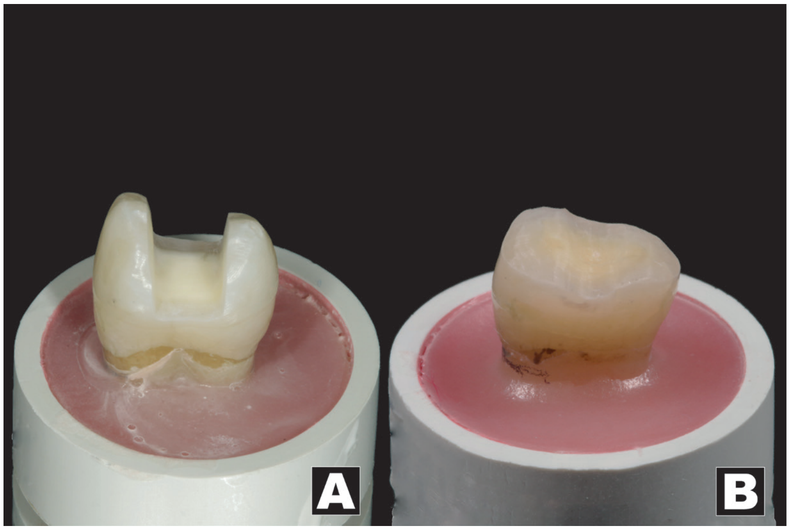

Figure 3. Preparation designs, 3 mm deep. (A): MOD preparation. (B): Cuspal coverage preparation.

Indirect Ceramic Restorations

Immediately after preparation, exposed dentin surfaces were treated applying the immediate dentin sealing (IDS) technique. The adhesive resin was applied as described above, and thereafter, a thin layer of flowable composite (Tetric Flow, Ivoclar Vivadent) was used to prevent undercuts, followed by 20 seconds of polymerization. After application of glycerin gel (K-Y, Johnson & Johnson), the surface was again polymerized for 40 seconds. Excess adhesive resin on the enamel outline was removed. A final impression (Aquasil, Dentsply, Milford, DE, USA) was made, and a provisional restoration was fabricated (Protemp 4, 3M ESPE) and cemented (Durelon, 3M ESPE). Afterward, samples were stored in water for another two weeks.

Pressed lithium disilicate ceramic restorations (Shofu Vintage LD Press, Shofu Dental Corporation) were fabricated by one dental technician and pressed in a ceramic oven (Programat EP5000, Ivoclar Vivadent), then glazed. Provisional restorations were removed using a scaler (SH6/H7 Hu-Friedy, Frankfurt am Main, Germany), and tooth surface was cleaned using pumice. The fit of the ceramic restorations was checked with a probe. The IDS layer was then silica coated (CoJet Sand, 3M ESPE) using an air-abrasion device (CoJet Prep, 3M ESPE) from a distance of 10 mm, angle of 45°, and 2-bar pressure until the surface became matte (one to two seconds). Enamel was etched with 38% phosphoric acid (Topdent Etch gel, DAB dental) for 30 seconds and rinsed. Silane (ESPE-Sil, 3M ESPE) was applied on the IDS layer and left to dry for 3 minutes. The ceramic restorations were etched for 20 seconds with 4.9% hydrofluoric acid (IPS ceramic etch, Ivoclar Vivadent) and rinsed in neutralizing water (IPS Ceramic neutralizing powder, Ivoclar Vivadent). Then, debris was removed with 38% phosphoric acid (Topdent Etch gel, DAB dental) for 30 seconds, followed by rinsing and ultrasonically cleaning (Emmi-4, Emag, Valkenswaard, the Netherlands) in distilled water for five minutes. Then, restorations were air-dried and silane-coupling agent was applied (Monobond Plus, Ivoclar Vivadent), which was subsequently heated at 100°C for 60 seconds (DI500, Coltene, Altstatten, Switzerland). Finally, adhesive resin (OptiBond FL, Kerr) was applied onto the restoration and tooth surface. Restorations were luted using heated (50°C, Ease-It composite heater, Rønvig Dental, Denmark) composite (Enamel Plus HFO, Micerium, Avegno, Italy); glycerin gel (K-Y, Johnson & Johnson) was applied at the margins of the restorations and polymerized for 40 seconds (>1000 mW/cm^2, Bluephase, Ivoclar Vivadent) at three sides. Excess cement was removed using scalers (SH6/H7 Hu-Friedy), scalpels, and EVA-system (Sirona Dental Systems GmbH, Bensheim, Germany); afterward, the margins were polished using rubber points (Shofu Dental Corporation).

