Do composite resin restorations protect cracked teeth? An *in-vitro* study

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Key points

- Provides an understanding on how to treat cracked teeth.
- Points out the importance of being aware of the risks in using composite to strengthen teeth.
- Discusses the behaviour of inlays and onlays.

Aims To evaluate whether bonded resin composite restorations can effectively immobilise the tooth segments in teeth with a synthesised crack under loading, by exploring the impact of the restoration type (direct versus indirect composite resin) and restoration design (inlay versus onlay) on the fatigue resistance. **Methods** Sound human third molars underwent large mesio-occluso-distal preparations and a groove was cut to simulate a crack. Standardised procedures were adopted and measures were taken during teeth selection so that systematic error and methodology bias were minimised. The teeth were randomly assigned to four groups. The specimens were submitted to cyclic loading and loaded until fracture or to a maximum of 185,000 cycles. The failure mode was recorded. **Results** No failure was observed in 'direct' groups up to the 1000 N force. Survival analysis revealed statistically significant higher survival rates for 'direct' groups compared to 'indirect' groups ($\chi^2 = 11.352$, df = 1, p = 0.001) while there was no significant difference between 'inlay' and 'onlay' groups ($\chi^2 = 0.015$, df = 1, p = 0.901) (pooled data). **Conclusions** Within the limitations of this *in-vitro* study, it can be concluded that the direct composite resin restorations sufficiently protected the cracked teeth regardless of the cavity design. As there was no statistically significant difference in survival rates between inlays and onlays it is not possible to favour one design type over the other.

Introduction

Although teeth are remarkably resilient structures and are made to withstand a considerable degree of masticatory load (≥700 N), tooth failure from a mechanical perspective is not uncommon.[1,2] Incomplete fractures (ITFs) may present with no loss or visible separation of tooth structure on inspection, while an asymptomatic fracture line may be visible within enamel and must be detected incidentally.[3] If such fractures progress, they may lead to varying degrees of failure ranging from minimal enamel fracture, to fracture of a whole cusp, and to root fracture.[4] ITFs may become highly symptomatic causing pain on biting, which stops once pressure is withdrawn, thermal sensitivity to cold and discomfort to the patient.[5,6]

Once a cracked tooth is estimated to need treatment and is considered to be restorable, treatment should aim to immobilise the segments, to minimise their flexure and to prevent crack propagation and microleakage of bacterial toxins into the pulp.[5,7] As the cracks have the tendency to propagate, their prognosis is questionable. Treatment should provide optimum protection and although it cannot guarantee success, it can improve a cracked tooth's prognosis.

Many restorative protocols and techniques have been described according to the type, location and extent of the crack, and with a restoring fracture strength to varying degrees.[5,7] A restoration that encases the entire occlusal surface, providing adequate cuspal protection and extends circumferentially has been deemed to be the most protective treatment option to prevent propagation and ultimately fracture.[5,6,8] Nevertheless, more conservative options have been used to rehabilitate teeth with incomplete fractures.[9–11] Among them, composite resin restorations seem to provide a clinically effective treatment option for cracked teeth, by providing a form of internal splinting.[11–17]

The aim of the current study was to evaluate whether bonded resin composite restorations can effectively immobilise the tooth segments in teeth with a synthesised crack under loading, by exploring the impact of the restoration type and restoration design on the fatigue resistance.

The objectives of the study were to determine the influence of restoration type (direct versus indirect composite resin) and restoration design (inlay versus onlay) on the *in-vitro* fatigue resistance and failure mode of compromised teeth. The null hypothesis tested was that there is no influence of restoration type as well as preparation design on the fatigue resistance and failure mode of composite resin restorations.

