dental materials 29 (2013) 324–331

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Fatigue resistance and crack propensity of large MOD composite resin restorations: Direct versus CAD/CAM inlays

Silvana Batalha-Silva[a], *Mauro Amaral Caldeira de Andrada*[a], *Hamilton Pires Maia*[a], *Pascal Magne*[b,*]

[a] *Department of Operative Dentistry, Federal University of Santa Catarina, Florianópolis, Brazil*
[b] *The Don and Sybil Harrington Chair in Esthetic Dentistry, Herman Ostrow School of Dentistry, University of Southern California, Los Angeles, USA*

ARTICLE INFO

Article history:
Received 23 February 2012
Received in revised form 1 July 2012
Accepted 15 November 2012

Keywords:
Composite resin
CAD/CAM
Fatigue resistance
Crack propensity
Shrinkage stress

ABSTRACT

Objectives. To assess the influence of material/technique selection (direct vs. CAD/CAM inlays) for large MOD composite adhesive restorations and its effect on the crack propensity and in vitro accelerated fatigue resistance.
Methods. A standardized MOD slot-type tooth preparation was applied to 32 extracted maxillary molars (5 mm depth and 5 mm bucco-palatal width) including immediately sealed dentin for the inlay group. Fifteen teeth were restored with direct composite resin restoration (Miris2) and 17 teeth received milled inlays using Paradigm MZ100 block in the CEREC machine. All inlays were adhesively luted with a light curing composite resin (Filtek Z100). Enamel shrinkage-induced cracks were tracked with photography and transillumination. Cyclic 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 at a maximum of 30,000 cycles each. Samples were loaded until fracture or to a maximum of 185,000 cycles.
Results. Teeth restored with the direct technique fractured at an average load of 1213 N and two of them withstood all loading cycles (survival = 13%); with inlays, the survival rate was 100%. Most failures with Miris2 occurred above the CEJ and were re-restorable (67%), but generated more shrinkage-induced cracks (47% of the specimen vs. 7% for inlays).
Significance. CAD/CAM MZ100 inlays increased the accelerated fatigue resistance and decreased the crack propensity of large MOD restorations when compared to direct restorations. While both restorative techniques yielded excellent fatigue results at physiological masticatory loads, CAD/CAM inlays seem more indicated for high-load patients.

1. Introduction

The longevity of dental restorations is influenced by multiple parameters such as material properties, patient's conduct and dentist's skills [1,2]. Polymerization shrinkage stress of composite resin restorations is one of the major problems related to direct techniques, especially in large and high C-factor defects [3,4]. Contraction stress challenges the dentin–resin hybrid layer and may result in gap formation and/or decreased dentin bond strength [5–7]. On the other hand, when using strong adhesives and achievingtotal

* *Corresponding author at*: The Herman Ostrow School of Dentistry – Oral Health Center, 3151 S. Hoover St., Los Angeles, CA 90089-7792, USA. Tel.: +1 213 740 4239; fax: +1 213 821 5324.
E-mail address: magne@usc.edu (P. Magne).
0109-5641/$ – see front matter
http://dx.doi.org/10.1016/j.dental.2012.11.013

bonding, the composite material will shrink and cause cuspal movements, deformation and cracking of the surrounding tooth structure [8–15].

