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Fatigue and marginal adaptation of bulk fill restoratives: Effect of the layering technique and cavity dimension of extensively damaged teeth

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ABSTRACT

Objectives: To evaluate the effect of layering technique and cavity dimension on the fatigue behavior and marginal adaptation of bulk fill (BF) restorations in extensively **damaged** teeth.
Methods: Seventy-two premolars received class II cavities (MOD) followed by endodontic treatment. Half sample had 1/3 of their palatal cusp removed. Teeth were restored using three techniques: (I) incremental, with conventional **resin composite** (RC); (C) combined, using BF flow and RC, (B) bulk fill, with regular BF. Specimens were subjected to fatigue (80 N, 2 Hz, 37° C water) for 1 million cycles (n = 12). The test was interrupted every 250,000 cycles to evaluate **tooth integrity, restoration fracture and adaptation using** FDI criteria. Images of the proximal surfaces were obtained before and after the cycling to measure the gap. Restoration fatigue survival and success were analyzed using Weibull distribution and Maximum Likelihood **Estimation**. Gap thickness was analyzed with Kruskal-Wallis and Student-Newman-Keuls tests (α = 0.05).
Results: For the survival analysis, Weibull modulus (β) and characteristic lifetime (η) were similar among groups. Yet, for the success analysis, in which only restorations that were free of technical complications were ranked as success, the bulk-fill technique resulted in higher β, while the combined technique produced restorations with higher η, for teeth that had their cusp removed. C-technique also resulted in smaller gaps than I and B.
Significance: The effect of the layering technique on the success of restorations was dependent on the cavity extension. The combined technique favors the adaptation and the longevity of extensively **damaged** teeth.

1. Introduction

Conventional **resin composites** (RC) remain the gold standard for direct dental restorations, and they are in constant optimization. Nevertheless, tooth-level factors, such as the cavity extension, number of lost walls, and presence of endodontic treatment, negatively impact the restorations survival rate [1–3]. In addition, to reduce the RC polymerization shrinkage, that induces stresses at the adhesive interface, a time-consuming and multiple-step incremental layering technique is required [4]. Therefore, aiming for a more efficient clinical treatment, low-shrinkage **resin composites** that can be used in increments up to 5 mm thick, known as Bulk Fill (BF) restoratives, were developed. Reduction in the polymerization shrinkage was achieved by the introduction of monomers that act as modulators in the polymerization reaction. A higher depth of cure was allowed by the use of more reactive photoinitiators and by increasing the materials' translucency [4–11]. The smaller number of increments also reduces the chances of incorporating voids between resin layers [5,7,8,12], and a faster technique is especially desired to restore teeth with extensive structure loss, such as the ones with endodontic treatment or with cusp fracture [13–18].

Systematic reviews and meta-analysis suggest that BF have similar or superior mechanical performance compared to conventional RC [6,8,9]. Furthermore, studies found similar marginal integrity and fracture resistance for endodontically treated teeth restored with BF and RC, regardless of the layering technique applied [15,17,18]. However, most of these studies failed to investigate the fatigue behavior of BF restoratives. Clinically, restorations are subjected to cyclic loads in a humid environment with varying temperature and pH, which could lead

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to the chemical degradation of the **resin composite**, the subcritical crack growth of pre-existing flaws, and the degradation of the bonding interface [19–23]. The aggressive conditions of the oral environment can result in tooth and/or restoration fractures, and marginal integrity failure [8,9,12,24–29].

BF restoratives can be found as flowable (BFF) or regular (BFR) materials. The flowable composite presents a smaller amount of filler particles and is commonly used as a cavity liner due to **its lower wear resistance and, in most cases, lower flexural strength than the regular ones**. Therefore, a combined technique is indicated, in which a regular BF or conventional RC is applied on the occlusal surface of the restoration [6,7,13,15,30]. Regular BF restoratives have a greater filler content than the flowable materials and can be used without a covering material to produce the restorations [6,7,15]. A 5-year clinical trial showed that the annual failure rate of class II restorations on vital teeth produced with the combined and the incremental techniques were 1.4 % and 2.1 % respectively [25]. On the contrary, a 4-year follow-up found greater marginal discoloration for **restoration** produced with the combined technique [26]. Clinical studies that compared the bulk fill and the incremental techniques reported comparable performance and low failure rates [9,12,24,27,28,30,31]. Tooth and restoration fractures, secondary caries, marginal discoloration and poor adaptation were the main reasons for failure [8,9,12,24–28]. Nevertheless, most clinical trials are restricted to a highly controlled environment, where tooth with endodontic treatment and extensive coronal destruction are not included [8,9].