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Material and methods

Sample selection

Sound human third mandibular molars, extracted for orthodontic reasons from patients who gave informed and signed consent, were collected. All teeth were scaled to remove residual desmodontal fibres and calculus and stored in 0.1% thymol solution.[18] Teeth were used within 6 months following extraction. As natural teeth present a wide range of shapes and sizes, from a pool of 112 third mandibular molars, 24 teeth of similar size and shape were selected to ensure homogeneity. The molars were examined under stereo microscope and checked to be free of existing cracks or defects.

Test specimen construction

A silicone impression of each tooth was made before any preparation was carried out. The selected teeth were mounted vertically in a cylindrical silicone matrix with freshly poured autopolymerising acrylic resin, embedding the root up to 2 mm below the cement-enamel junction (CEJ), which is roughly the level of alveolar bone in healthy teeth.[19] The roots of each tooth were covered with aluminium foil of 0.2 mm thickness, coated with petroleum jelly and positioned in the resin block until acrylic resin was fully cured. The aluminium foil was then replaced by polyvinylsiloxane material (Virtual Extra Light Body; Ivoclar Vivadent AG) rubber to simulate the periodontal ligament.[20]

The specimens were randomly assigned to one of the following groups, using a computer-generated random-number table:

- **Group DCI:** Direct bonded resin composite inlays
- **Group DCO**: Direct bonded resin composite onlays
- **Group ICI**: Indirect bonded resin composite inlays
- **Group ICO**: Indirect bonded resin composite onlays.

Cavity design and preparation

The specimens were prepared with a large mesio-occluso-distal (MOD) defect without proximal boxes. The buccolingual width of the MOD cavity was 4.5 mm (approximately one-half of the intercuspal width of the tooth) and the depth was 4.5 mm.[19,21] The interproximal gingival finish lines of the cavity were positioned 1.0 mm above the cemento-enamel junction.[21] For the onlay preparation, both the lingual and buccal cusps of the half of the specimens were further reduced by 2.0 mm.

Fig. 1 Inlay preparation

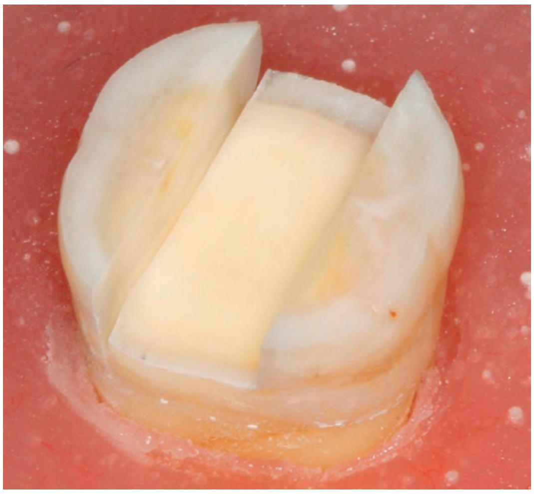

Fig. 2 Onlay preparation

Teeth were prepared in a 5-axis machining centre CNC (DECKEL_MAHO MH600C). A vertical 1 mm deep groove was created across the inner edge formed by the lingual wall and floor of the isthmus (Figs 1 and 2), using a 0.15 mm-thick diamond disc (911H.104.180; Komet Dental). The grooves were created using a 3-axis CNC milling machine (Lilian, controller Heidenhein 530i TNC). The tooth was mounted on an articulated support in order to ensure its accurate placement by the aim of a reference plate. In this way, the path of the cutting disc was achieved and the groove geometry was reproducible for all samples.

Direct composite resin restoration

Teeth belonging to the Groups DCI and DCO were etched, thoroughly rinsed with water spray and dried. Adhesive (Adhese Universal, Ivoclar Vivadent AG) was applied meticulously, according to the manufacturer's recommendations, and light-curing was carried out. A flowable composite (Tetric Evoflow) was used to cover the groove and the cavity was filled with direct composite resin (Tetric EvoCeram), using the incremental technique concept to minimise polymerisation shrinkage stresses.[22]

For standardixation purposes, all restorations should have the same occlusal anatomy. Thus, a stamp was created to shape the occlusal surface of the resin before curing. A sound mandibular third molar with ideal occlusal morphology was used as a template.