Fatigue, Fracture Test, and Analysis

The specimens were fatigued in a chewing simulator (SD Mechatronik GmbH, Feldkirchen-Westerham, Germany) by mechanically loading (1,200,000 cycles, 50 N, 1.7 Hz) with a zirconia ball, which was positioned into the central fossa. During loading, the specimens were simultaneously thermocyclic aged for 8000 cycles between 5°C and 55°C in distilled water. After fatigue, samples were evaluated for cracks and fractures using 40x magnification (Wild M5A, Heerbrugg, Switzerland). Load-to-failure testing was performed in a Universal Testing Machine (MTS 810, MTS, Eden Prairie, USA). Specimens were mounted in a metal base at an angle of 45° and the stainless steel round indentor was applied (1 mm/min) to a stable location on the palatal cusp. The maximum load to failure (newtons) was recorded. Failure types were evaluated under magnification. Fractures above the CEJ were furthermore classified as reparable and those below the CEJ extending in the root as nonreparable.

Additionally, representative fractured specimens were analyzed using scanning electron microscopy (LyraTC, Tescan, Brno, Czech Republic). Specimens were first sputter-coated with a 3-nm-thick layer of gold (80%)/palladium (20%) (90s, 45mA; Balzers SCD 030, Balzers, Liechtenstein). Images were taken at 15 kV at a magnification of 32x to 27,000x.

Data analysis was performed using IBM SPSS Statistics 23 (SPSS Inc). Data were subjected to the test of homogeneity of variances (*p*=0.352). As the variances were equal in all groups, 3-way analysis of variance was applied to compare the groups, in combination with the dependent variable fracture strength and the various independent variables design, depth, and material. Interaction effects were further analyzed using the independent sample *t*-test for equality of means. Significance level was set on α=0.05 in all tests. Failure modes were analyzed by a χ^2 likelihood ratio as the assumptions for a χ^2test were violated.

RESULTS

All samples withstood the masticatory fatigue simulation, with no visible cracks found in the tooth or the restoration. Mean fracture strengths and standard deviations (N) are shown in Table 3. Figure 4 shows a boxplot of the fracture strengths. There was no three-way interaction found (*p*=0.468). Found interactions within the analysis of variance were as follows: design depth (*F*(1.72)=6.725; *p*=0.012) and design-material (*F*(1.72)=7.947; *p*=0.006). Subsequently independent sample *t*-tests were performed to further explore the interactions. Only ICI5 (*t*(18)=3.087; *p*=0.010) and DCO3 (*t*(18)=2.425; *p*=0.026) gave significantly less fracture strength in comparison with the control group. The deep indirect ceramic inlays on 5 mm obtained significantly lower fracture strengths in comparison with direct composite inlays on 3 mm (*t*(18)=2.938; *p*=0.009). Within restorations at preparation depth of 3 mm, direct composite overlays obtained a significantly lower fracture strength in comparison to indirect ceramic onlays (*t*(18)= -2.756; *p*=0.013) and direct composite inlays (*t*(18)=2.395; *p*=0.028). In restorations at a depth of 5 mm, significantly higher fracture load values were observed in indirect ceramic overlays compared with the inlays (*t*(18)=-2.807; *p*=0.018). When we compared the individual restorations at different depths, there were no significant differences, but the inlays (direct and indirect) show a strong tendency of lower fracture strengths in deeper preparations. Indirect ceramic overlays on 3 mm were significantly stronger than the deep inlays in ceramic (*t*(18)=-3.633; *p*=0.002) and tend to be stronger than the deep direct composite inlays. The indirect ceramic overlay on 5 mm was significantly stronger than the 3-mm direct composite overlay (*t*(18)=-2.364; *p*=0.030).

