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Influence of Deep Margin Elevation and preparation design on the fracture strength of indirectly restored molars

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ABSTRACT

The objectives of this *in-vitro* study were to investigate the influence of Deep Margin Elevation (DME) and the preparation design (cusp coverage) on the fracture strength and repairability of CAD/CAM manufactured lithium disilicate (LS_2) restorations on molars.

Sound extracted human molars (n = 60) were randomly divided into 4 groups (n = 15) (inlay without DME (InoD); inlay with DME (IWD); onlay without DME (OnoD); onlay with DME (OnWD)). All samples were aged (1.2×10^6 cycles of 50N, 8000 cycles of 5–55 °C) followed by oblique static loading until fracture. Fracture strength was measured in Newton and the fracture analysis was performed using a (scanning electron) microscope. Data was statistically analyzed using two-way ANOVA and contingency tables.

DME did not affect the fracture strength of LS_2 restorations to a statistically significant level ($p = .15$). Onlays were stronger compared to inlays ($p = .00$). DME and preparation design did not interact ($p = .97$). However, onlays with DME were significantly stronger than inlays without DME ($p = .00$). More repairable fractures were observed among inlays ($p = .00$). Catastrophic, crown-root fractures were more prevalent in onlays ($p = .00$). DME did not influence repairability of fractures or fracture types to a statistically significant level ($p > .05$).

Within the limitations of this *in-vitro* study, DME did not statistical significantly affect the fracture strength, nor the fracture type or repairability of LS_2 restorations in molars. Cusp coverage did increase the fracture strength. However, oblique forces necessary to fracture both inlays and onlays, either with or without DME, by far exceeded the bite forces that can be expected under physiological clinical conditions. Hence, both inlays and onlays are likely to be fracture resistant during clinical service.

1. Introduction

An indirect ceramic restoration may be a good treatment alternative to restore large cavities (Mangani et al., 2015; Morimoto et al., 2016). Since the margins of large cavities often extend beyond the cemento-enamel junction (CEJ), isolation, impression taking, and the adhesive procedure itself may be a clinical challenge. Yet, these aspects are crucial to the durability of indirect adhesive restorations (Baader et al., 2016; Van den Breemer et al., 2019; Keys and Carson, 2017; Veneziani, 2010). Poor isolation may result in a suboptimal marginal seal, which in turn may lead to secondary decay and damage to periodontal tissues (Magne and Spreafico, 2012). Application of an Immediate Dentin Sealing (IDS) has the potential to increase the bond strength of indirect restorations to dentin and might therefore be useful in the indirect adhesive procedure (Magne et al., 2007).

Two clinical techniques can be used to facilitate isolation, impression taking and eventually cementation of the restoration. The first approach is to surgically relocate the gingival margin by performing a surgical crown-lengthening procedure (SCL). It remains a matter of debate whether SCL produces gingival rebound or re-establishes biological width (Al-Sowygh, 2019). Bone reduction is often necessary to provide adequate distance from the bone crest to the cervical margin of the

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restoration (Padbury et al., 2003). Since attachment loss is created, the crown to root ratio is compromised, and furcations and root concavities may become exposed (Magne and Spreafico, 2012).

The second approach, Deep Margin Elevation (DME), was introduced by Dietschi and Spreafico (1998), over 25 years ago. DME elevates the cervical margin of a subgingival preparation by using a composite material. Rubberdam isolation is well advised for a successful adhesive procedure (Browet and Gerdolle, 2017; Heintze et al., 2015; Keys and Carson, 2017; Magne and Spreafico, 2012). Luting of ceramic restorations directly to dentin leads to higher percentages of gap-free margins, when compared to bonding of indirect restorations to DME (92% vs. 84%) (Frankenberger et al., 2013).

Additional research needs to investigate the influence of DME on the fracture strength and fracture pattern of the tooth-restoration complex (Juloski et al., 2018), which is the innovative aspect of the present study. In one *in-vitro* study, the influence of DME on the fracture strength and the fracture pattern of endodontically treated molars was investigated (Ilgenstein et al., 2015). No significant difference was found between the fracture strength of groups restored with and without DME, independent of the used overlay material (Ilgenstein et al., 2015). Also, several materials were tested that served as DME without an apparent effect on the fracture strength (Grubbs et al., 2020). There is little clinical data available in the literature to support or discourage the use of DME in clinical practice. In a recent clinical evaluation, an overall survival rate of 97% for partial lithium disilicate (LS_2) restorations over a 12-year observation was reported (Bresser et al., 2019).