Composite resin restorative materials are increasingly popular. Advances in filler technology and in formulation of the resin matrix have resulted in significantly improved mechanical properties and reduced polymerization shrinkage [16]. However, to optimally prevent the side-effects of polymerization shrinkage, it is recommended to use stabilized and post-polymerized luted restorations [17–22]. Composite resin inlays/onlays can be fabricated using laboratory indirect techniques. A more recent trend is the use of chairside semi-direct techniques including direct and extraoral inlays and computer-aided design/computer-assisted manufactured restorations (CAD/CAM). Wassel et al. [23] did not find clinical advantage of semi-direct post-polymerized inlay technique over direct incremental placement using the same material, after 5 years, in matched pairs of restorations. An extend review about clinical evaluations of restorative techniques [2] demonstrated that indirect composite resin restorations had a higher mean annual failure rate (2.9%) compared with direct composite restorations (2.2%). Opdam et al. [24], in a 12-year survival retrospective study, found high survival rates (85%) for large three-, four- and five-surface direct composite resin restorations. In spite of the above-mentioned, indirect restorations are considered the gold standard to restore large defects [1,2,25,26], especially in consideration of shrinkage-induced crack in enamel and dentin. Stress resulting from polymerization shrinkage induces cuspal flexure [11,12] but is less of a concern in luted restorations because it is restricted to a thin cement layer, accounting for a superior marginal quality [27,28]. Significant additional advantages of inlays are the facilitated anatomic form, marginal adaptation, and appropriate proximal contact, contour and occlusion, especially in case of large class II preparations since the restoration is fabricated in a removable die [20–23]. CAD/CAM restorations are predictable alternatives with high success rate, color stability, excellent marginal adaptation and a clinically acceptable wear [2,29–32]. In this particularly innovative approach, the dentist is able to deliver chair-side luted porcelain restorations from an optical impression of the tooth preparation in a single appointment, avoiding the costs of dental technicians and impression materials [33,34]. Lately, composite resins blocks also became available for CAD/CAM restorations, opening the range of material options [35,36]. Industrial manufacturing allows the use of postcuring methods, which can improve the mechanical properties of the direct composite resin versions [21,22]. Furthermore the composite resin CAD/CAM blocks present acceptable wear properties [37] and because it is a less brittle material than porcelain, it can be used in thinner layer, allowing more conservative preparation designs and more resistant restorations [38,39]. The combination of CAD/CAM technique, Paradigm MZ100 resin blocks for Cerec and immediate dentin sealing (IDS) has proven to be a conservative and biomimetic solution under fatigue loading [40,41].

This research assessed the accelerated fatigue strength and shrinkage-induced enamel crack propensity of large Class II mesial-occlusal-distal (MOD) CAD/CAM composite inlays compared to direct composite restoration in same cavity size and shape. The null hypotheses were that (1) no significant difference would be found in accelerated fatigue resistance and mode of failure among the restorative techniques used, and (2) there would be no difference in enamel crack propensity (induced by shrinkage stress) between two groups.

2. Materials and methods

Upon approval by Ethics Committee of the Federal University of Santa Catarina, Brazil and Institutional Review Board of University of Southern California, 32 extracted sound human third maxillary molars with similar size and shape were carefully selected from a large collection of teeth, scaled, pumiced and stored in 0.1% thymol solution. Each tooth was mounted in a special positioning device using acrylic resin (Palapress, Heraeus Kulzer GmbH, Dormagen, Germany), embedding the root up to 3 mm below the cementoenamel junction (CEJ). For the purpose of “enamel crack tracking” during the experiment, each surface of each tooth was photographed at baseline under standardized conditions at $\times$1.5 magnification (Nikon D50 and Sigma 105 mm macro lens) using a macro ring-flash (Sigma EM-140 DG). A second set of images was generated using transillumination (Microlux, Addent, Danbury, CT, USA) in order to detect existing cracks and for detection of new cracks following the subsequent procedures.

2.1. *Specimen preparation*

Standard preparations simulated a large MOD defect (Fig. 1) using tapered diamond burs (313.029 and 314.021, Brasseler, Savannah, GA) and a high-speed electric handpiece under continuous water cooling, followed by photographic enamel crack tracking. Teeth were then randomly distributed in two groups: *MZ100* ($n = 17$) – Indirect restorations (CEREC inlay with Paradigm MZ100, 3M-ESPE, St. Paul, MN, USA), and *M2* ($n = 15$) – Direct microhybrid composite resin restoration (Miris 2, Coltène-Whaledent, Altstätten, Switzerland).

For M2 restorations only, a 0.5–1 mm 45° bevel at the cervical and proximal angles was created with a flame shape fine diamond bur (274, 011904U0, Brassler). For MZ100 Group, immediate dentin sealing (IDS) was applied to the freshly cut dentin with a three-step etch-and-rinse dentin bonding agent (Optibond FL, Kerr, Orange, CA, USA) following a previously published protocol [42] and according to manufacturer’s recommendations. The adhesive was light polymerized for 20 s at 1000 mW/cm^2 (Valo, Ultradent, South Jordan, UT, USA) followed by an additional 10 s light polymerization under an air-blocking barrier (K-Y Jelly, Johnson & Johnson, Montreal, Canada).