Indirect composite resin restoration

Immediate Dentin Sealing procedure[22–24] was adopted immediately after tooth preparation. The dentine bonding agent was applied according to the manufacturer's instructions. Flowable composite resin was used to block the groove. In order for the oxygen-inhibition layer to be eliminated, an air barrier coating (Liquid Strip; Ivoclar Vivadent AG) was applied, followed by 10 seconds of additional

Table 1 Failure of specimens under cyclic loading							
Force	**100 N**	**200 N**	**300 N**	**400 N**	**600 N**	**800 N**	**1000 N**
Total cycles	**5000**	**35000**	**65000**	**95000**	**125000**	**155000**	**185000**
Group DCI	No failure	No failure	No failure	No failure	No failure	No failure	No failure
Group DCO	No failure	No failure	No failure	No failure	No failure	No failure	No failure
Group ICI	No failure	No failure	No failure	No failure	**1 failure**	**1 failure**	**2 failures**
Group ICO	No failure	No failure	No failure	No failure	No failure	**1 failure**	**3 failures**

curing light exposure. The water-soluble air barrier coating was removed by abundant water rinsing and air. The enamel margins were re-finished with a diamond bur.

Fine detail impression of the cavity was created using light body and heavy body addition-reaction silicones (Virtual Light and Virtual Heavy Body; Ivoclar Vivadent AG). Working dies were produced using Type IV Dental Die Stone, within 24 hours of recording the impression. The composite resin inlays and onlays were fabricated by one technician employing a standardised technique. An indirect composite resin system (SR Nexco Paste; Ivoclar Vivadent AG) was used according to manufacturer's recommendations. The marginal fit of the restoration was examined on the die and the tooth. Any restoration considered unsatisfactory was rejected and remade.

Pre-treatment procedures of the restoration and the preparation took place. The internal surface of the composite inlays and onlays was sandblasted with 80–100 μm Al_2O_3 particles at 1 bar/15 psi, thoroughly rinsed with water spray, dried and then Monobond Plus (Ivoclar Vivadent AG) was applied. Enamel was etched, thoroughly rinsed with water spray and dried. Adhese Universal was then scrubbed into the tooth surface and light-cured. The indirect restorations were inserted into the cavity and fixed in place, using light-curing resin composite (Variolink Esthetic DC; Ivoclar Vivadent AG), according to manufacturer's instructions.

Following the adhesive restoration placement, each specimen was stored in distilled water at ambient temperature for at least 24 hours,[23] to allow for any postcuring of the luting agent that might have occurred. Care was taken to prevent the dehydration of the specimens while teeth were kept moist throughout testing.

Test conditions

Fatigue test

Cyclic load was applied to the specimens, using a closed-loop controlled servohydraulic machine (INSTRON 8801) which simulated masticatory forces. The chewing cycle was replicated by isometric contraction (load control) applied through a ceramic sphere with 6 mm diameter. The sphere was in tripod contact with the cusps of the standardised occlusal anatomy.[25] The load chamber was filled with distilled water at ambient temperature to submerge each specimen during testing.[18,25]

A baseline preload of 50 N was applied to ensure stability of the servohydraulic testing machine and continuous contact between the restored tooth and the load sphere.[19] Cyclic load was applied at a frequency of 5 Hz, starting with a warm-up load of 100 N for 5,000 cycles (preconditioning stage) followed by stages of 200, 300, 400, 600, 800, 1000 N at a maximum of 30,000 cycles each (staircase loading). Specimens were loaded until fracture or to a maximum of 185,000 cycles. The loading protocol adopted was modified from Fennis *et al.*,[26] Kuijs *et al.*[27] and Magne *et al.*[25] The fracture load was determined by the load step at which the machine stopped and the number of endured cycles was recorded.

