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Optimization of large MOD restorations: Composite resin inlays vs. short fiber-reinforced direct restorations

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ABSTRACT

Objective. To compare mechanical performance and enamel-crack propensity of direct, semi-direct, and CAD/CAM approaches for large MOD composite-resin restorations.

Methods. 45 extracted maxillary molars underwent standardized slot-type preparation (5-mm depth and bucco-palatal width) including immediate dentin sealing (Optibond FL) for the inlays (30 teeth). Short-fiber reinforced composite-resin (EverX Posterior covered by Gradia Direct Posterior) was used for the direct approach, Gradia Direct Posterior for the semi-direct, and Cerasmart composite resin blocks for CAD/CAM inlays. All inlays were adhesively luted with light-curing composite-resin (preheated Gradia Direct Posterior). Shrinkage-induced enamel cracks were tracked by transillumination photography. Cyclic axial isometric chewing (5-Hz) was simulated, starting with a load of 200 N (5000 cycles), followed by stages of 400, 600, 800, 1000, 1200, and 1400 N (maximum 30,000 cycles each) until fracture or to a maximum of 185,000 cycles. Survived specimens were subjected to cyclic-load-to-failure test at 30-degree angle on the palatal cusp.

Results. Only small shrinkage-induced cracks were found in 47% of the direct restorations compared to 7% and 13% of semi-direct and CAD/CAM inlays, respectively. Survival to accelerated fatigue was similar for all three groups (Kaplan–Meier $p > .05$) and ranged between 87% (direct) and 93% (semi-direct and CAD/CAM). Cyclic-load-to-failure tests did not yield significant differences either (Life Table analysis, $p > .05$) with median values of 1675 N for CAD/CAM inlays, 1775 N for fiber-reinforced direct restorations and 1900 N for semi-direct inlays.

Significance. All three restorative techniques yielded excellent mechanical performance above physiological masticatory loads. Direct restorations performed as good as inlays when a short-fiber reinforced composite-resin base was used.

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1. Introduction

Techniques for restoring anterior or posterior teeth include direct, semi-direct, semi-indirect and indirect restorations [1]. Large direct restorations present several challenges, especially in the posterior dentition. Mastering of shape, contours and occlusal anatomy/function requires particular skills [2,3]. But it also raises the problem of polymerization shrinkage [4,5]. Contraction stresses challenge the dentin–resin hybrid layer and may result in gap formation and/or decreased dentin bond strength [4,6]. However when using strong adhesives, shrinkage will likely cause cuspal deformation and cracking of the enamel at the cusp base [7,8].

Many methods have been proposed in an attempt to reduce those stresses when choosing direct techniques [9], such as sophisticated layering techniques [10], sandwich approaches with glass ionomer bases [11] and fiber patches [12], pulse delay and slow-start light polymerization protocols [13]. To achieve clinically relevant conversion, the majority of the shrinkage stress is developed during and after the vitrification stage and even in the absence of light ("dark" cure stage), which does not permit stress relaxation on the time scales proposed for those "soft" polymerization protocols [14]. Sandwich restorations may represent the most convenient way to help control part of the shrinkage stresses when used in form of a novel "super-closed" technique [8]. Layering protocols have been demystified by a number of studies showing that layering does not necessarily decrease shrinkage stresses [15,16] but might even make them worse compared to bulk filling [17]. Hence, in the recent years, manufacturers have shifted their attention toward simplification using new materials for bulk filling, with encouraging results (stress reduction, strength) in both flowable and packable form [18–20]. In 2013, a new short fiber-reinforced material (EverX Posterior, GC, Lueven, Belgium) to be used as a bulk dentin replacement was introduced and recommended for high-stress bearing area [21]. It presents a higher fracture toughness and flexural modulus within the family of bulk-fill materials but can be used easily in 4-mm deep increments and can potentially match the toughness of dentin [22,23].

However, when it comes to the ultimate way of controlling polymerization stresses in large MOD restorations, luted inlay techniques have proven to be the most efficient [8,24] because the shrinkage is limited to the very thin layer of luting material. There are at least three techniques for the dentist to fabricate a composite resin inlay [25]: the intraoral inlay (isolating and using the tooth itself as a die) [26], the extraoral inlay (using an alginate impression and a fast-setting silicon model) [25] and the CAD/CAM inlay [27]. Filtek MZ100 (3M-ESPE, St. Paul, MN, USA) was the first composite resin CAD/CAM block introduced in 2001 [27]. It demonstrated outstanding performance, wear properties, color integration and millability in thin layers [28–32]. In a recent accelerated fatigue study, large MOD Filtek MZ100 CAD/CAM inlays showed 100% survival unlike all other direct techniques [8]. The positive outcome of Filtek MZ100 may have triggered the development of new CAD/CAM composite resin blocks such as Lava Ultimate (3M-ESPE, Seefeld, Germany), Cerasmart (GC, Lueven, Belgium), Katana Avencia (Kuraray Noritake Dental Inc., Tokyo, Japan) and Block HC (Shofu, Kyoto, Japan).

This research assessed the accelerated fatigue strength and cracks propensity of a large MOD short fiber-reinforced direct composite restoration compared to composite resin inlays made with either a new CAD/CAM material or using the intraoral inlay technique. The null hypotheses were that (1) no significant influence would be found in mechanical performance among the restorative technique used, and (2) there would be no difference in enamel crack propensity (induced by shrinkage stress) between three groups.