Whether to perform cusp coverage in preparation design is an ongoing debate. Cusp coverage is recommended to protect thin and weakened cusps (Kuijs et al., 2006). It also provides favorable distribution of stresses in teeth and it is presumed to reduce the risk of cuspal fracture (Mondelli et al., 1980). But, molars with and without cusp coverage show the same fracture resistance and fracture types at preparation depths of less than 3 mm (Cubas et al., 2011; Fonseca et al., 2007; Stappert et al., 2008).

The objectives of this *in-vitro* study are to investigate the influence of DME and the preparation design (cusp coverage) on the fracture strength and repairability of CAD/CAM manufactured restorations of LS_2 to restore molars. The hypotheses are that DME and preparation design do not have a major influence on the fracture strength of ceramic restorations. Furthermore, it is hypothesized that DME and preparation design do not impact the fracture type.

2. Material and methods

2.1. Description of the experimental groups

Sixty sound mandibular molars, free of caries lesions, restorations, root canal treatments and cracks were used. The roots of the molars were embedded in polymethylmethacrylate resin (PMMA) (Probase Cold, Ivoclar Vivadent, Schaan, Liechtenstein) as far as 3 mm apical of the CEJ. All samples were stored in water at room temperature and then randomly divided into four groups ($n = 15$): inlay without DME (InoD), inlay with DME (IWD), onlay without DME (OnoD) and onlay with DME (OnWD). Groups IWD and OnWD received a 2 mm composite layer (DME) on both sides (mesial and distal) ending at the CEJ. The preparation designs of the in- and onlay groups are shown in Fig. 1. A flowchart of the experimental design is shown in Fig. 2. The brands, types, main chemical compositions, manufacturers and batch numbers of the materials used in this study are listed in Table 1.

2.1.1. Tooth preparation

Prior to every preparation, each sample was scanned with an intraoral scanning device (Cerec Omnicam SW 4.3.1, Dentsply Sirona, Bensheim, Germany). In addition, silicone putty impressions of the samples were made (Provil novo, Kulzer, Tokyo, Japan) to provide them of a temporary restoration after preparation. The dimensions of each

A B

Fig. 1. Preparation designs. A) inlay preparation with DME. B) onlay preparation without DME.

preparation were drawn on the specimens using an electronic scale and marker to ensure accurately control the dimensions of the preparations. The inlay preparations (InoD and IWD) were made using a tapered diamond bur (Inlay TPS 2-12, Ref 4180, Komet, Lemgo, Germany). The depth of the isthmus preparation was 5 mm, measured from the highest cusp of the sample. The width of the isthmus preparation was 3 mm. The mesial and distal boxes were made using a long-tapered diamond bur (Chamfer TPS 2-9, Ref 4180, Komet, Lemgo, Germany), to create a sharp outline. The outlines of the boxes were located 2 mm below the CEJ and had an axial width of 2 mm. The apical width of the boxes was 3 mm, the occlusal width was 5 mm.

OnoD and OnWD also received a similar mesial-occlusal-distal (MOD) inlay preparation but an additional cusp coverage of 2 mm was provided using a cylindrical diamond bur (Komet Diamant FG 835.314.012, Komet, Lemgo, Germany).

The fresh prepared dentin surface of each sample was immediately sealed with an etch and rinse adhesive resin (Optibond FL, Kerr, CA, USA). The dentin was etched with 38% phosphoric acid (Ultra-Etch, Ultradent, South Jordan, USA) for 10 s, then rinsed thoroughly for 15 s and air dried. After this step, primer (Optibond FL Prime, CA, USA) was delicately brushed on the dentin for 15 s using a microbrush and air dried for 5 s. Following, Optibond FL Adhesive was lightly applied on the dentin for 15 s using a microbrush and probe and then light cured for 10 s using a Light Emitting Diode (LED) polymerization device (Bluephase 20i, Ivoclar Vivadent, Schaan, Liechtenstein), with an output of >1000 mW/cm^2 throughout the entire experiment. The IDS layer was covered using a thin layer of flowable composite (Essentia Hi-Flo, GC Europe, Tokyo, Japan) on top of the Optibond FL Adhesive. The surface was completely polymerized with the LED polymerization device for 40 s. This was repeated after applying glycerine gel (Panavia Oxyguard II, Kuraray Noritake, Okayama, Japan).