Failure behaviour

The failure mode was recorded. Following a two-examiner agreement under stereo microscope (OLYMPUS SZX9/camera OLYMPUS DP50), a distinction was made between fractures above or below the CEJ or for cohesive fracture (within the restoration) or fracture at the interface (adhesive fracture).[21]

Statistical analysis

After collecting the data from the cycling loading procedure, the fatigue resistance of the four groups was compared by applying the product limit method of Kaplan and Meier.[28] The number of specimens starting each load stage intact and the number of specimens fracturing during this stage were counted. Survival curves were obtained and compared on the basis of the Log-Rank Test at a significance level of 0.05. *Post hoc* comparisons were performed using the Log-Rank Test. Additional comparisons were performed by pooling the data according to the restoration design (inlay versus onlay) and according to the restoration type (direct versus indirect). The analyses were performed with the statistical software IBM SPSS Statistics v19 statistical software.

Results

Fatigue test

The fatigue test was performed using a servohydraulic fatigue testing machine (INSTRON 8801) equipped with a digital controlling system capable of monitoring the test process and recording the measuring data (number of cycles, load, displacement). After collecting the data, it was found that all the specimens belonging to Group DCI and Group DCO withstood the 185,000 loading cycles up to the 1000 N force. One specimen from the Group ICI failed prior the completion of 125,000 cycles at the load step of 600 N while two more (one from Group ICI and one from Group ICO) failed prior the completion of 155,000 cycles (800 N load step). Five more failures occurred at the loading step of 1000 N prior the completion of 185,000 cycles; two fractures in Group ICI and three in Group ICO (Table 1).

The survival rate was 33.3% for the Group ICI and 33.3% for the Group ICO.

There was statistically significant difference among the four survival curves ($\chi^2 = 11.518$, df = 3, p = 0.009). Detailed *post hoc* tests revealed significantly higher survival rates for Group DCI and Group DCO compared to Group ICI ($\chi^2 = 5.453$, df = 1, p = 0.020) and Group ICO ($\chi^2 = 5.401$, df = 1, p = 0.020). There was not statistically significant difference between Group ICI and Group ICO (Table 2). No comparison was made between survival rates in Group DCI and in Group DCO because they had exactly the same results.

Additional comparisons by pooling the data by restoration type revealed statistically significant higher survival rates for direct groups compared to indirect groups ($\chi^2 = 11.352$, df = 1, p = 0.001). There was no fracture in

Table 2 Post hoc comparisons using Log-Rank Test at a significance level of 0.05

	Group DCI	Group DCO	Group ICI	Group ICO
DCI	–			
DCO		–		
ICI	χ^2 = 5.453, df = 1, p=0.020	χ^2 = 5.453, df = 1, p = 0.020	–	
ICO	χ^2 = 5.401, df = 1, p = 0.020	χ^2 = 5.401, df = 1, p = 0.020	χ^2 = 0.103, df = 1, p = 0.748	–

Table 3 Types and number of failure modes

	Intact	Minimal tooth fracture	Less than half of restoration lost	Severe fracture of tooth & restoration
DCI	6	0	0	0
DCO	6	0	0	0
ICI	2	1	0	3
ICO	2	0	1	3

direct groups. The survival rate for indirect groups was 33.3% and the fractures occurred at a median load of 1000 N.

There was no significant difference between inlay and onlay groups (χ^2 = 0.015, df = 1, p = 0.901) by pooling the data by restoration design. The survival rate for the inlay groups was 66.7% and the fractures occurred at a median load of 900 N, whereas, the survival rate for the onlay groups was 66.7% and the fractures occurred at a median load of 1000 N.