2.2. *Restorative procedures*

Inlays were generated with the Cerec 3 CAD/CAM System (v. 3.03, Sirona Dental Systems, GmbH, Bensheim, Germany) with an average thickness of 3.5 mm at the central groove. To standardize form and anatomy, the original design of the restoration was not edited, only the position tools were used to ensure correct thickness. Restorations were milled using Paradigm MZ100 blocks (3M-ESPE, size 14) and mechanically

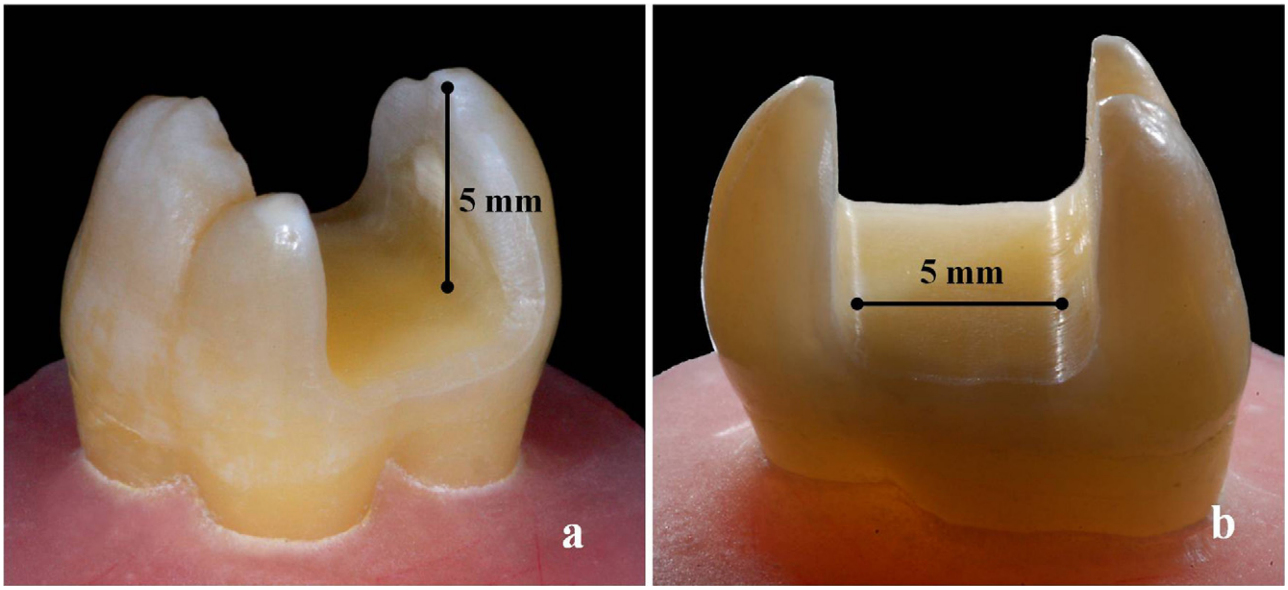

Fig. 1 – Standard MOD tooth preparation and corresponding measurements. (a) All preparations had 5 mm in depth and (b) 5 mm in bucco-palatal width.

polished using a commercial polishing kit (Kit 4477 Q-Polishing System, Komet, Lemgo, Germany). Internal surface conditioning of milled restorations included airborne-particle abrasion (RONDOflex plus 360, KaVo Dental, Charlotte, NC, USA) with 27 μm aluminum oxide at 0.2 MPa, followed by cleaning using 35% phosphoric acid (Ultradent, South Jordan, UT, USA) with a gentle brushing motion for 1 min. After rinsing for 30 s, the inlays were immersed in distilled water in an ultrasonic bath for 2.5 min, air-dried and silanated (Silane, Ultradent) and dried at 100 °C for 1 min (DI500 oven; Coltène Whaledent AG, Alstätten, Switzerland). Tooth preparations were treated by airborne-particle abrasion with 27-μm aluminum oxide at 0.2 MPa, etching for 30 s with 35% phosphoric acid and abundant rinsing 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 (Filtek Z100, 3M-ESPE), preheated for 5 min at 68 °C in Calset (Addent, Danbury, CT, USA), was inserted into the preparation and followed by the complete seating of the inlay. After careful elimination of composite resin excesses, each surface was light polymerized for a total of 60 s (20 s per surface, repeated 3 times) and another 10 s under an air-blocking barrier. The margins were finished and polished mechanically using tungsten carbide burs and composite resin polishers with diamond grit (kit 4477, Q-Polishing System Komet, Lemgo, Germany). Two teeth of this group (one right and one left third maxillary molar), were not used for testing but served as a guide to copy the cusp inclination and occlusal anatomy while layering restorations in M2 Group.