Therefore, the aim of this study is to evaluate the effect of the layering technique (incremental, combined and bulk-fill) and cavity dimension (presence or absence of palatal cusp) on the fatigue behavior and marginal adaptation of endodontically treated teeth restored with BF and RC restoratives. The time required to produce a restoration with the different layering techniques was also evaluated. The study hypotheses are: (1) the type of layering technique has no influence on the survival and success of restorations subjected to fatigue; (2) the partial removal of a cusp affects the survival and success of restorations subjected to fatigue; (3) the type of layering technique affects the marginal adaptation between tooth and restoration; (4) the type of layering technique influences the time required to produce the restoration.

2. Materials and methods

The study was approved by the local Ethics in Research Committee (protocol n. 4.472.369). Seventy-two healthy human upper premolars, without caries, without visible resorptions or cracks, were obtained from the Biobank of the Dental School and stored in distilled water. Periodontal curettes were used to remove calculus and soft tissue deposited around the tooth. Teeth included in the study had the following dimensions: 8.47–10.59 mm in the buccolingual direction and 6.38–8.19 mm in the mesiodistal direction [15].

The restorative materials used in the study are described in Table 1. Two independent variables were investigated: layering technique (I – incremental, C – combined, B – bulk fill) and cavity dimension (c – presence of all cusps, nc – absence of 1/3 of the palatal cusp). The experimental groups are presented in Table 2 and Fig. 1a. The study outcomes were: (1) survival and success of tooth/restoration subjected to fatigue; (2) marginal adaptation of the restoration; (3) time required to produce the restoration.

2.1. Specimens preparation

All teeth were prepared with Class II MOD cavities by a single operator with #2214 diamond bur (KG Sorensen, Cotia, SP, Brazil) in a high-speed handpiece (Kavo, Joinville, SC, Brazil), under water cooling. The handpiece was coupled to a device that allows standardization of the preparation. Burs were replaced every 10 cavity preparations. The cavity dimensions are presented in Fig. 1a [13]. Half of the sample was randomly assigned to group no cusp (nc), in which 1/3 of the **palatal** cusp was removed after cavity preparation, as shown in Fig. 1a.

After the cavity preparations, standard endodontic accesses were performed with a #1012 diamond bur (KG Sorensen, Cotia, SP, Brazil) and Endo Z bur (Dentsply Maillefer, Ballaigues, Switzerland) with a high-speed handpiece (Kavo, Joinville, SC, Brazil) under water cooling. The coronal pulp was removed with a curette. Endodontic instrumentation was performed at the level of the apical foramen with a Reciproc R40 file (VDW, Munich, Bavaria, Germany) and a X-Smart Plus motor handpiece (Dentsply Sirona, Ballaigues, Switzerland). The irrigating substances used were saline solution and 2 % chlorhexidine gel. Subsequently, teeth were filled with gutta-percha cones and endodontic cement (AH Plus, Dentsply, Konstanz, Germany) using the lateral

Table 1
Description of the restorative materials used in the study.

Material	Type	Organic composition[c]	Inorganic composition
Filtek Z350XT[a]	RC - Resin Composite	Bis-GMA, UDMA, TEGDMA and bis-EMA.	Silica (20 nm) and zirconia (4–11 nm) filler: 78.5 % weight (63.3 % volume)
Filtek Bulk Fill Flowable Restorative[a]	BFF - Bulk Fill Flow Resin Composite	Bis-GMA, Bis-EMA, UDMA and procrylat resins	Silica (20 nm), zirconia (4–11 nm) and ytterbium trifluoride (100 nm) filler: 64.5 % weight (42.5 % volume).
Filtek One Bulk Fill Restorative[a]	BFR - Bulk Fill Regular Resin Composite	AFM (dynamic stress-relieving monomer), AUDMA, UDMA and 1, 12-dodecane-DMA	Silica (20 nm), zirconia (4–11 nm) and ytterbium trifluoride (100 nm) filler: 76.5 % weight (58.5 % volume)
Condac 37 %[b]	37 % Phosphoric Acid	-	-
Single Bond Universal Adhesive[a]	Universal Adhesive	MDP Phosphate Monomer, Dimethacrylate resins, HEMA, Vitrebond Copolymer, Filler, Ethanol, Water, Initiators and Silane	-

[a] Information provided by 3 M Oral Care, St Paul, MN, USA.
[b] Information provided by FGM, Joinville, SC, Brazil.
c Subtitle: Bis-GMA - bisphenol A-glycidyl methacrylate; UDMA - urethane dimethacrylate; TEGDMA - triethylene glycol dimethacrylate; bis-EMA - bisphenol A ethoxylated dimethacrylate; AUDMA - aromatic urethane dimethacrylate; MDP - Methacryloyloxydecyl dihydrogen phosphate; HEMA - hydroxyethyl methacrylate.

Table 2
Description of the experimental groups.