Representative fractured specimens are shown in Figure 5. Different failure types were seen among the groups (Figure 6). There was a statistically significant relationship between the type of restoration and the failure mode ($\chi_2(32)=152.243$; p<0.001). With

Table 3: *Fracture Strength Results (Newton) of Experimental Groups: Mean, Standard Deviation, Minimum, Maximum and Confidence Intervals (95%)*

Group	n	Mean	Standard Deviation	Minimum	Maximum	95% Confidence Interval for Mean	
						Lower Bound	**Upper Bound**
C	10	804	307	190	1158	584.7	1024.1
DCI3	10	829	353	438	1715	576.4	1081.2
DCI5	10	528	351	167	1469	277.2	779.8
ICI3	10	681	265	297	1152	490.8	870.5
ICI5	10	482	120	263	697	396.3	568.5
DCO3	10	507	236	156	868	338.2	676.3
DCO5	10	635	202	411	989	490.5	779.8
ICO3	10	816	265	408	1281	627.1	1005.8
ICO5	10	858	406	385	1619	567.9	1149.0

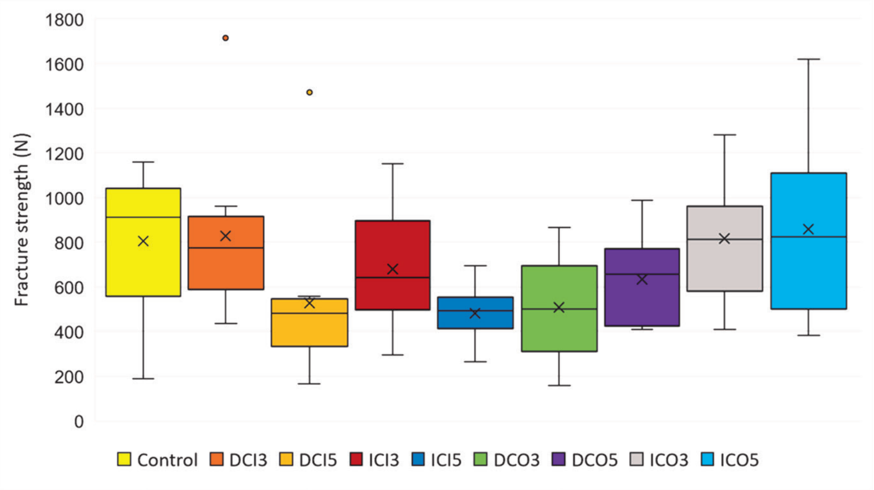

Figure 4. *Fracture strength of the groups. Abbreviations: x = mean; ° = outlier.*