Additionally, IWD and OnWD were provided with a DME in both the mesial and distal boxes. A 2 mm thick layer of composite was placed in the boxes of the samples, that terminated at the CEJ. This layer was made using Essentia Universal composite (essential Universal Composite, GC Corporation, Tokyo, Japan) and composite instruments (LM Dental, Parainen, Finland).

2.1.2. Temporary restoration

Each sample was provided with a temporary restoration until the indirect restoration was adhesively bonded to mimic the clinical workflow. The silicone putty impression of the sound samples was used to fabricate the temporary restoration (Protemp 4, 3M ESPE, Seefeld, Germany). The temporary restoration was cemented using a carboxylate luting cement (Durelon, 3M ESPE, Seefeld, Germany). Excess luting cement was removed using a probe after an initial setting time of 3 min.

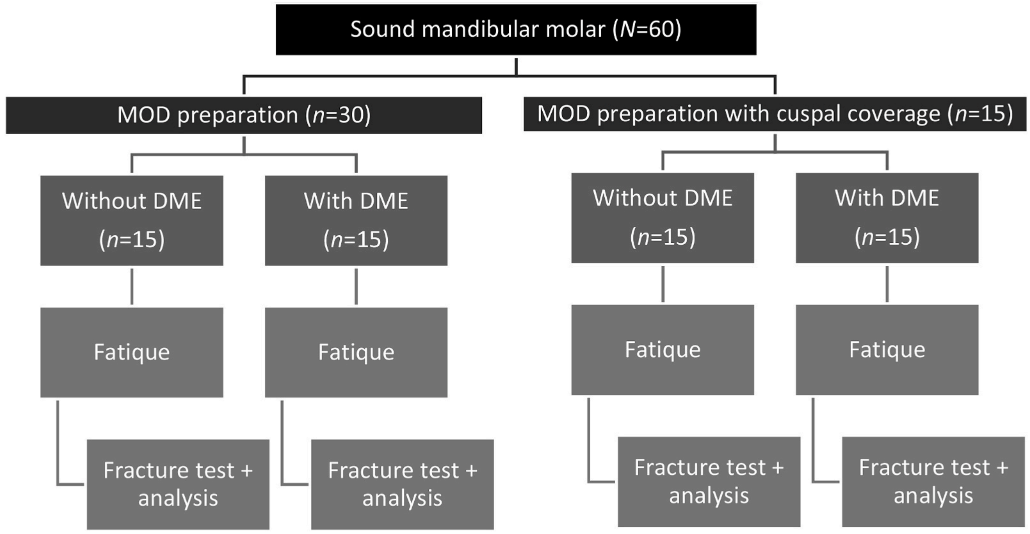


Fig. 2. Flow chart showing experimental sequence and allocation of groups.

Table 1
Overview of materials used in the study.

Brand	Type	Chemical composition	Manufacturer	Batch number
Ultra-Etch	Acid etchant	38% phosphoric-acid solution	Ultradent Products INC., South Jordan	W98974 X08880
OptiBond FL	Adhesive resin	Primer: 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, Orange, CA, USA	5,254,762 5375858
Essentia HiFlo Universal	Light-cured composite with high flowability	Isopropylidenedifenole, methylpropane acid, bismethylacrylate, dimethylmethacrylate, fomardehyde polymers, benzotriazolecresole, butylxylenole	GC Corporation, Tokyo, Japan	1706131
Essentia Universal composite	Light-cured radiopaque universal composite restorative	Urethane dimethacrylate, ytterbium trifluoride, bismethacrylate, isopropylidenediphenol, methylpropenoic acid, benzotriazolcresol	GC Corporation, Tokyo, Japan	170613
IPS e.max CAD Glaze Fluo	Dental ceramic	Glassceramic	Ivoclar Vivadent, Schaan, Liechtenstein	WZ1008
CoJet-Sand	Blasting particles	Aluminium trioxide particles coated with silica. Particle size: 30 μm	3M ESPE, Seefeld, Germany	3831868
Porcelain Etch	Buffered hydrofluoric acid gel	9% Hydrofluoric acid	Ultradent, South Jordan, USA	406/BFTKV
IPS Ceramic neutralizing powder	Acid neutraliser	Sodium carbonate	Ivoclar Vivadent, Schaan, Liechtenstein	R62013
Bis-Silane	Ethanol-based 2-part silane coupling agent	Part A: ethanol, propylmethylpropenoic acid Part B: ethanol, posphoric acid	Bisco, Schaumburg, USA	1800000494
Enamel Plus HFO UD2	Microhybrid, radiopaque light-curing composite	Butandioldimethacrylate, urethandimethacrylate, bis-GMA	Micerium, Avegno, Italy	2017009393
IPS e.max CAD	Lithium disilicate glass ceramic	$Li_2Si_2O_5$	Ivoclar Vivadent, Schaan, Liechtenstein	ref626408/ x35190 ref605329/ x35375