For direct composite restorations in M2 Group, the same previous three-step total-etch bonding agent was used (OptiBond, FL, USA). The natural layering technique (enamel and dentin shades) in seven increments was applied. First, proximal walls were raised with a 2-mm thick dentin shade (Miris S2) increment and followed by a 2-mm thick enamel shade (Miris NR) increment for the marginal ridge. The remaining class I defect was filled with two 1.5-mm horizontal increments of the same dentin shade and one increment of the same enamel. Special attention was used to strictly emulate the cuspal inclination and occlusal anatomy of the reference CAD/CAM inlays. Each increment was polymerized for 20 s at 1000 mW/cm^2 and final light polymerization was performed under an air-blocking barrier (KY Jelly, Johnson & Johnson) for 10 s. Finishing procedures were the same as for the MZ100 Group.

2.3. *Fatigue testing*

Restored specimens were kept in distilled water at ambient temperature for 1 week following adhesive procedures. Each tooth surface was then subjected again to enamel crack tracking (transillumination and photography). An artificial mouth using closed-loop servohydraulics (Mini Bionix II; 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) post-polymerized at 100 °C for 5 min [43]. These composite resin spheres contacted simultaneously and equally the mesiobucal, distobucal and lingual cusps (tripod contact) with isometric chewing under a 5 Hz of frequency. The load chamber was filled with distilled water until complete immersion of specimens and, the first 5000 cycles was a warm-up load of 200 N, followed by stages of 400, 600, 800, 1000, 1200 and 1400 N at a maximum of 30,000 cycles each (Fig. 2). Specimens were loaded until fracture or to a maximum of 185,000 cycles and the number of endured cycles was registered. Under optical microscope and with a two-examiner agreement, the distinction between restorable or non-restorable fractures was made (Fig. 3). A restorable fracture is usually above the cementum–enamel junction, meaning that even in case of major coronal substance loss, the tooth can be re-restored. A non-restorable

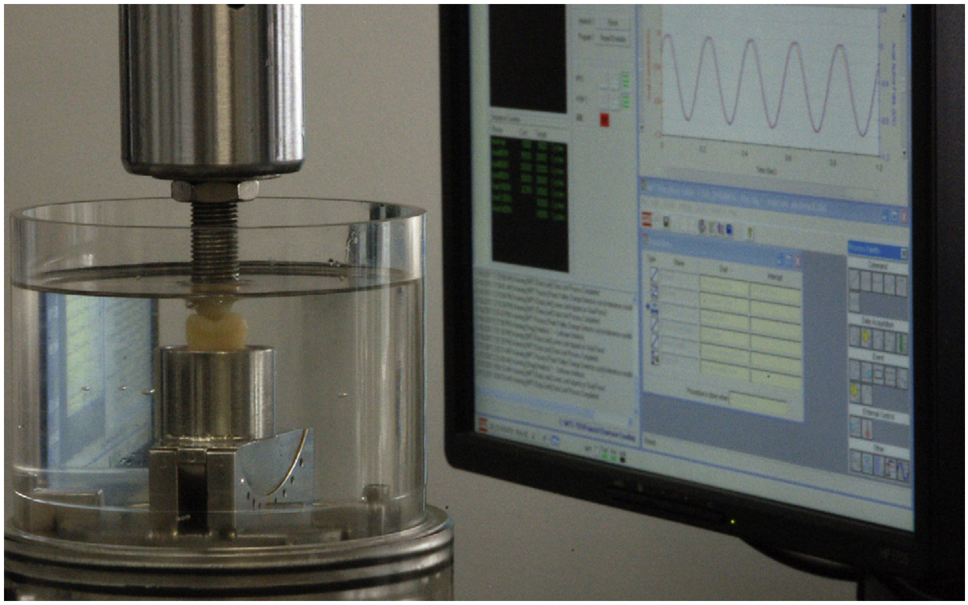

Fig. 2 – Load chamber with submerged specimen under isometric loading and the attached computer where the software controls and simulates masticatory forces.

fracture involves a large portion of the tooth and extends below the cementoenamel junction.