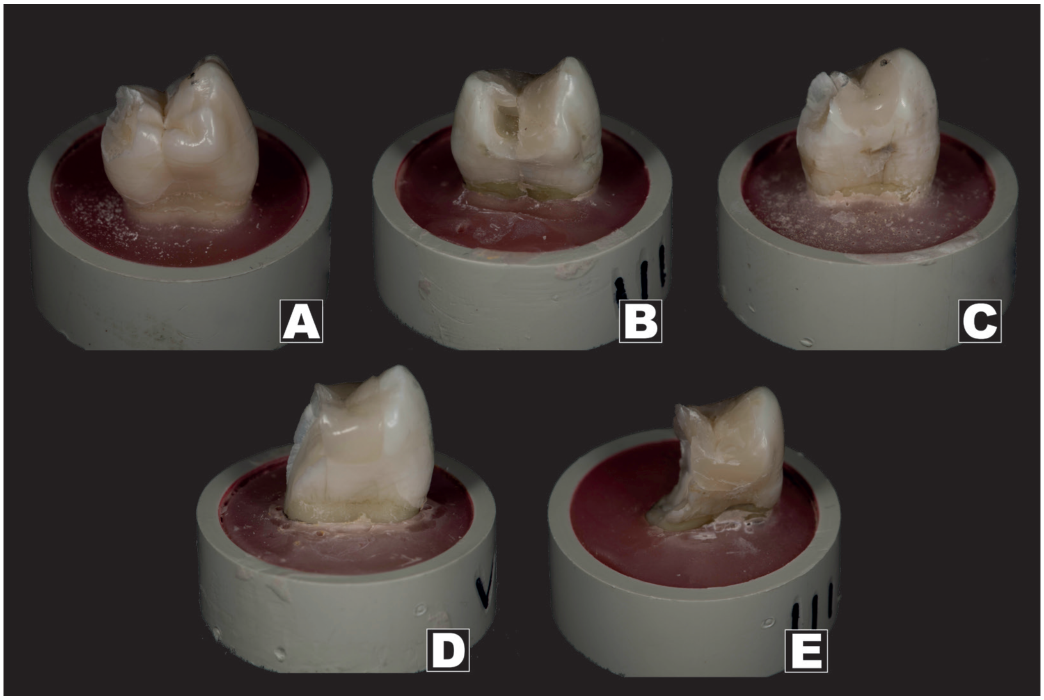

Figure 5. *Representative fractured specimens. (A): Type I: enamel fracture. (B): Type II: restoration fracture. (C): Type III: restoration and enamel fracture. (D): Type IV: restoration and dentin fracture. (E): Type V: rrown-root fracture.*

a Cramer V of 0.717, it was a moderately strong to strong relationship. Failure types in inlays with preparation a depth of 3 mm were predominantly fractures in restoration and enamel, whereas deeper inlays more often presented fracture of restoration and dentin. Regardless of the group, the greater part of the specimens were considered reparable, except for the ceramic overlays, where nonreparable crown-root fractures were seen.

A scanning electron microscopy image of a representative fractured specimen (Figure 7) showed that the resin composite-lithium disilicate link was broken. Together with the resin-dentin link, it's considered the weakest link of the adhesive interface.

DISCUSSION

The aim of this study was to compare fracture strength and failure types of direct and indirect restorations with

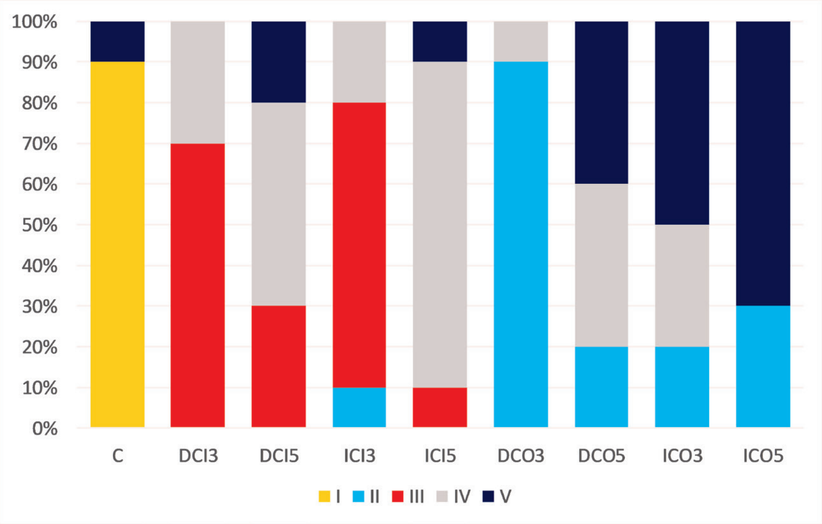

Figure 6. *Frequencies of failure modes by each group in percentages. Type I: enamel fracture; Type II: restoration fracture; Type III: restoration and enamel fracture; Type IV: restoration and dentin fracture; Type V: crown-root fracture.*