2.1.3. *Manufacturing of the indirect restoration*

All indirect restorations were manufactured using a Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) workflow. The samples were scanned prior and after preparation, using an intraoral scanning. The software designed indirect restorations based on the Biogeneric Copy function of the Cerec software due to that the prepared samples were restored in their original shape. The indirect restorations (IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein) were made using a milling machine (InLab MC XL, Dentsply Sirona, Bensheim, Germany). The indirect restorations were subsequently sintered by a dental technician at a temperature of 850 °C, glazed and finally fired at a temperature of 820 °C (Programat EP 5000, Ivoclar Vivadent, Schaan, Lichtenstein).

2.1.4. *Adhesive bonding of the indirect restoration*

Before adhesive luting of the indirect restorations, the temporary restorations were carefully removed using a scaler. The fit of the indirect restorations was checked using a probe and microscope (10x, OpmiPico Zeiss). All the carboxylate cement was removed using a scaler. Subsequently, the IDS and DME surfaces (if present) were silica coated (CoJet Sand, 3M ESPE, Seefeld, Germany) using a chair side air-abrasion devise (CoJet Prep, 3M ESPE, Seefeld, Germany) for 2-3 s. This was repeated until the entire IDS surface appeared dull. The surfaces were then thoroughly rinsed and air dried. The intaglio of the indirect restorations was etched for 60 s with 9% hydrofluoric acid (Porcelain Etch, Ultradent, South Jordan, USA) and rinsed in neutralizing water (IPS Ceramic neutralizing powder, Ivoclar Vivadent, Schaan, Liechtenstein). The restorations were cleaned from glass debris using 38% phosphoric acid (Ultra-Etch, Ultradent) for 60 s and ultrasonically cleaned (Bandelin Sonorex, Sigma-Aldrich, Berlin, Germany) in distilled water for 5 min, dried and silane coupling agent was applied (Bis-Silane, Bisco, Schaumburg, USA). The silane was then heated at 100 °C for 60 s in an oven (D.I.-500 Furnace, Coltène AG). The enamel surface of the samples was etched with 38% phosphoric-acid (Ultra-etch, Ultradent) for 30 s and subsequently rinsed for 15 s. Silane (BisSilane, Bisco) was applied to the IDS and to the DME-surfaces and dried for approximately 3 min, until the surface no longer appeared wet. Finally, adhesive resin (Optibond FL, Kerr) was applied onto the indirect restoration and the entire preparation surfaces. The indirect restorations were bonded using photopolymerizing composite resin cement (Enamel Plus HFO, Micerium, Avegno, Italy). Excess resin was removed using a probe and brushes. Glycerine gel was applied at the restoration margins (Panavia Oxyguard, II, Kuraray Noritake, Okayama, Japan) and polymerized for 40 s each side (Bluephase, Ivoclar Vivadent). Excess cement after polymerization was removed using a surgical knife and the EVA-system (Sirona Dental, Bensheim, Germany). The restoration margins were polished using ceramic polishers (Ceragloss yellow, Edenta, St. Gallen, Switzerland). After delivery, the specimens were again stored in water at room temperature (14 days).

2.1.5. Aging

To simulate the clinical situation as closely as possible, all samples were aged by thermal-mechanical loading (1.200.000 (1.7 Hz) at 50N, 8000x in 5 °C and 55 °C, dwell time of 30 s) (Chewing Simulator SD Mechatronik GmbH, Feldkirchen-Westerham, Germany). After ageing, all samples were visually assessed using a microscope (Wild M5Z).