2. Materials and methods

Upon approval from the Ethical Review Committee of the University of Southern California (Los Angeles, CA) (proposal # HS-16-00544), forty-five caries-free maxillary molars were collected from a large collection of teeth, scaled, pumiced and stored in 0.1% thymol solution (Aqua Solutions Inc, Deer Park, TX, USA). It was chosen teeth which presented few or no cracks.

The roots were embedded up to 3 mm below the cementoenamel junction (CEJ) using acrylic resin (Palapress vario; Heraeus Kulzer, Armonk, NY, USA) and mounted in a special positioning device. With the aim of "enamel crack tracking" during the experiment, each surface of the tooth was photographed under standardized conditions at 1.5× magnification (Nikon D610 with Nikkor 105 mm macro lens) and using transillumination (IL-88-FOI Microscope Light Source, Scienscope, Chino, CA). After every procedure, a new set of images would be taken to precisely detect existing cracks.

In order to evenly distribute the teeth according to their size and shape, all specimens were organized in groups of three ("triplets" with similar buccolingual and mesiodistal size and height) and subsequently re-assigned randomly to groups ($n = 15$) which received (1) a fiber-reinforced composite resin base (EverX Posterior, GC) layered with direct composite (Gradia Direct posterior; GC, Lueven, Belgium), (2) a semi-direct inlay (Gradia Direct Posterior; GC, Lueven, Belgium) or (3) a CAD/CAM inlay (Cerasmart; GC).

2.1. *Specimens preparation*

A standardized MOD slot-type tooth preparation was applied with 5-mm bucco-palatal width and 5-mm depth by using tapered diamond burs (Brasseler, Savannah, GA, USA) and continuous water cooling in a high-speed electric handpiece (Fig. 1a and b). For direct restorations only, a 0.5–1 mm 45° bevel at the cervical and proximal angles was created with a spherical shape fine diamond bur (#8801-018, Brasseler). After preparation completion, photographic enamel crack tracking was performed to determine if preparation would have caused any damage to the specimens.

Immediate dentin sealing (IDS) was performed to the freshly cut dentin of the semi-direct and CAD/CAM inlay preparations, using a three-step etch-and-rinse dentin bonding agent (Optibond FL; Kerr, Orange, CA, USA) according to previously published protocol [33]. The adhesive was polymerized for 20 s at 1000 mW/cm^2 (VALO Curing Light, Ultradent

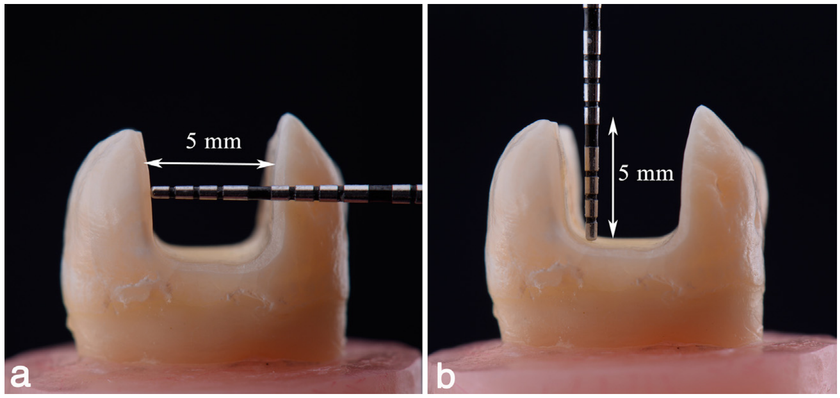

Fig. 1 – Standard MOD tooth preparation and corresponding measurements: (a) 5-mm in bucco-palatal width and (b) 5-mm in depth.

Products, Inc., South Jordan, UT, USA) followed by an additional 10 s light polymerization under an air-blocking barrier (KY Jelly; Johnson & Johnson Inc, Montreal, QC, Canada). The enamel margins were re-finished with a spherical shape fine diamond bur (Brasseler) in order to eliminate excesses of adhesive resin.

2.2. *Restorative procedures*

For CAD/CAM inlays restorations, each prepared tooth underwent digital impression scanning using the Cerec CAD/CAM system (Sirona Dental Systems GmbH, Bensheim, Germany), aided with a contrast powder (Cerec Optispray; Sirona Dental, Inc., Charlotte, NC, USA) and restorations were designed using the 4.4 Cerec software. To standardize form and anatomy, the original design of the restoration was not edited, only the position tools were used to ensure correct thickness. Nanofilled composite resin restorations (Cerasmart; GC) were milled (Fig. 2a), carefully adjusted to their preparations under optical microscopy (Leica MZ 125, Leica Microsystems, Wetzlar, Germany), and mechanically polished.