Failure behaviour

The type of fractures was recorded (Table 3). No failure was observed in Group DCI and Group DCO. One specimen belonging in Group ICI presented a minimal tooth fracture that considered restorable as it was located above the CEJ (Fig. 3). In another specimen belonging in Group ICO less than half of the restoration was lost while the failure was located above the CEJ (Fig. 4). Six specimens (three from Group ICI and three from Group ICO) presented cohesive fracture (within the composite resin restoration) that was extended below the CEJ (Fig. 5).

Discussion

Microcracks being developed at the interface between the restoration and the surrounding dental tissues have multifactorial origins. Large preparations under repeated functional occlusal loading as well as harmful stress concentrations may control the cuspal flexure, violate the elastic limits of the tooth and predispose it to cracks or fracture.[18] Clinically, such incomplete tooth fractures become visible in the dentine at the base of the involved cusp after the existing restoration's removal.[15]

Among the suggested treatment modalities, direct and indirect bonded resin composite restorations have been considered effective as they accomplish an 'internal splinting' for the stabilisation of the two fracture sites.[12,15,17] Tooth structure is preserved and at the same time the biomechanical, structural, and aesthetic integrity of teeth is restored. However, some authors have questioned the ability of composite resin restorations to strengthen the weakened, cracked teeth with wide preparations and therefore they have recommended treatment with full coverage crowns.[5,6,8]

The current study presents a unique design of molars with a synthesised crack, restored with direct or indirect inlays or onlays, subjected to cycling loading. Despite the considerable time required for fabrication of each specimen, standardised procedures were adopted to obtain comparable specimens: positioning of the teeth using a specially designed fixture, preparations using a 5-axis machining centre, groove formation using a 3-axis CNC milling machine, and restorations using a mould from the occlusal anatomy of an original sound mandibular molar. However, natural variations in tooth morphology and discrepancies in the remaining tooth tissue thickness could not be regulated. Thus, measures were taken during teeth selection to keep such variation to a minimum. Moreover, the confounding variables were minimised by generating standardised restoration shape, size, and occlusal anatomy.

The simulation of the periodontal ligament was achieved by means of a layer of silicone rubber surrounding the root while the adjacent epoxy resin imitated the alveolar bone.[20] These artificial materials and the natural tissues that they simulate, operate correspondingly in transmitting stress since their elastic modulus is similar.[29] The silicone films in the current study presented accelerated degradation but this incident did not destabilise the servohydraulic control system. The accelerated degradation was the reason previous studies omitted the periodontal ligament simulation.[21,25]

The fatigue load protocol adopted attempted to imitate clinical conditions. According to Kuijs *et al.*,[27] the low loads at the start and high loads at the end was considered to be a good conciliation between the available *in-vitro* testing methods and a clinical representative situation. It has been documented that the restored posterior molar must withstand cyclic loads ranging from 60 to 200 N during mastication while the maximum occlusal force during clenching or bruxism can reach 500–800 N.[30] Higher loads can be recorded when individuals masticate a hard item accidentally or in case of trauma.[21] Certainly, neither the *in-vitro* cycling loading nor these absolute data can be transferred directly to the *in-vivo* situation. The testing method adopted was time consuming as testing of multiple specimens was not feasible and the fatigue test duration for each specimen was one day.[25]

A parameter that could influence the fatigue resistance of the specimens was the material used to simulate the antagonistic cusp. In former studies either metal or composite resin spheres were used for this purpose.[21,31]. From a biomechanical perspective, porcelain is the most 'enamel-like' material. A ceramic sphere with 6 mm diameter was used to provide the best combination of moment of force and lateral component of deformation.[32]

In this study, there was no statistically significant difference between inlay and onlay groups (by pooling data by cavity design) regarding their effect on the fatigue resistance, indicating that the adhesive restorations can be successful in the definitive restoration of cracked teeth, regardless of the cuspal coverage. This finding was in accordance with the results of a six-month clinical evaluation[15] as well as the results of a 4- to 6-year retrospective clinical study.[12] Both clinical studies highlighted that the bonding between the cracked tooth structure and the restoration may not be strong enough to withstand the forces applied on functionally loaded teeth in the long term.[12,15] Additionally, the cuspal overlap approach required additional removal of sound dental tissue and when these teeth fractured under load, they presented more frequently unrepairable fractures;[26] a finding that was also confirmed by the current study.