2.4. *Enamel crack detection and tracking*

Specimens were evaluated multiple times during the experiment in order to detect new enamel cracks at ×1.5 magnification in standardized conditions and with transillumination (Nikon D50 and Sigma 105 mm macro lens using a macro ring-flash Sigma EM-140 DG or Microlux, Addent) before and after tooth preparation, 1 week after restoration, and at the end of the fatigue test. In case of doubt, the sample was evaluated in a two-examiner agreement and analyzed under optical microscope at 10:1 magnification (Leica MZ 125, Leica Microsystems, Wetzlar, Germany). Special attention was taken to differ between pre-existed cracks from those created by polymerization shrinkage. Since many different sizes of cracks were observed, a classification with three categories

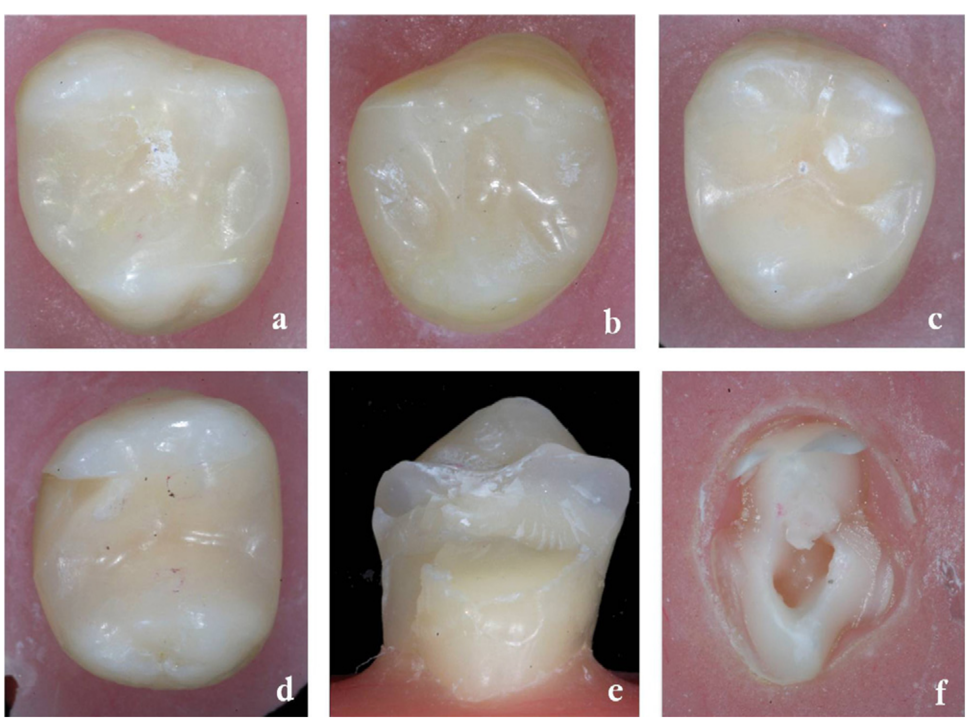

Fig. 3 – Fractured specimens. (a and b) Survived samples of MZ100 Group, (c) survived specimen of M2 Group, (d) restorable fracture (above CEJ) in M2 Group and (e and f) non-restorable fracture in M2 Group.

Table 1 – Failure types, numbers and percentages.

Group	Intact specimen	Fracture above CEJ or restorable	Fracture below CEJ or non-restorable
Inlay MZ100 ($n = 15$)	15 (100%)	0 (0%)	0 (0%)
M2 ($n = 15$)	2 (13%)	10 (67%)	3 (20%)