The inner surface of all restorations was air-abraded (RONDOflex plus 360; KaVo Dental, Charlotte, NC, USA) using 30-μm silica-modified aluminum oxide (Rocatec Soft; 3M-ESPE, St. Paul, MN, USA) for 10 s at a distance of 10 mm with a pressure of 30 psi. Cleaning was performed by immersion in distilled water using ultrasonic bath for 2.5 min, followed by air drying. Silane (Silane; Ultradent, South Jordan, UT, USA) was then applied for 20 s and heat-dried at 100 °C for 1 min in a small oven (D.I.-500; Coltene, Altstatten, Switzerland). Tooth preparations were treated by air-abrasion using 30-μm silica-modified aluminum oxide, etching for 30 s with 35% phosphoric acid (Ultra-Etch, Ultradent, UT, USA) and abundant rising and drying. Adhesive resin (Optibond FL, bottle 2; Kerr) was applied to both fitting surfaces (tooth and inlay) and left unpolymerized until the luting material (Gradia Direct posterior; GC), preheated for 5 min in Calset (Addent; Danbury, CT, USA), be inserted into the preparation and followed by complete seating of the inlay (Fig. 2b). After removal of composite resin excesses, each surface was ultimately light polymerized (VALO Curing Light) for a total of 60 s (20 s per surface, repeated three times) and additional 10 s under an air-blocking barrier (KY Jelly, Johnson & Johnson). The margins were finished and mechanically polished. Two extra teeth of this group (one right and one left) were used as a guide to copy the cusp inclination and occlusal anatomy while layering in the following groups (direct and semi-direct).

For direct composite restorations, a three-step etch-and-rinse bonding agent was used (Optibond FL; Kerr) and light polymerized for 20 s at 1000 mW/cm^2 (VALO Curing Light). A standardized natural layering technique (enamel and dentin shades) was applied in seven increments. The proximal walls were raised with a 2-mm thick dentin shade (Gradia Direct posterior, GC) increment, followed by a 2-mm thick enamel shade increment for the marginal ridge. Approximately 2-mm of the remaining class I defect was filled using fiber-reinforced composite (EverX Posterior; GC), packed horizontally for optimal fiber orientation and according to the manufactures' instructions (Fig. 2c). A final layering was performed using a 1-mm increment of dentin shade followed by cuspal increments of enamel shade individually polymerized (Fig. 2d). Special attention was given to strictly emulating the cuspal inclination and occlusal anatomy of the CAD/CAM inlays previously designed. Each increment was polymerized for 20 s at 1000 mW/cm^2 and final light polymerization was performed for 10 s under an air-blocking barrier (KY Jelly, Johnson & Johnson). Finishing procedures were the same as for the previous group.

For semi-direct group, the teeth preparations were isolated with a thin layer of teflon tape and vaseline (Petroleum Jelly; Unilever, Trumbull, CT, USA) (Fig. 2e). The natural layering technique (enamel and dentin shades – Gradia Direct posterior; GC) was similarly applied in seven increments into the cavity, starting with the proximal walls. Each increment was polymerized for 20 s at 1000 mW/cm^2 and final polymerization was performed under an air-blocking barrier for 10 s. Again, special care was given to strictly emulating the occlusal anatomy of the CAD/CAM inlays. The semi-direct restorations were retrieved from the preparations by using a composculp instrument (Hu-Friedy, Chicago, IL, USA) (Fig. 2f) and underwent post-polymerization at 100 °C for 5 min in the oven (D.I.-500; Coltene). The restorations were finished and mechanically polished. The luting procedures were the same as for the CAD/CAM inlay group.

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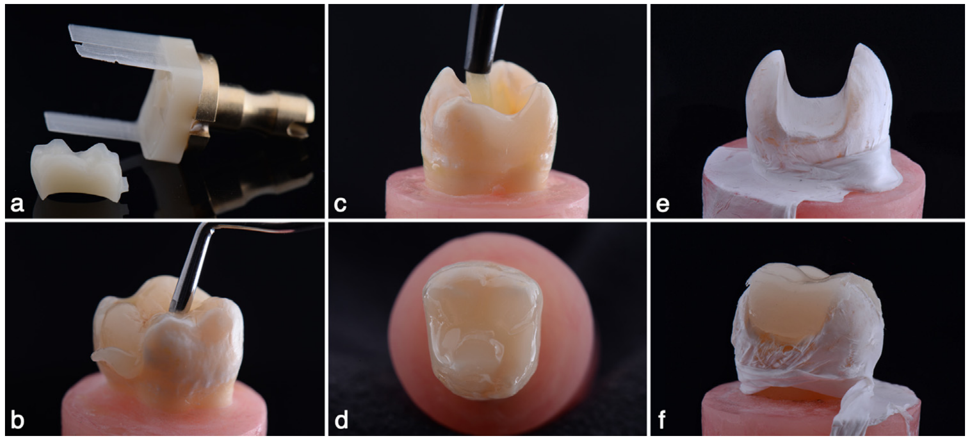

Fig. 2 – Restorative procedures for all groups: (a) CAD/CAM composite resin inlay restoration milled; (b) luting of the inlay using preheated restorative composite resin (Gradia Direct posterior); (c) fiber-reinforced composite (EverX Posterior) being horizontally pa) direct restoration completed after last enamel composite lacked to the cavity for the direct restoration; (dyer (Gradia Direct posterior); (e) isolation of the tooth preparation before the natural layering technique for the semi-direct group; (f) a semi-direct restoration being retrieved from the preparation to proceed the post-polymerization.