2.2. Fracture test

The fracture strength of each specimen was measured with the Universal Testing Machine (MTS 810, Eden Prairie, USA), in random order. To mimic the clinical situation as close as possible, the samples were mounted in a metal base at an angle of 15° and the stainless-steel round load cell was applied to the cusps (Fig. 3). The maximum force until fracture (1 mm/1 min) of the sample was recorded. Additionally, each test was video recorded to check if the stress releasing point was equivalent to the moment the fracture took place.

2.3. Failure types

2.3.1. Classification

The types of fracture were classified using an optical microscope (Zeiss OpmiPico, Carl Zeiss, Jena, Germany) and digital photographs were taken from the specimens. The failure types were categorized as follows: enamel fracture, ceramic fracture, ceramic-enamel fracture, ceramic-dentin fracture or crown-root fracture. All fractures above the CEJ were classified as repairable, but below the CEJ as irreparable.

Fig. 3. Position of the load cell in relation to the occlusal surface in the universal testing machine (angle of 15°).

2.3.2. Scanning electron microscope (SEM)

To observe the structural changes, the most representative fractured specimens from each failure type were analyzed, using a cold field emission SEM (LyraTC, Tescan, Brno, Czech Republic). The surfaces were first sputter-coated with a 3 nm thick layer of gold (80%)/palladium (20%) (90s, 45 mA; Balzers SCD 030, Balzers, Liechtenstein). Images were taken at 15 kV at a magnification of 32x to 10.000x.

2.4. Statistical analysis

Bearing data from previous experiments at our department with the same test setup in mind, an a priori power analysis was conducted using G*Power3 (Faul et al., 2007). A two-way Analysis Of Variance (ANOVA) with 2 predictor variables (DME and preparation design) for determining the main effects of and the interaction between these two variables was foreseen. Given a medium effect size ($d = 0.50$) and an alpha of .05, the result showed that a total of 34 samples would be required to achieve a power of .80. As cyclic loading and thermocycling are known to have a considerable impact on the specimen (Sterzenbach et al., 2012), total sample size was set at 60 samples (15 per group), to compensate for samples that would not endure the full ageing process.

Boxplots present the data and visually inspect for outliers. Two mild outliers were observed, which were 1.5 times greater than the interquartile range (IQR) (Fig. 4). Data were subjected to the Levene's test of homogeneity of variances ($p = .88$). The Shapiro-Wilk test was conducted to test for normality, data of all groups were normally distributed ($p > .05$).

A two-way (ANOVA) was conducted, to investigate whether DME and preparation design had a main effect on the fracture strength. Additional custom hypothesis testing was performed to test the combined influence of preparation design and DME on the fracture strength of all 4 groups univariately.

The fracture types and repairability were analyzed using chi-square tests. Fishers exact tests were used when assumptions for chi-square were violated. Post-hoc tests were conducted if a variable significantly influenced fracture type or repairability. Bonferroni corrections were made to the p-values. A 2-tailed p-value $< .05$ was considered to be statistically significant in all tests. The data was analyzed using statistical software IBM SPSS Statistics version 26.

3. Results

All samples survived the ageing procedure. One sample showed wear of a cusp and another sample showed wear of the ceramic restoration (10x, OpmiPico, Zeiss). The raw data was collected and filed in accordance with the applicable guidelines and can be obtained on request.

DME did not statistical significantly influence the fracture strength (F (1,56) = 2.19, $p = .15$). However, onlays presented with higher fracture strengths compared to inlays (F (1,56) = 18.12, $p = .00$) (Fig. 4). No significant interaction effect was observed between DME and preparation design (F (1,56) = 0.002, $p = .97$). Additional custom hypothesis testing was performed to test the combined influence of preparation design and DME on the fracture strength. Onlays with DME were stronger compared to inlays without DME (F(3,56) = 6.77, $p = .001$).

Fractures were categorized by type and by repairability (Fig. 5, Table 2). InoD predominantly consisted of ceramic fractures (type II). IWD consisted of an equal number of ceramic fractures and of crown-root fractures (type II and V) (Fig. 6A–B). OnoD and OnWD presented with crown-root fractures (type V) (Figs. 6B and 7).