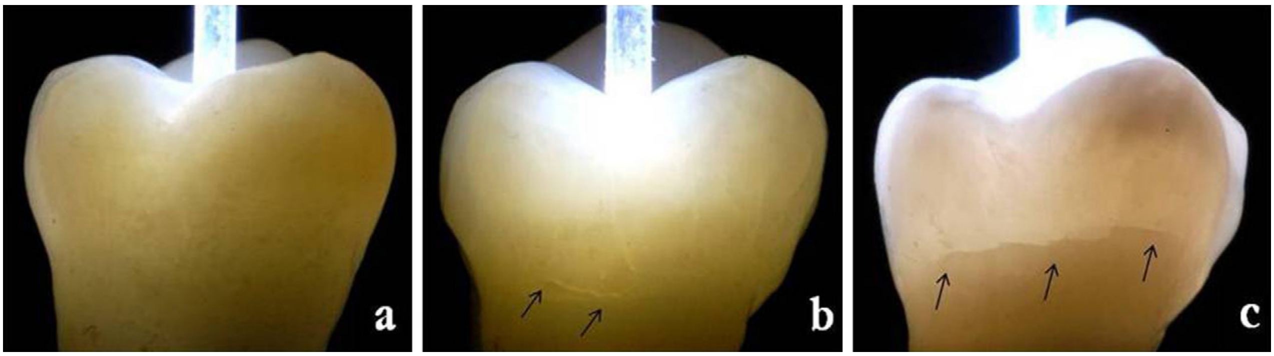

Fig. 4 – Examples of crack tracking with transillumination. (a) No visible cracks, (b) small visible crack with less than 3 mm, and (c) severe crack with more than 3 mm.

was created: (a) no cracks visible, (b) visible cracks smaller than 3 mm, and (c) visible cracks larger than 3 mm (Fig. 4).

2.5. *Statistical analysis*

The fatigue resistance of the two groups was compared using the life table survival analysis. At each time interval (defined by each load step), the number of specimens beginning the interval intact and the number of fractured specimens during the interval were counted, providing the survival probability (%) at each load step. The influence of the restorative technique and material on the fatigue resistance was observed comparing the survival curves using the log rank test at a significance level of .05.

3. Results

Survival in MZ100 Group was 100%. Life table survival analysis revealed significant differences among groups ($P < .001$). Survival of M2 Group was 13% and the average fracture was 1213 N (11,475 cycles), with a single early failure at 800 N. Most of the failures of M2 Group occurred at 1200 and 1400 N loads (Fig. 5). In M2 Group, 67% of fractured teeth were considerable restorable (Fig. 3d), and 20% were clearly below CEJ (Fig. 3e and f) and difficult to restore (Table 1).

No new cracks were observed after tooth preparation. After restoration and 1 week of water storage, the crack propensity (new cracks, Table 2) was higher for M2 Group (47%) than for MZ100 Group (7%), with the presence of severe cracks only in M2 Group and in 40% of the specimens. After fatigue testing, no new horizontal cracks were found but multiple vertical enamel cracks in most specimens.

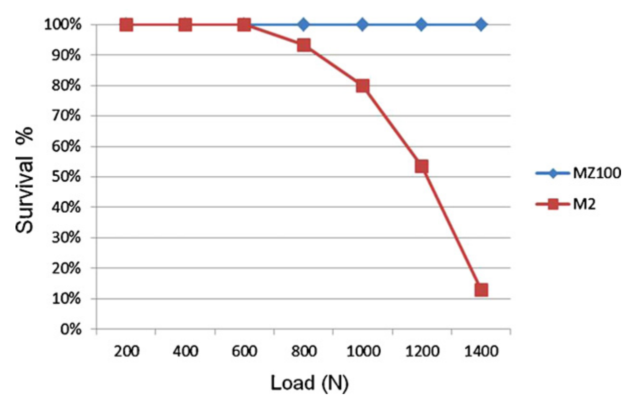

Fig. 5 – Life table survival distribution of groups at each load step ($n = 15$).

4. Discussion

Within the limitations of this in vitro study, the null hypotheses can be rejected. First, MZ100 composite resins inlays significantly increased the fatigue resistance of large Class II MOD defects when compared to direct Miris 2 composite resin restorations. The second null hypothesis can be also rejected since M2 Group showed a higher crack propensity and more severe enamel cracks compared to MZ100 inlays.

Table 2 – Crack propensity after 1 week of restoration and before fatigue test.