2.3. *Accelerated fatigue test*

Restored specimens were kept in distilled water at ambient temperature for 1 week. Enamel crack tracking (transillumination and photography) was performed for each tooth surface. An artificial mouth using closed-loop electrodynamic system (Acumen 3; MTS Systems, Eden Prairie, MN, USA) was used to simulate the masticatory forces with an antagonist 7-mm diameter composite resin sphere (Filtek Z100; 3M-ESPE, St. Paul, MN, USA) post-polymerized at 100 °C for 5 min in the oven (D.I.-500; Coltene) [8]. A tripod contact was created by simultaneous and equal contact of the composite resin spheres to the mesiobucal, distobucal and lingual cusps (Fig. 3a and b). The load chamber was filled with distilled water to submerge the sample during testing (Fig. 3c). Cyclic load (isometric contraction, load control) was applied at a frequency of 5 Hz, starting with a load of 200 N (warm-up of 5000 cycles), followed by stages of 400, 600, 800, 1000, 1200 and 1400 N at a maximum of 30,000 cycles each. Specimens were loaded until fracture or to a maximum of 185,000 cycles and the number of endured cycles was registered. After the test, each sample was evaluated by transillumination and optical microscope (Leica MZ 125; Leica Microsystems) at 10:1 magnification (two-examiner agreement).

2.4. *Cyclic-load-to-failure test*

Considering the amount of survived specimens (between 87% and 93%), the samples were then subjected to a second test (cyclic-load-to-failure). All specimens were placed in the load chamber at 30-degree angulation to create a single contact on a flat surface prepared at the palatal cusp. The loading point was equidistant to the cusp tip and central groove (Fig. 4) [34]. The load chamber was filled with distilled water and cyclic load applied at a frequency of 5 Hz, starting with a warm-up load of 100 N for 300 cycles (preconditioning stage), followed by incremental increase of 50N each 150 cycles, up to the limit of 2900 N. Specimens were loaded until fracture or to a maximum of 8700 cycles. A visual distinction was made among three fracture modes, considering the reparability of the tooth (Fig. 5a). Restorable fracture (RE) is usually above the cementoenamel junction (CEJ) and possibly restorable (PR) (Fig. 5b) comprehends failures that are below CEJ and above acrylic resin base (ARB). Both, even in case of major coronal substance

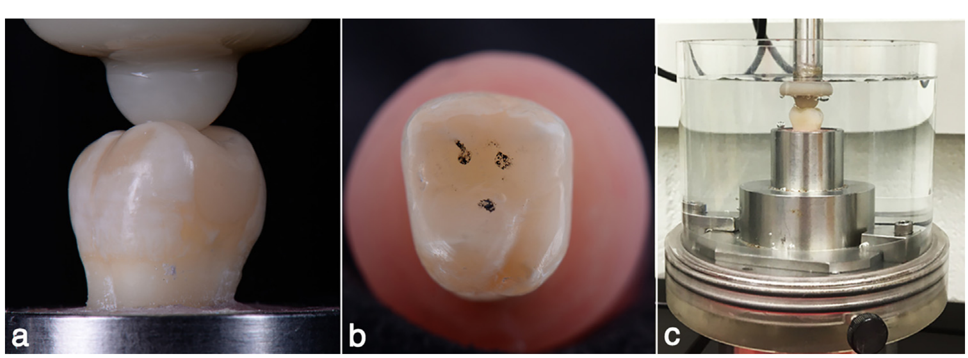

Fig. 3 – Positioning of specimen for accelerated fatigue test. (a) Specimen with 7-mm diameter composite resin sphere during control of occlusal tripod contact before testing; (b) tripod contact created; (c) submerged specimen in load chamber under isometric cyclic loading.

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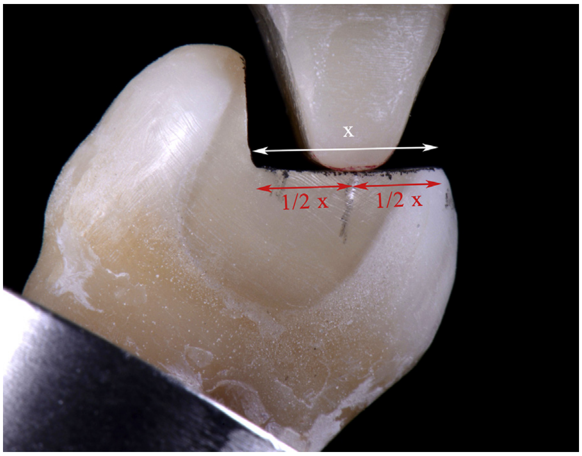

Fig. 4 – Positioning of specimen for cyclic-load-to-failure test at 30-degree angulation, and a semicylinder (2.5-mm radius) post-polymerized resin creating a single equidistant contact on the flat surface (palatal cusp).

loss, the tooth can be re-restored. A non-restorable fracture (NR) (Fig. 5c) involves a large portion of the tooth/root and extends below the ARB that would require tooth extraction.

2.5. *Enamel crack detection and tracking*

In order to detect new enamel cracks, specimens were evaluated four times during the experiment at 1.5× magnification (Nikon D610 with a Nikkor 105 mm macro lens) in standardized conditions and with transillumination (IL-88-FOI Microscope Light Source, Scienscope): before and after tooth preparation, 1 week after restoration, and at the end of the fatigue test. Samples were evaluated, in case of doubt, in a two-examiner agreement and analyzed under optical microscope at 10:1 magnification (Leica MZ 125, Leica Microsystem). Special care was taken to differentiate between pre-existing cracks from those created by polymerization shrinkage. To categorized the cracks, a three level classification was used based on a previous study [8]: (a) no cracks visible, (b) visible cracks smaller than 3 mm, and (c) visible cracks larger than 3 mm (Fig. 6).