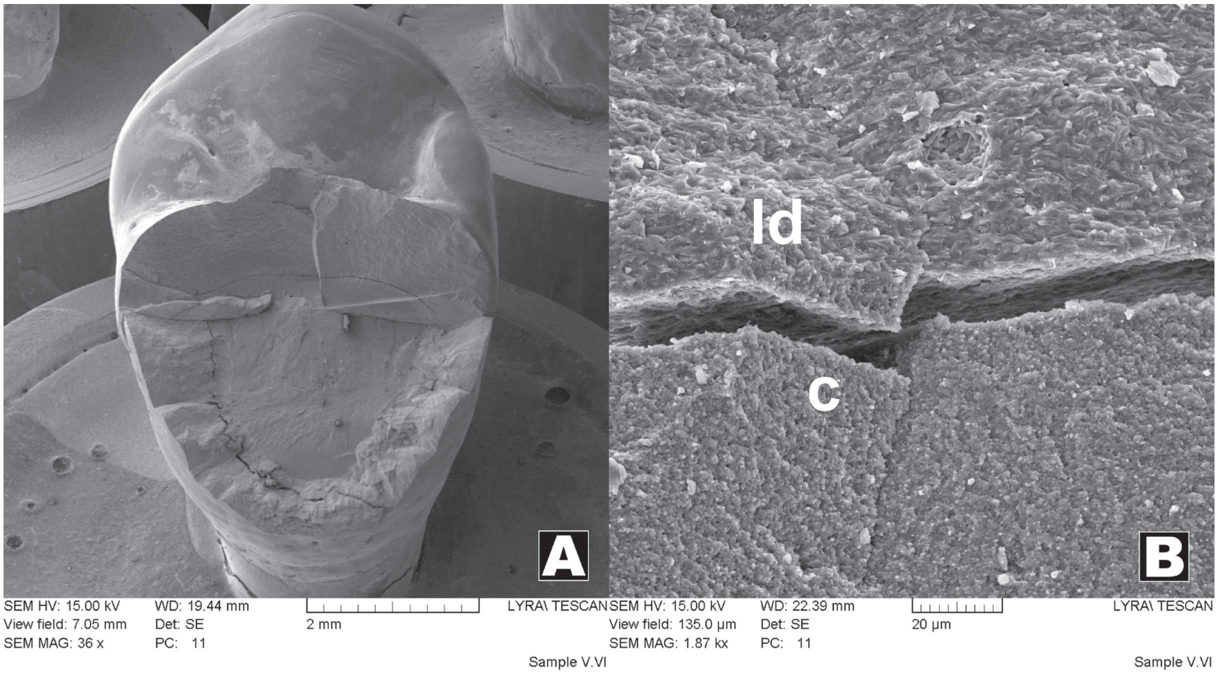

Figure 7. *Corresponding scanning electron microscope image of representative type IV failure (group ICI5). (A): Overview of restoration and dentin fracture (36x). (B): The image clearly shows a detachment of the resin composite cement from lithium disilicate ceramic (1.87kx). Abbreviations: c, resin composite cement; ld, lithium disilicate ceramic.*

different preparation depths in the presence or absence of cuspal coverage.

Since preparation depth has no influence on the fracture strength, the first null hypothesis could be accepted. There is, however, a strong tendency that 5-mm-deep indirect and direct inlays are weaker than 3-mm-deep inlays. Older studies report that preparation width and depth affect the cuspal deflection and thereby affects the fracture strength negatively.[8] However, recent studies have shown that indirectly restored molars and premolars with and without cuspal coverage have similar fracture resistance and failure types.[13-16]

The second null hypothesis, which states that cuspal coverage will not affect the fracture strength, could be partially rejected. Ceramic onlays on 5-mm depth are significantly stronger than their inlay counterparts. On the 3-mm direct composite groups, the inlays were, in contrast, stronger than the overlay group.

Most of the direct composite overlays on 3-mm depth gave a failure of the restoration, without failure of the tooth. Therefore, the composite material could have insufficient strength in these dimensions. When bulk was used (in 5-mm groups), this problem was not found. The reduced amount of cohesive failures in direct material of sufficient thickness was also found in other studies.[33]

The third null hypothesis, which states that the restorative material has no influence on fracture strength, could be partially rejected. The direct composite overlays on 3 mm obtained significantly less fracture strength than the indirect ceramic overlay on 3 mm. As stated before, direct composite in smaller dimensions is possibly weaker, as the indirect ceramic overlay on 3 mm is significantly stronger than direct composite and indirect ceramic inlays on 5 mm, ceramic tends to be a good cusp coverage material. The results obtained in this study were similar for the same materials in other studies.[27-30,34,35]