Group	No cracks	Cracks with less than 3 mm	Cracks with more than 3 mm
MZ100 ($n = 15$)	14 (93%)	1 (7%)	0 (0%)
M2 ($n = 15$)	8 (53%)	1 (7%)	6 (40%)

In this study, because of the high level of standardization procedures (tooth dimensions, tooth preparations, loading protocol, occlusal anatomy developed by a single operator), it was possible to limit considerably the amount of confounding variables normally found in clinical studies. Clinical evaluation represents the ultimate assessment of restorative materials and techniques. However, the influence of patients' masticatory and dietary habits, individual caries susceptibility, as well as the need for multiple operators and evaluators considerably weakens the significance of the data, especially in cross-sectional clinical studies [1,24]. This in vitro investigation rather aims at reproducing controlled, prospective and longitudinal clinical investigations because restorations are placed under ideal conditions, patients are often selected from easily available groups as dental students or dental school staff, who are highly motivated for oral health associated with excellent dentists, specially trained for the specific study [1,2]. Unlike those prospective clinical investigations, however, the present study yielded significant results in an extremely timely fashion. Clinical trials require 5 years or more, they limit the experimenter to a small sample population (due to the high costs) and may yield inconclusive results due to the variability in the patient population [44]. As it relates to the topic in this investigation, differences could be easily detected between the two experimental groups while clinical studies have not been able to reveal those differences between inlays and directs composite resin restorations [1,2,23]. Above all, a number of materials and products used for a clinical study might not be available in the market by the end of the trial due to the extremely high productivity of dental manufacturers and short product half-lives. The best laboratory reproduction of clinical situation is represented by the accelerated fatigue used in this research, originally introduced by Fennis et al. [45], because it is an intermediate test between the simple load-to-failure experiment and classical fatigue tests [40,43,46]. Static load experiments are not realistic because the specimen is forced to fail under displacement control of the load system, and generates data under drastic circumstances, with limited clinical significance [39]. At the same time, true fatigue tests (low-load/high-cycle) are time-consuming as demonstrated by Kuijs et al. [46] who reported that, in some pilot studies, specimens only failed after more than 1,000,000 cycles under moderate load. The closed-loop servo-hydraulics used in the present study reproduces closely a physiologic human mastication since it provides constant feedback alike the neuromuscular system and indicates an excellent agreement with clinical data [44]. Therefore, this mid-term fatigue test is considered a beneficial compromise between a clinically representative situation and the available in vitro testing methods [46].

A new approach in the present experiment is the use of enamel crack tracking before/after placing the restoration in a tooth as a whole. This represents an innovative way to evaluate the effects of polymerization shrinkage in a more clinically relevant fashion rather than measuring isolated composite resin specimens or cuspal flexure. This protocol could represent a new standard for the evaluation of direct composite resin materials. Large horizontal enamel cracks (Fig. 4c) are expected at the cusp base in case of large direct MOD restorations [11,14]. The results revealed that luted inlays represent the golden standard because only one specimen out of 15 in the MZ100 Group displayed some cracking (minor cracking only) 1 week after restoration. It can be anticipated that major cracking at the cusp base like observed in 40% of M2 specimens may induce microleakage and postoperative sensitivity. While this result was to be expected (large amount of shrinking composite resin), it was unanticipated that 53% of M2 specimens did not present any cracks 1 week after restoration. Two elements may account for this result. First, the use of Optibond FL (Kerr) as an adhesive system, may have contributed to the partial absorption of shrinkage stresses because of its viscosity and thickness exceeding 100 μm [47,48]. Second, because Miris 2 is a highly filled microhybrid material (65% by volume, 80% by weight) with nanoparticles (range of particle size 0.02–2.5 μm), resulting in lower shrinkage values compared to earlier formulations (Miris). Miris 2 is indicated for all purposes (direct and indirect, anterior and posterior teeth). It is particularly indicated for its simplicity of use, unique shade guide system, and tooth-like anatomical layering concept, "enamel shades for enamel replacement and dentin shades for dentin" yielding most favorable optical properties [49] and low slumping behavior and optimal consistency for sculpturing [50].