2.6. *Statistical analysis*

With the aim of identify any premature failure, all fatigue tests were continuously recorded and monitored using transillumination and macro video camera (Canon Vixia HF S100, Canon USA, Melville, NY). The number of endured cycles, load-at-failure and failure mode of each specimen were recorded. The fatigue resistance of the groups was compared using the Kaplan–Meier (for survived cycles) for the accelerated fatigue test and for the cyclic-load-to-failure test. Post hoc Log Rank test was used to analyze the influence of the restorative procedure (direct, semi-direct and CAD/CAM inlay) on the fatigue resistance of the teeth on a significance level of 0.05.

The fracture load step at which the specimen failed was compared using Life Table analysis followed by Wilcoxon test at a significance level of 0.05. At each time interval (defined by each load step), the number of specimens starting the interval intact and the number of specimens fracturing during the interval were counted, allowing the calculation of survival probability at each interval. For all statistical analyses, the level of significance was set at 95%. The data were analyzed with statistical software (SPSS 23, SPSS Inc, Chicago, IL).

3. Results

Survival at the accelerated fatigue test was similar for all three groups (Kaplan–Meier followed by Log Rank test $p > .05$) and ranged between 87% (direct) and 93% (semi-direct and CAD/CAM inlays). No difference could be found within groups, considering either cycles (Fig. 7) or load (1400 N median for all groups) (Table 1).

For the cyclic-load-to-failure test, none of the specimens withstood all 8700 cycles. Since all samples failed (Table 1), the mean cycles and median load to failure could be obtained (Figs. 8 and 9). Survival at the cyclic-load-to-failure test was also similar for all three groups when analyzing either cycles (Kaplan–Meier and Log Rank post hoc test $p > .05$) or load (Life Table followed by Wilcoxon test $p > .05$) (Table 2). The average cycles survived were 5010 for CAD/CAM inlay, 5393 for fiber-reinforced direct restoration and 5457 for semi-direct inlay, with no significant differences among groups (Table 2).

Life Table and post hoc Wilcoxon significance test for the median load at failure revealed no significant differences among groups (Table 2, $p > .05$) with median values of 1675 N for CAD/CAM inlays, 1775 N for fiber-reinforced direct restorations and 1900 N for semi-direct inlays. The statistical distribution (descriptive statistics) of the data is also presented in a box and whisker diagram in Fig. 9.

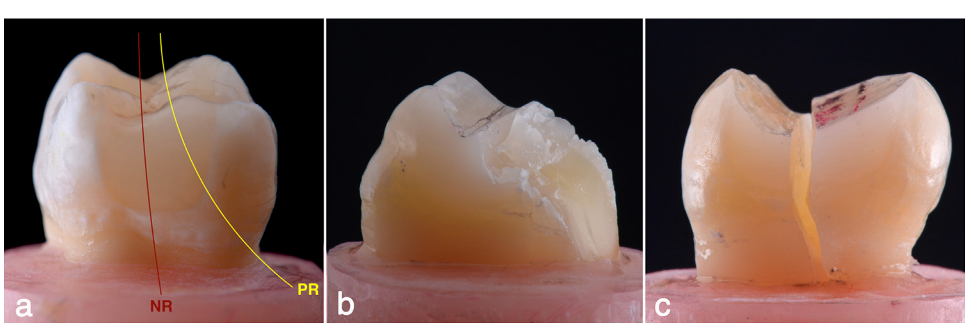

Fig. 5 – (a) Failure mode of the specimens after cyclic-load-to-failure test. (b) Possibly restorable fracture (PR) and (c) non-restorable fracture (NR).

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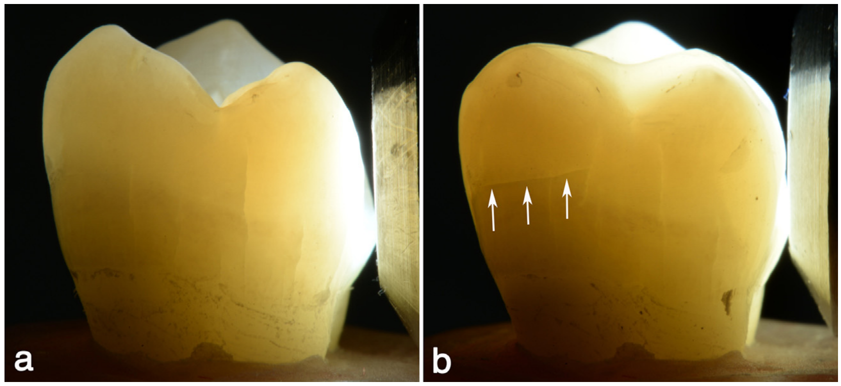

Fig. 6 – An example of visible crack smaller than 3 mm using transillumination tracking. (a) Immediately after tooth preparation and (b) after 1 week of restorative procedures.