Groups	Layering Technique	Cavity dimension
I-c	Incremental technique: 2-mm thick increments of RC	Class II MOD
C-c	Combined technique: 4-mm thick layer of BFF + 2-mm thick increments of RC	Class II MOD
B-c	Bulk-fill technique: 5-mm thick increments of BFR	Class II MOD
I-nc	Incremental technique: 2-mm thick increments of RC	Class II MOD + 1/3 palatal cusp removal
C-nc	Combined technique: 4-mm thick layer of BFF + 2-mm thick increments of RC	Class II MOD + 1/3 palatal cusp removal
B-nc	Bulk-fill technique: 5-mm thick increments of BFR	Class II MOD + 1/3 palatal cusp removal

Subtitle: RC - Resin Composite; BFF - Bulk Fill Flow Resin Composite; BFR - Bulk Fill Regular Resin Composite; MOD – mesio-occlusal-distal.

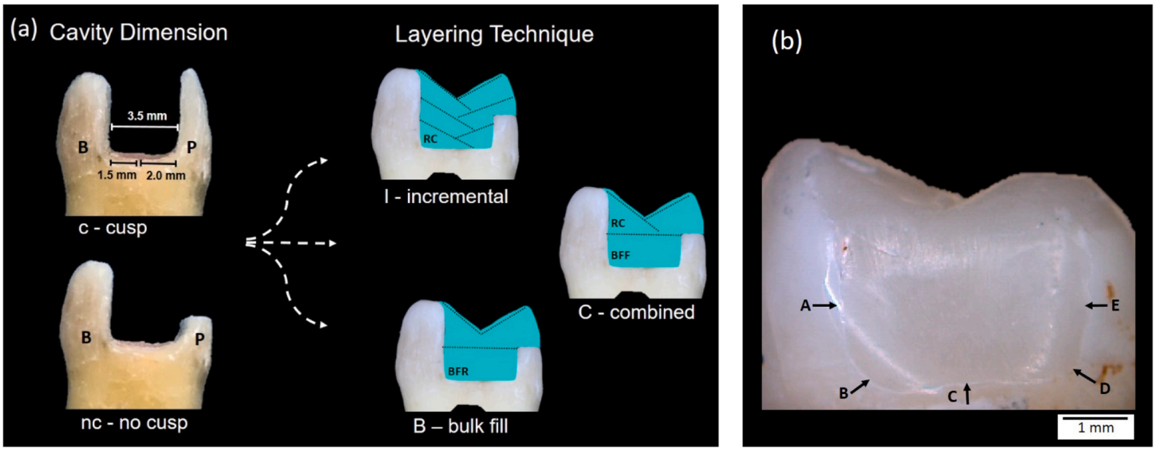

Fig. 1. (a) Images of the teeth with MOD cavities prepared as follows: total bucco-palatal (B-P) length of 3.5 mm, 1.5 mm in the buccal direction and 2.0 mm in the palatal direction, starting from the center of the occlusal surface. The cervical margin was placed 1 mm above the cementoenamel junction. Cusp and no-cusp groups and the respective layering techniques, I – incremental, C – combined, B – bulk fill. (b) Image of a restored teeth from group B-nc showing the five (A to E) measurement regions used to evaluate the gap thickness between tooth and restoration. RC – **Resin Composite**; BFF - Bulk Fill Flow **Resin Composite**; BFR - Bulk Fill Regular **Resin Composite**.

condensation technique, 1 mm short of the working length. Cones were cut 3 mm below the entrance of the root canals, which was sealed with temporary cement (Coltosol, Vigodent-Coltene, Rio de Janeiro, Brazil). Teeth were stored in 37 °C distilled water for 24 h to allow the materials to fully set. The temporary cement was fully removed prior to the restorative steps.

Prepared teeth received an artificial periodontal ligament to properly simulate the oral conditions during the fatigue test [32]. Roots were covered with a layer of wax of 0.2–0.3 mm thickness at 2-mm distance from the cervical margin. Waxed roots were placed in PVC cylinders containing epoxy resin (Crystal Epoxy Resin, Redelease, Sao Paulo, Brazil). After the material was set, the teeth were taken out, and the wax was removed with hot water. The space was filled with polyether (Impregum Soft, 3 M Oral Care, St Paul, MN, USA), followed by the insertion of the teeth back into the artificial alveolus.

2.2. Restorative procedure

Teeth were randomly assigned into 6 experimental groups (n = 12), as described in Table 2. Selective acid etching of enamel was used for all groups. The enamel was treated with 37 % phosphoric acid (Condac 37 %, FGM, Joinville, SC, Brazil) for 30 s, rinsed with water for 60 s and then air-dried. A single layer of universal adhesive (3 M Single Bond Universal Adhesive, 3 M Oral Care, St Paul, MN, USA) was applied over the dentin and enamel surface for 20 s under friction, air-dried for 5 s (to evaporate the solvent) and photoactivated for 20 s. The same light curing unit was used to produce all restorations (1200 mW/cm^2, Radii-cal, SDI, Bayswater, Australia). Subsequently, a metallic matrix was fixed on each prepared tooth to allow the construction of the proximal walls of the restoration, and a modified hemostatic forceps was used to simulate the function of an interdental wedge in order to ensure correct marginal adaptation.