Preparation design statistical significantly influenced the repairability of the fractures ($\chi^2(1) = 22.5$, $p = .00$) and also on the fracture type ($\chi^2(3) = 22.67$, $p = .00$), but DME did not ($p > .05$). Bonferroni

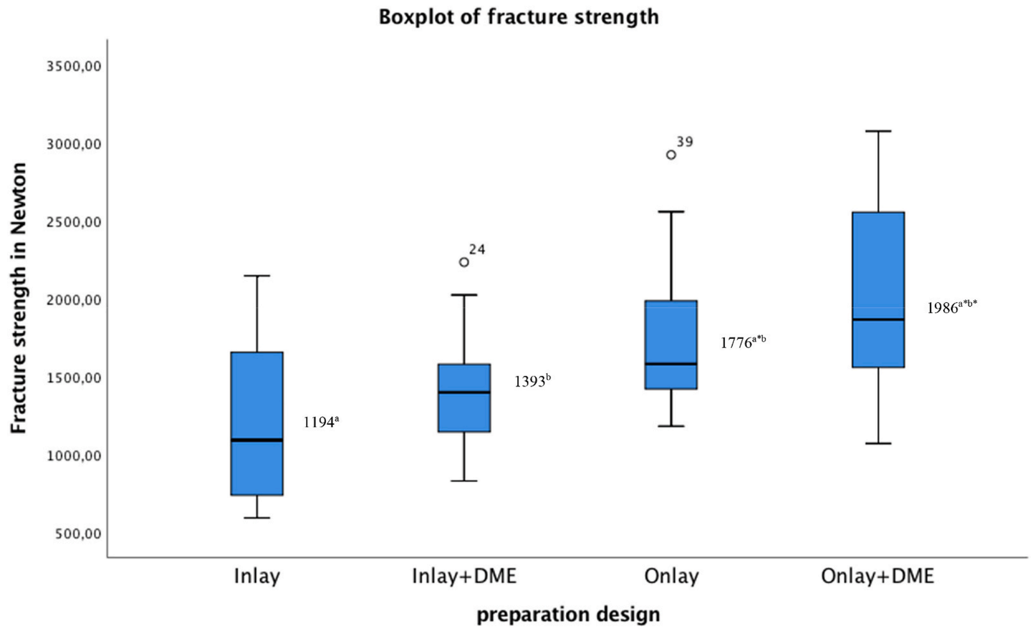


Fig. 4. Boxplots of preparation design and presentation of the marginal means in Newton. *$p < .05$.

Fig. 5. An overview of the different fracture types in each experimental group. Green: repairable; red: irreparable. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Fracture types and repairability categorized by preparation design and the presence.

Fracture type	1	2	3	4	5
N	2	16	6	0	36
Inlay *n (%)*	2 (100)	14 (87.5)	5 (83)	0	9 (25)
Onlay *n (%)*	0	2 (12.5)	1 (17)	0	27 (75)[a]
Repairability	**repairable**	**irreparable**			
N	24	36			
Inlay *n (%)*	21 (88)[b]	9 (25)			
Onlay *n (%)*	3 (13)	27 (75)[b]			

Type 1 = enamel fracture, type 2 = ceramic fracture, type 3 = ceramic-enamel fracture, type 4 = ceramic-dentin fracture, type 5 = crown-root fracture.
Bonferroni adjusted p-values [a] = $p < .0125$, [b] = $p < .00625$.

correction was applied to the p-values ($\alpha = 0.05/4 = 0.0125$) in order to investigate the influence of preparation design on the reparability of fractures by conducting post-hoc tests. Inlays fractured more frequently in a repairable manner compared to onlays (($\chi^2(1) = 22.47$, $p < .00$). A Bonferroni correction was also applied to the p-values ($0.05/8 = 0.00625$) to investigate the influence of preparation design on the fracture type. Crown-root fractures occurred more often in the onlay group (($\chi^2(3) = 22.47$, $p < .00$) (Table 2).

3.1. *Scanning Electron Microscopy*

A scanning Electron Microscopy (SEM) picture was chosen of a sample restored with an onlay and DME, to illustrate the different layers and interfaces that were present (Fig. 6). Furthermore, the interface between dentin and composite resin is shown in great detail (Fig. 6D).

4. Discussion

The objectives of this *in-vitro* study were to investigate how the restorative technique (Deep Margin Elevation, DME, or not) and the preparation design (cusp coverage or not), influenced the fracture strength and fracture pattern of CAD/CAM manufactured lithium disilicate restorations in mandibular molars. The combination of the objectives is innovative compared to other studies and distinguishes this paper from others.