The clinical significance of shrinkage-induced enamel cracking may be questioned. Opdam et al. [24] did not report significant problems in large direct restorations (three, four and five surfaces) after 12 years. Clinical studies do not usually include postoperative crack-tracking using transillumination, therefore, it might not be possible to make any significant conclusion from such data. Enamel cracking is a normal aging process, and unless involving esthetic regions, enamel or restoration cracks are usually unnoticed by patients. Nevertheless, it is reasonable to state that cracking is not a desirable event. It may be also hypothesized that subsequent water-sorption, which is a known phenomenon of resin-based materials, may have slowly compensated for the shrinkage stress, hence allowing for reversing the negative effects of shrinkage cracks. As a matter of fact, polymerization shrinkage can be totally compensated by hygroscopic expansion within 4 weeks in teeth restored even with hydrophobic composite resin [51]. The "stress reversing" effect of water sorption might not have been possible in the present experiment because specimens were tested in accelerated fatigue only 1 week after restoration placement, thus possibly contributing to the difference between the two groups.

MZ100 inlays, were made from a "prepolymerized" material and logically did not yield any postoperative stress and related microfractures. Alike Miris 2, MZ100 is a microhybrid material (66% by volume, 85% by weight) with patented spheroidal zirconia–silica nanofillers. Magne and Knezevic [40,43] had previously compared MZ100 and M2 in an accelerated fatigue test using onlays on endodontically treated molars, which yielded to similar fatigue resistance. The excellent behavior of luted MZ100 and M2 restorations is in contrast with existing data from the literature. Results from studies about the survival rates of indirect composite resin restorations may have suffered from the early marketing of materials with particularly low elastic modulus (less than 6 GPa) and filler content (less than 60% in volume). Those early indirect systems, unlike MZ100 and M2, were designed to satisfy the dental technician's requirements in order to simulate handling properties similar to those of the porcelain. This flowable behavior allowed then to be placed with a brush (alike ceramics) but correlated with their poor physical performances [2,52]. Another element that may have contributed to the high success rate of MZ100 inlays in the present work is the use of the IDS technique and its combination to the use of a preheated restorative composite resin as a luting material. This delivery protocol has proven to produce extremely cohesive interfaces [39–41,43].

It can be concluded that both experimental groups yielded excellent results up to 1200 N, which largely exceeds physiological human masticatory forces of 8–880 N [53]. Even maximum bite forces of 600–900 N [54,55] were sustained by all specimens in both groups and differences could be found only in the last load steps (1200 and 1400 N). Those high loads are rarely reached in ordinary circumstances but only in trauma or masticatory accidents. Above all, most of failures in M2 were re-restorable. Based on all the above, it cannot be concluded that large direct MOD defects are contraindicated for restoration with direct composite resin Miris 2. Such restorations, even though presenting a higher crack propensity and failure rate at high load, may serve well the patients of practitioners who have limited access to the newer CAD/CAM tools.

5. Conclusions

Within the limitations of this in vitro study, it can be concluded that:

1. CAD/CAM composite resin inlays seem to be ideal to restore large MOD defects. They increased the fatigue resistance of restored molars when compared to direct composite resin restorations. None of the inlays failed after 185,000 cycles, while only 2 specimens survived all fatigue cycles in the direct composite group (13%).
2. For direct composite resin restorations, the majority of the fractured teeth presented a restorable failure (67%).
3. Large direct composite restorations has significantly higher crack propensity (47%), induced by polymerization shrinkage, compared to inlays (7%).
4. While both CAD/CAM and direct composite resin restorations yielded excellent fatigue results at physiological masticatory loads to restore large MOD defects, CAD/CAM inlays indications can be extended even to high-load patients.

Acknowledgments

The authors wish to express their gratitude to Elisa Oderich for her assistance in statistical analysis; 3M-ESPE, St. Paul, MN, for Paradigm MZ100 blocks and Filtek Z100 composite resin; Kerr, Orange, CA, for Optibond FL; Ultradent, South Jordan, UT, for Ultra-etch 35% Phosphoric Acid and Silane; Addent, Danbury, CT for Microlux; Heraeus Kulzer, Armonk, NY, for Palapress; Komet, Lemgo, Germany, for kit 4477 Q-Polishing System; and Coltène-Whaledent, Altstätten, Switzerland, for Miris2 composite resin. Based on a thesis submitted to Federal University of Santa Catarina, in partial fulfillment of the requirements for PhD degree. This investigation was supported in part by Brazilian Federal Agency for Support and Evaluation of Graduate Education - CAPES (grant no. BEX 2383-10-1).

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