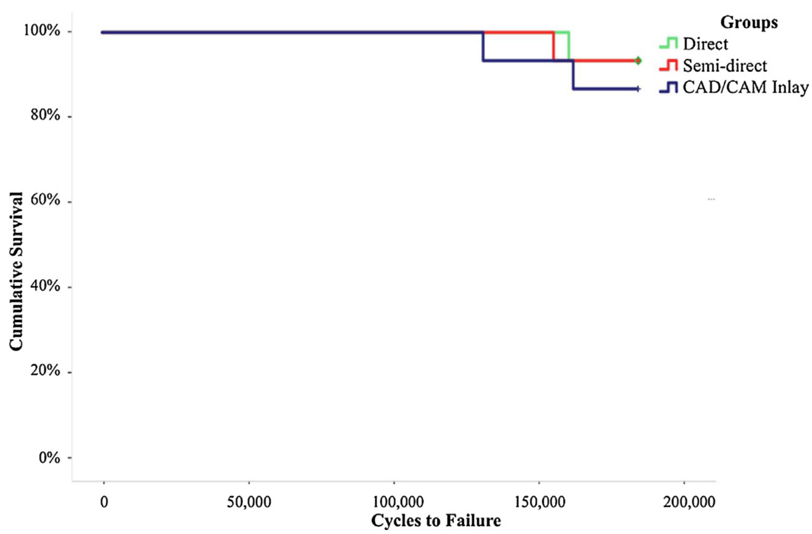

Fig. 7 – Kaplan–Meier fatigue resistance survival curves for all four groups considering the accelerated fatigue test.

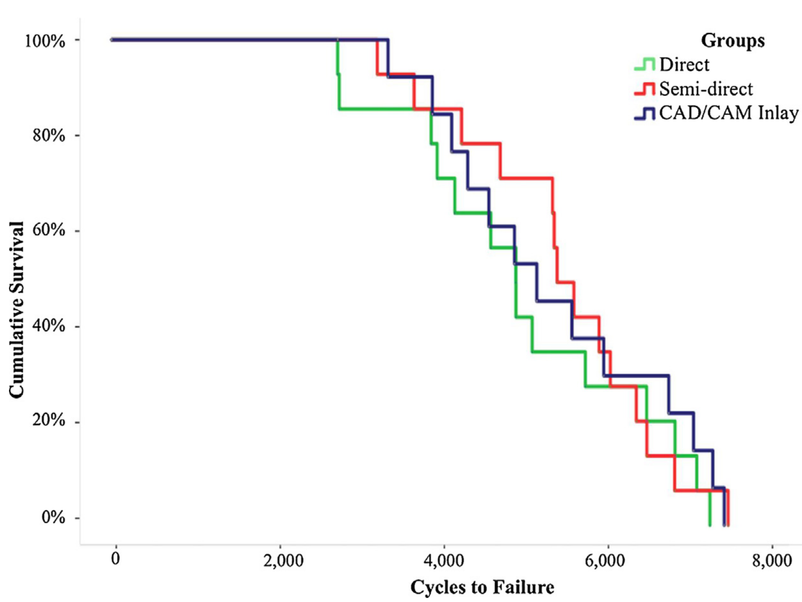

Fig. 8 – Kaplan–Meier fatigue resistance survival curves for all four groups considering the cyclic-load-to-failure test.

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Table 1 – Comparison of accelerated fatigue test and cyclic-load-to-failure test results.

Groups	Specimen	Accelerated fatigue test		Cyclic-load-to-failure test
		Maximum load	Cycles	Maximum load
Direct	1	1400 N	162,613	Failed accelerated fatigue test
	2	Survived	185,000	2250 N
	3	Survived	185,000	2000 N
	4	Survived	185,000	1150 N
	5	Survived	185,000	1650 N
	6	Survived	185,000	1450 N
	7	Survived	185,000	1400 N
	8	Survived	185,000	1750 N
	9	Survived	185,000	1300 N
	10	Survived	185,000	1900 N
	11	Survived	185,000	1550 N
	12	Survived	185,000	2450 N
	13	1200 N	131,500	Failed accelerated fatigue test
	14	Survived	185,000	2500 N
	15	Survived	185,000	2350 N
Semi-direct	1	Survived	185,000	1450 N
	2	Survived	185,000	2050 N
	3	Survived	185,000	2500 N
	4	1400 N	155,800	Failed accelerated fatigue test
	5	Survived	185,000	2150 N
	6	Survived	185,000	2000 N
	7	Survived	185,000	1100 N
	8	Survived	185,000	1800 N
	9	Survived	185,000	1800 N
	10	Survived	185,000	1900 N
	11	Survived	185,000	2200 N
	12	Survived	185,000	1600 N
	13	Survived	185,000	1800 N
	14	Survived	185,000	2300 N
	15	Survived	185,000	1250 N
CAD/CAM inlay	1	Survived	185,000	950 N
	2	Survived	185,000	1550 N
	3	Survived	185,000	2450 N
	4	Survived	185,000	1700 N
	5	Survived	185,000	1950 N
	6	Survived	185,000	1650 N
	7	1400 N	161,091	Failed accelerated fatigue test
	8	Survived	185,000	2200 N
	9	Survived	185,000	1300 N
	10	Survived	185,000	1350 N
	11	Survived	185,000	950 N
	12	Survived	185,000	1650 N
	13	Survived	185,000	2300 N
	14	Survived	185,000	1400 N
	15	Survived	185,000	2600 N

Table 2 – Cyclic-load-to-failure pairwise post hoc comparison.

	Direct	Semi-direct	CAD/CAM inlay
Direct	-	0.808	0.560
Semi-direct	0.947	-	0.408
CAD/CAM inlay	0.405	0.629	-

Shaded cells = resistance to fatigue post hoc tests for cycles (Kaplan–Meier followed by Log Rank test); clear cells = resistance to fatigue post hoc tests for load (Life Table followed by Wilcoxon–Gehan test).