There was no adhesive failure in the specimens treated with direct composite resin restorations regardless of the cavity design (Group DCI and Group DCO); a result that adds to the benefits of less invasiveness and lower cost that direct composite restorations have over the indirect restorations. One might expect the indirect type to preform in a better way compared to direct type as laboratory-processed composites have been proved to have improved mechanical properties *in vitro*.[33] However, in the current study the direct restorations significantly increased the fatigue resistance of the cracked specimens when compared to the indirect restorations (pooled data). The fatigue threshold may be affected by various factors, like the composition, the inherent microstructure and extrinsic toughening mechanisms.[34] The nano-hybrid composite used contained an optimum blend of different fillers and filler sizes (82–83% weight) with particle size ranging from 40 nm to 3,000 nm (mean particle size of 550 nm). The light-curing lab composite used, contained microopal fillers (64–65% by weight, 46–47% by volume) with particle size ranging from 10 to 100 nm. The inorganic filler content and morphology has been considered to have a significant influence on the composite's flexural strength and modulus, and modulus of elasticity.[35,36] It has been argued that the fracture toughness is improved when the filler content exceeds 65% by volume[37] providing an explanation for the improved performance of the direct composite. Flexural strength is a critical physical property for brittle materials while the rigidity of the material is described with the modulus of elasticity.[36] The nano-hybrid composite used has been recorded as having a flexural strength of 120 MPa and a flexural modulus of 10,000 MPa. The lab composite used has been recorded as having a flexural strength of 90 ±10 MPa and modulus of elasticity of 6,500 ± 500 MPa. Composite resins are compliant materials and tend to distribute the stress by deformation and materials with lower elastic modulus allow more absorption of functional stresses.[32] Therefore, more loads were absorbed within the direct system than indirect composites where failures of the restoration and the compromised underlying tooth structure occurred.

The performance of indirect composite restorations could have been affected by both the surface treatment before bonding and the

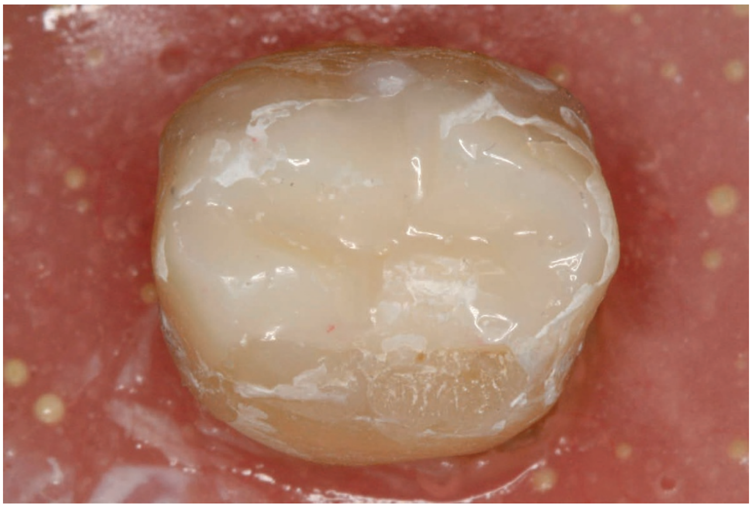

Fig. 3 Inlay with indirect composite restoration that suffered a restorable fracture (above the CEJ)

Fig. 4 Onlay with indirect composite restoration that suffered a restorable fracture (less than half of the restoration is lost)