The first null hypothesis that DME would not affect the fracture strength of ceramic restorations could not be rejected ($p = .15$), although the data tentatively suggest that restorations with and without DME do not differ considerably regarding their fracture strength. One earlier *in-vitro* study on the fracture strength of teeth restored in conjunction with DME is in concordance with these results (Ilgenstein et al., 2015). The strength of restorations with DME may be positively influenced by the shorter proximal extensions of the indirect restorations with DME. This facilitates full seating of the restoration to the preparation margin

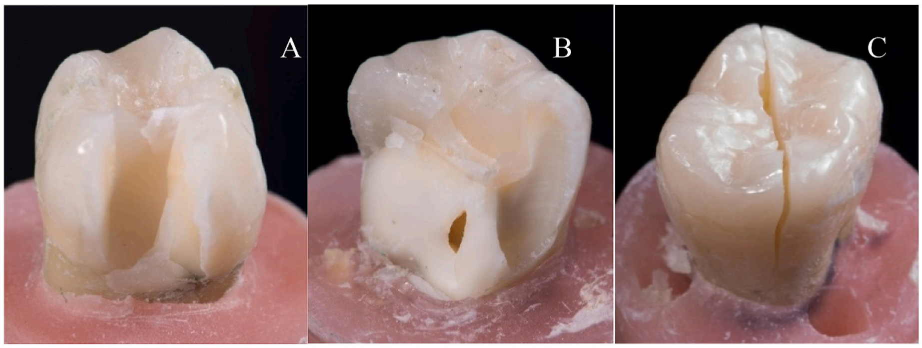
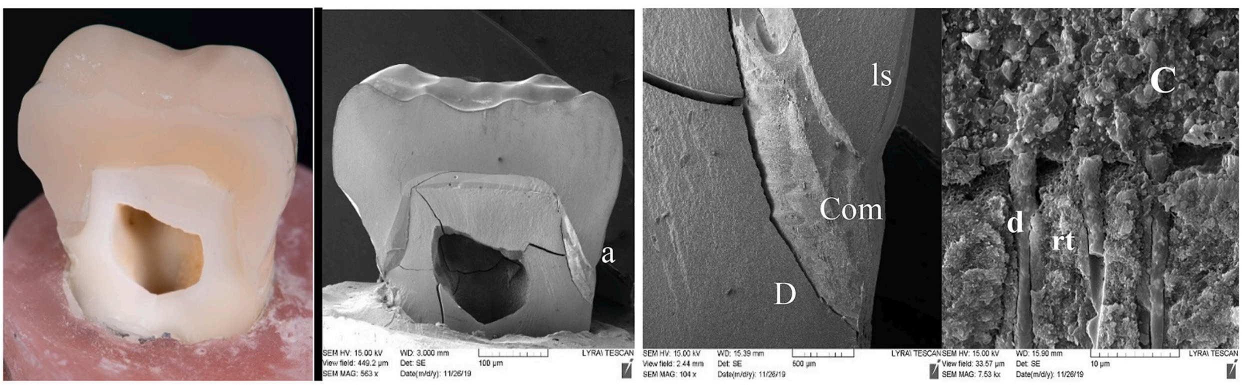


Fig. 6. Digital pictures of the most frequently shown fracture types. A) Ceramic fracture of a sample restored with an inlay and DME. B) Crown-root fracture of a sample restored with an inlay and DME. C) Crown-root fracture of a sample restored with an onlay without DME.



A B C D

Fig. 7. Picture and SEM pictures of a crown-root fracture, presented in a sample restored with an onlay and DME. A) Buccal view of the sample, with a clear view of the pulp chamber, the surrounding dentin and ceramic material. B) SEM overview of the sample presented in A), at a magnification of 563x. C) Detailed SEM picture (104x) of section a presented in B). Note the detachment of the adhesive resin from the dentin. (D = dentin, Comp = composite resin/DME layer, ls = lithium disilicate ceramic). D) A detailed SEM picture (7.53 kx) of the dentin-composite resin interface. The distinct resin tags in the dentin tubules are shown (comp = composite resin, d = dentin, rt = resin tags in the dentin tubules).

(Sandoval et al., 2015). A better marginal adaptation may serve to avoid tooth fracture by loading in the long term also (Krifka et al., 2009).