Table 3 – Crack propensity after 1 week of restorative procedures and before accelerated fatigue test.

Group	No cracks	Cracks of less than 3 mm	Cracks of more than 3 mm
Direct ($n = 15$)	8 (53%)	7 (47%)	0 (0%)
Semi-direct ($n = 15$)	14 (93%)	1 (7%)	0 (0%)
CAD/CAM inlay ($n = 15$)	13 (87%)	2 (13%)	0 (0%)

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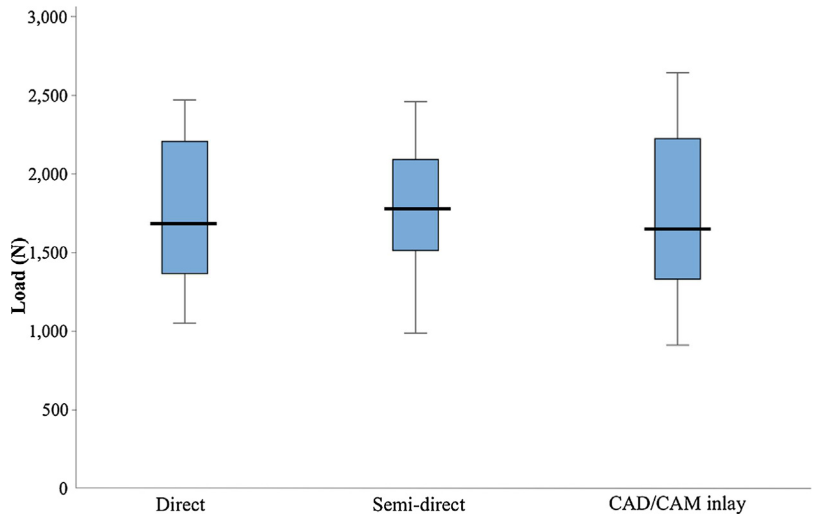

Fig. 9 – Box-and-whisker diagram of fracture loads for the cyclic-load-to-failure test, presenting the median (bold black horizontal line), the minimum and maximum values (vertical "t" lines, or whiskers) and the interquartile range (blue box).

Table 4 – Failure types, numbers, and percentages after cyclic-load-to-failure test.

Group	Restorable (above CEJ)	Possibly restorable (below CEJ above ARB)	Non-restorable (below ARB)
Direct ($n = 13$)	0 (0%)	3 (23%)	10 (77%)
Semi-direct ($n = 14$)	0 (0%)	7 (50%)	7 (50%)
CAD/CAM inlay ($n = 14$)	0 (0%)	4 (29%)	10 (71%)

Abbreviations: CEJ: cementoenamel junction; ARB: acrylic resin base.

No new cracks were observed after tooth preparation. After restoration and 1 week of water storage, the crack propensity was higher for fiber-reinforced direct group (47%) than for semi-direct group (7%) and CAD/CAM inlay group (13%). The presence of shrinkage-induced cracks was demonstrated by the exhibition of cracks smaller than 3 mm for all groups (Table 3 and Fig. 6).

The evaluation of failure mode was performed with the aid of transillumination and magnification in order to classify the fracture as restorable, possibly restorable and non-restorable. Non-restorable failure (below the acrylic resin base limit) was considered predominant for fiber-reinforced direct and CAD/CAM inlay groups, and ranged between 71% and 77%, respectively. Semi-direct group showed equal amount of possibly restorable and non-restorable failures (Table 4 and Fig. 5). No delamination, adhesive failures, nor interlayer separations were observed, except for one specimen in the CAD/CAM inlay group, which seemed to have failed adhesively. This specimen was included in the "possibly restorable" failure type due to the crestal fracture of the lingual cusp.

4. Discussion

This work assessed the influence of three restorative approaches (direct, semi-direct intraoral and CAD/CAM) for large MOD composite resin restorations and their effects on the mechanical performance and enamel crack propensity. The null hypotheses are accepted in part because there was no significant difference found in mechanical performance among the restorative technique used. There were, however, differences in enamel crack propensity.

In this study, the authors focused on the high level of standardization of all procedures (tooth dimensions, preparations, loading steps, occlusal morphology). Hence, it was possible to limit considerably the amount of confounding variables normally found in clinical studies (patients' masticatory and dietary habits, individual caries susceptibility, as well as the need for multiple operators and evaluators, etc.). Only upper molars, with comparable outer size and geometry of crowns and roots, were selected from a larger choice and distributed evenly into each experimental group using the innovative randomly reassigned multiplets method described in the material and methods section. True fatigue tests at low-load/high-cycle are extremely time-consuming. In some pilot tests, specimens will fail after more than 1,000,000 cycles when moderate load is used [35]. Hence the best laboratory reproduction of clinical performance is represented by the accelerated fatigue used in this work. It was originally introduced by Fennis et al. [36] as an intermediate test between the simple load-to-failure experiment and classical fatigue tests. The Acumen 3 (MTS) electrodynamic system used in the present study provides highly precise load and motion control. The design features a rigid load frame and a direct-drive linear motor. The multipurpose software suite also enables automatic setup, smooth task flow, simplified actuator control and intuitive limit setting, thus reducing the risk of human error. The methods and load protocol of the present study followed that of previously published works on the comparison of large direct and CAD/CAM MOD restorations performed at the same facil-