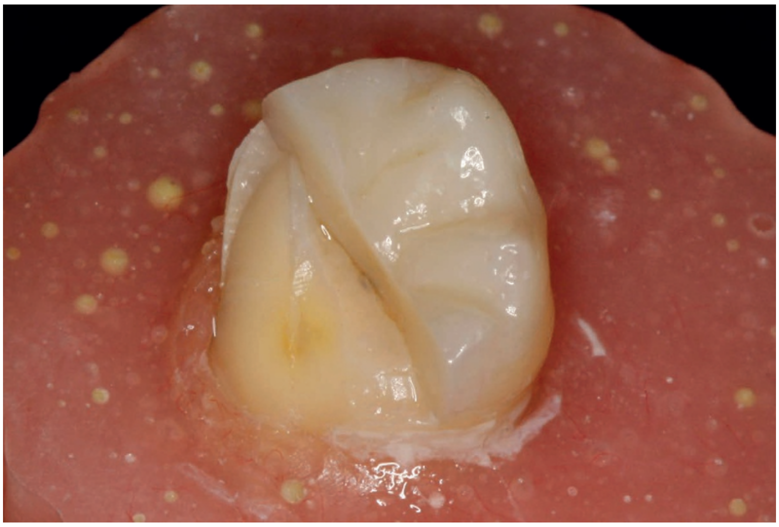

Fig. 5 Severe fracture of tooth and restoration (non-restorable)

bonding of the luting agent to the tooth and the restorative material. The surface treatment should ensure a strong enamel bond; if the enamel is not re-prepared after performing the immediate dental sealing (IDS) step then the adhesive can interfere with the ability to etch the enamel adequately at the placement, leading to a weaker bond predisposing the restoration to breakage. The transfer of the loads through the restoration-tooth complex was different due to the interference of the thicker cement layer in the indirect restorations compared to the bonding layer in direct systems.[23] Characteristics of this interface zone, such as the elastic behaviour of the constituents, the thickness of the cement layer and the degree of interaction,[38] may have significantly affected the fracture resistance outcome. Also, the exactness in following an adhesive technique can be a variable among clinicians.

In all the tested groups, no failures occurred at the 'fracture' line. The most frequent fracture mode that appeared in the specimens restored with indirect composites involved the compromised cusp and part of the restoration. These cohesive failures revealed that the bond between the tooth and the restoration was strong enough to withstand the load. In the single case where the fracture involved a part of the compromised cusp, the bond between the tooth and the restoration was the weakest link. The fracture location is directly associated with the clinical prognosis of the tooth after the restoration's failure.[26,27] The cases where the fracture line is below the CEJ are more difficult or impossible to be restored. Most failures were located below the CEJ.

The limitations of this study cannot be ignored. The experimental method used was an attempt to simulate the conditions under which cracked teeth function in the oral environment but it was far from the multidimensional clinical reality. Extracted teeth tested *in vitro* may not behave like teeth *in vivo* and the natural cracks may behave differently to the synthesised cracks. Also, the current study only simulated the vertical vector of the mastication process while during physiological function teeth are additionally loaded with a horizontal component, parallel to the masticating surface.[39] Moreover, the sample size was small, undermining the reliability of the results. Nevertheless, standardised procedures were adopted and measures were taken during teeth selection and randomisation so that systematic error and methodology bias to be minimised.

Therefore, clinical extrapolation of these experimental results must be done with caution. Ideally, further research should direct in developing test methods to mimic more closely the actual masticatory function.

Conclusions

The null hypothesis that there was no influence of cavity design and restoration type on the fatigue resistance of restored cracked teeth was rejected in part because direct restorations performed better when compared with indirect restorations (pooled data).

Within the limitations of this *in-vitro* study, it can be concluded that all techniques were able to 'splint' the crack, and only some differences were seen in the used materials:

1. Direct composite resin restorations sufficiently protected the cracked teeth regardless of their cavity design
2. As there was no statistically significant difference in survival rates between inlays and onlays it is not possible to favour one design type over the other.

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