The preparation design did influence the fracture strength of ceramic restorations, as onlays were significantly stronger compared to inlays (p = .00). So, the second null hypothesis could be rejected. As for the inlays in the present study, essentially the interface was tested, due to the placement of the load cell. This could have contributed to a lower measured fracture strength compared to other studies where the load was directed axially (Cubas et al., 2011; Saridag et al., 2013; Stappert et al., 2008; Wafaie et al., 2018). After ageing, the samples were mounted in a metal base at an angle of 15° to mimic the clinical situation as closely as possible. The round, stainless steel load cell was placed in the fossa of the supporting buccal cusps. In other comparable studies, the load cell was placed perpendicular to the long axis of the buccal and lingual cusps and resulting force consisted only of a normal, perpendicular direction (Cubas et al., 2011; Habekost et al., 2006; Saridag et al., 2013; St-Georges et al., 2003; Wafaie et al., 2018). By altering the inclination of the load cell to 15°, the resulting force consists of a normal force and a torque force. This might explain why the inlay group presented with lower fracture strengths compared to the onlay group. However, one study reported contradicting results; lower fracture strength of ceramic onlays compared to ceramic inlays (Habekost et al., 2006). This result was attributed to a lower resilience of ceramics compared to natural tooth tissue, hence reducing the ability to absorb shocks and suffer deformations (Dalpino et al., 2002).

This *in-vitro* study contains some limitations. Some variation in fracture strength between specimen was noted. This could be explained by 2 factors. Surgically removed human molars were used and stored in tap-water. Some molars were extracted 6 months prior to the study, others just a few days before. Literature supports a drastic decrease in microhardness of extracted teeth when stored for longer than 2 months (Aydin et al., 2015). That being the case, the variation of fracture resistance and fracture types to some degree could be explained by this. Furthermore, all molars had slightly different dimensions, yet standardized preparations were performed to achieve equal dimensions of the indirect restorations. Consequently, the indirect restorations were supported by a slight fluctuation in volume of tooth structure. The samples were randomized into four groups to reduce the effect of both factors on the outcome of this study.

Inlays fractured significantly more often in a repairable manner compared to onlays. However, the (mean) fracture strength values under oblique loading (1194-1986 N) exceeded the reported voluntary maximum axial bite forces in dentate women and men (480-788 N), by far (De Abreu et al., 2014; Varga et al., 2011). Normal masticatory forces vary between 17 N and 450 N (Morneburg and Pröschel, 2002) and are lower compared to the voluntary maximum axial bite force (Varga et al., 2011). Patients with bruxism tend to produce involuntary forces up to 400-1100 N (Van der Bilt, 2011) which does not differ that much from 1194 N. However, reported *in-vitro* values are forthcoming from axial loading while chewing is composed of both axial and lateral movements and forces. Lateral physiological chewing forces are likely to be even lower than axial forces (Koolstra et al., 1988; Koolstra and van Eijden, 1992). Hence, both inlays and onlays are likely to be fracture resistant during physiological clinical service, and other aspects then fracture strength could be taken into account when deciding upon a particular preparation type.

More irreparable crown-root fractures were observed in comparison to literature (Ilgenstein et al., 2015; Saridag et al., 2013; Wafaie et al., 2018). Wafaie et al. did report catastrophic fractures, mostly in samples restored with inlays, but to a lesser extent (Wafaie et al., 2018). The cause of these fractures was assigned to the high tensile stress at the interface due to different stress and strain behaviors of dentin, ceramic and cement (Habekost et al., 2006). This could also be an explanation for the present catastrophic fractures, while the loadcell of the current study was also placed at the interface of the inlays. In the present study, ceramic fractures were mostly seen for the inlay group, complete fractures for the onlay group. This is in contradiction to some literature, where only a few crown-root fractures were observed for inlays and onlays (Ilgenstein et al., 2015; Saridag et al., 2013).

5. Conclusion

Oblique forces necessary to fracture both inlays and onlays, either with or without DME, by far exceeded the bite forces than can be expected under physiological clinical conditions. Hence, both inlays and onlays, with and without DME, are likely to be fracture resistant during clinical service.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

R.A. Bresser: Formal analysis, Writing - original draft, Visualization, Methodology, Conceptualization. **L. van de Geer:** Investigation, Methodology, Visualization, Writing - original draft, Conceptualization. **D. Gerdolle:** Conceptualization. **U. Schepke:** Investigation, Conceptualization. **M.S. Cune:** Writing - review & editing, Formal analysis, Supervision. **M.M.M. Gresnigt:** Resources, Methodology, Supervision, Conceptualization, Visualization, Investigation, Writing - review & editing, Funding acquisition.

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