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ity [8,11,12]. However, because of the unexpected amount of survived specimens, the experiment was completed with an ultra-accelerated cyclic-load-to-failure at an angle of 30 degrees. In the first part of the test, the load was applied axially and distributed on three opposing cusps of the crown. For the second part of the test the angle of force was modified to 30 degrees and applied to the working cusp using a composite resin cylinder (Filtek Z100; 3M-ESPE) as an antagonist. This measure increased the stress to the restoration and simulates an extreme load configuration (nonworking contact). Additionally, the low stiffness and tooth-like wear of the composite resin cylinder allowed realistic simulation of tooth contacts through wear facets distributing the load without reaching the compressive limit of the tissues or restorative materials.

Despite the fact that extreme loads were used (way beyond physiological masticatory forces), the first part of the experiment (accelerated fatigue test) demonstrated outstanding survival rates and did not yield any differences between the three restorative techniques. However, it can be compared to the previously published works performed at the same facility. Large MOD Filtek MZ100 inlays had previously survived 100% [8] while only 1 Cerasmart CAD/CAM inlay and 1 Gradia Direct posterior semi-direct intraoral inlay failed in the present experiment. Cerasmart is filled 71% by weight with silica and barium glass nanoparticles while MZ100 is filled 85% by weight with spheroidal zirconia–silica nanofillers, which may explain this slight difference in performance. The lack of difference between CAD/CAM and semi-direct intraoral techniques is also consistent with other accelerated fatigue tests comparing Filtek MZ100 and semi-direct intraoral restorations (made of Miris 2, Coltene) in form of onlays on endodontically-treated molars [32,37]. The same adhesive system (Optibond FL; Kerr) and protocol was used in all those experiments, including the immediate dentin sealing technique, which may also account for the high level of performance achieved. Excellent resin-to-resin bonding was also observed (luting composite to inlay material), no delamination or adhesive failures, nor interlayer separations, except for 1 specimen in the CAD/CAM group that seemed to have failed adhesively. The cohesiveness between the luting composite and the inlay material can be explained by the combination of micromechanical interlocking (surface roughness created by air-abrasion) and chemical bonding through the use of the silane (covalent siloxane bond to the filler particle) and co-polymerization to the unreacted C=C bonds (up to 20–30% of the resin matrix in the CAD/CAM material).

The direct technique in the present experiment was able to match the performance of the semi-direct approaches, not only during the accelerated fatigue test (87% survival rate) but also in the cyclic-load-to-failure test (1775 N). None of the direct techniques in the sister experiments [8,11] (including sandwich techniques and the use of fiber patches) had been able to survive more than 40% following the accelerated fatigue test. These previously published works were performed in identical conditions using the same load protocol. This confirms the efficiency of the EverX short fiber-reinforced dentin base. The extreme loads required to fracture the restored teeth speak for the ability of the fiber-reinforced base to function in high-stress bearing area [21] and its potential ability to match the toughness of dentin [22,23]. Improving mechanical properties of composites using short fibers is depending on the geometry and amount of fibers that can be included. The fiber aspect ratio (length/diameter) is determinant for the performance of the composite resin [38] as well as the fiber length [39]. When fibers are below a critical length (0.5–1.6 mm) [39], they act more as a microfiller and such material display properties alike particulate filler composites (PFCs) [40,41]. On the other hand, the millimeter-scale discontinuous E-glass fibers fillers in EverX increase tolerance to crack propagation (fracture toughness) compared conventional restorative materials without fibers. It was demonstrated that reduction of the stress intensity at the crack tip, crack blunting and bridging phenomena explain the improved toughness of EverX [23].

In agreement with existing data produced in the same conditions [8,11], it can be stated that the fiber-reinforced direct and semi-direct restorations performed similar to the CAD/CAM inlay restorations with respect to the type of failures presented after the accelerated fatigue test. No catastrophic failures were observed, as it was shown in the previous studies when using MZ100 inlays [8,11]. In light of the excellent performance of all groups, the samples were then subjected to a second test (cyclic-load-to-failure), and notwithstanding the fact that the restorations underwent elevated forces at 30-degree angulation, fiber-reinforced direct restorations yielded catastrophic failures amount (77%) similar to the CAD/CAM inlay group (71%).

Another significant outcome of this experiment is the absence of major cracks induced by shrinkage. Only minor cracks less than 3-mm long were observed and mainly in the direct technique group. Absence of shrinkage-induced cracking is not a surprise with inlays. However, in direct techniques, the very limited incidence of cracks speaks again for EverX's performance. This stress-reducing ability seems even to outperform the other direct techniques using sandwich approaches [11].

From a clinical standpoint, it is undeniable that occlusion and morphology are best mastered with inlays rather than direct techniques. Cost-effectiveness for the patient, however, might be limiting. Further clinical studies should confirm the alternative choice of bilayered restorations using the short fiber-reinforced composite as a dentin substitute.

5. Conclusions

The challenge of restoring large MOD defects has been assessed using three restorative approaches (direct, semi-direct and CAD/CAM). All three restorative techniques yielded excellent mechanical performance even above physiological masticatory loads. Large MOD direct restorations can perform as well as inlays (either semi-direct or CAD/CAM) when a short-fiber reinforced composite resin base is used.

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