Considering failure modes, there was a significant interaction with the restoration type. In deeper preparations, more tooth substance was involved in the fracture, which led to more severe failure modes. This was seen in all groups but was very explicit in the indirect ceramic inlays. The 3-mm-deep inlays gave mostly fractures of the restoration and enamel, where 5-mm-deep inlays also gave fracture of dentin. Due to smaller dimensions, the composite material in 3-mm overlays tend to be weaker. Regardless of preparation depth, more severe, nonreparable crown-root fractures were seen in the ceramic overlays. Ceramic overlays achieved higher fracture strengths but gave more severe failure types. The same tendency is found in other studies.[18,33] In detail, the fractures occurred on the link between resin composite cement and dentin or lithium disilicate. Other studies also conclude that the link between dentin and resin composite could be considered as the weakest link.[36,37]

This study simulated the clinical situation by using fatigue prior load to failure testing. Nevertheless, there are several limitations, as there is a lot of variance in the fatigue procedure in between studies.[38] The influence of repetitive movements results in a different kind of distribution of the stress.[39,40] The samples in this study were loaded for 1,200,000 (1.7 Hz) times at 50 N and simultaneously thermocycled at a temperature varying between 5°C and 55°C (for 8000 cycles).[41,42] This corresponds to a clinical function of approximately five years.[40] The load capacity of 50 N is in consensus with the forces used during swallowing and mastication.[43-45] The number of loading cycles, 1,200,000, is based on the assumption that 250,000 cycles represent a clinical year in the oral cavity.[38,42] The thermal load simulates cold and hot substances in the oral cavity. A polished zirconia antagonist loaded the samples to mimic enamel-enamel contact wear.[39]

Another limitation is the loading during the load to failure test. This study loaded the palatal cusp at an angle of 45°. In many studies, samples are loaded perpendicular to the occlusal surface; this can lead to different fracture strength and failure types.[5,6,8,14-17,19,21,27,29,30] This axial loading may simulate the occlusal forces at which material characteristics like restoration thickness and elastic modulus may determine the survival of the restorative material; however, in a clinical situation, lateral movements and forces during chewing and other (para)functions always come along with these axial forces. In that respect, durability of restorations may also include durability under shear stresses and bending forces. Nevertheless, the load to failure fracture test is a good and widely used method for comparing fracture strengths.[46]

It could be questioned if the obtained study results would survive maximum bite forces. The mean maximum masticatory forces range from approximately 600 N for females to 900 N for males.[47] But chewing forces usually stay under 270 N.[47] The obtained fracture strength, between 482 and 858 N, are considerably higher than average chewing forces.

The preparation depth in this study is based on the inflection plane. This is found to halve the anatomic crown roughly in the middle, allocating volumetric dominant distributions. This gives a volumetric occlusal half of the coronal structure of the posterior teeth as enamel dominant in sharp contrast to the remaining cervical half, which is dentin dominant.[32] The relative amount of dentin and enamel could influence the fracture strength due to their difference in elastic modulus.[48] Deeper preparations remove more supporting dentin and thereby could lead to lower fracture strengths. Cuspal coverage could be needed to support the underlying tissue.

CONCLUSIONS

Within the limitations of this *in vitro* study, the following can be concluded:

1. Preparation depth did not influence the fracture strength significantly, but there is a strong tendency that 5-mm-deep indirect ceramic and direct resin composite inlays are weaker than 3-mm-deep inlays.
2. Different failure types were observed among the groups. More severe fractures occurred in 5-mm-

deep inlays as compared to 3-mm-deep inlays. Regardless of the preparation depth, more fatal, nonreparable crown-root fractures were seen in the ceramic complete cuspal coverage groups.

3. A beneficial effect of cuspal coverage could be observed at deeper cavity depth in which ceramic is the preferred restorative material of choice.
4. Minimally invasive preparation, without cuspal coverage, is advisable in case of shallow cavity depth. Thereby, direct composites are the preferred material.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the human subjects oversight committee guidelines and policies of University Medical Center Groningen. The approval code issued for this study is M20.246733.

Conflicts 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.

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