Groups I-c and I-nc were restored with conventional **resin composite** (RC - Filtek Z350XT, 3 M Oral Care, St. Paul, MN, USA) following the incremental technique. Each increment had a maximum thickness of 2 mm and was individually light-cured for 20 s. Groups C-c and C-nc followed the combined technique, where the pulp chamber and cavity floor were filled with one 4-mm increment of a flowable bulk fill restorative (BFF - Filtek Bulk Fill Flowable Restorative, 3 M Oral Care, St. Paul, MN, USA) and light-cured for 40 s at the occlusal surface. A 2-mm thick covering layer of RC was inserted into the occlusal surface and light-cured for 20 s. Groups B-c and B-nc were restored with a regular bulk fill restorative (BFR - Filtek One Bulk Fill Restorative, 3 M Oral Care, St Paul, MN, USA) in 5-mm thick increments, light cured for 20 s on the buccal, occlusal and palatal surfaces. A millimeter probe was used to measure the depth of the cavities and to standardize the thickness of the increments for all experimental groups. **For all restorations, when the last increment of resin composite was inserted (before light curing), tooth and antagonist were placed in an alignment device and the antagonist was used to shape the occlusal anatomy as to guarantee standardization and tripoidism contacts.**

A surface finishing protocol was performed using Sof-Lex Pop-On discs (3 M Oral Care, St Paul, MN, USA) and rubber polishing burs (Ultra-Gloss, American Burrs, Palhoca, SC, Brazil) using a low-speed motor with irrigation, by one trained operator. The quality of the surface finish was **verified** with a stereomicroscope (Stemi 2000, Zeiss). Restored teeth were kept in 37 °C distilled water prior to adaptation analysis and fatigue testing.

2.3. Time evaluation

The time required to produce each restoration was measured for all prepared teeth. Time was measured, in seconds, from the beginning, defined as the moment of insertion of the first **resin composite** increment into the cavity, to the end of the restorative procedure, when light curing was completed.

2.4. Fatigue test

The fatigue test was performed in a pneumatic mechanical cycling machine, with 2 Hz frequency, in water at 37º C. A load of 80 N was applied **in the vertical direction** to the restoration occlusal surface by an anatomic piston (tripoidism contact at cusps and crystal ridge) produced with a dentin analogue material (NEMA G10, glass-fiber reinforced epoxy resin), for a total time of 1 million cycles [20]. **A negative copy of the occlusal surface of a premolar was used to design the pistons, which were milled using a mechanic lathe (Romi GL240, Romi Industries S.A., Santa Barbara d'Oeste, SP, Brazil). The antagonist was always in contact with the restoration occlusal surface during the test, aiming to avoid impact and wear. Each restoration was loaded by a new piston.**

Three previously calibrated researchers were responsible for evaluating the specimens using the FDI World Dental Federation criteria [33]. **The system is based on three categories, aesthetic, functional and biological, which are further divided in subcategories. Three types of functional criteria were assessed in the present study: tooth**

integrity, restoration fracture and marginal adaptation. These variables were classified into five categories (scores) [33]: 1 - excellent, 2 - good, 3 - satisfactory, 4 - unsatisfactory but repairable, 5 - need for replacement. Interexaminer reliability was measured **by Cohen's kappa comparing each examiner with a gold-standard examiner, with previous experience in FDI criteria. The kappa value for FDI criteria** ranged between 0.81 and 0.92. Specimens were evaluated at 5 pre-defined periods: before the test (baseline) and after 250,000, 500,000, 750,000 and 1 million cycles.

Subsequently, for the variable restoration fracture, two outcomes were generated, one for the fatigue survival analysis and another for the success analysis. Survival was considered when restoration was ranked as 1, 2 and 3; success was considered when restoration was ranked as 1 and 2. For the success analysis, restoration chipping (score 3) was considered failure [20].

2.5. Marginal gap measurement

All specimens were taken to a stereomicroscope (Stemi 2000, Zeiss) to obtain images of the restoration margins at the proximal surfaces (mesio and distal), before and after the fatigue test (1 million cycles). The proximal surface was mapped and sub-divided in five regions, in which images were taken with 5.0 x magnification [5]. Gaps thickness (μm) at 5 regions, each of them equally spaced across the interface, were measured using image editing software *(Image J)* by a single calibrated researcher as shown in Fig. 1b.

2.6. Statistical analysis

The frequency of each FDI score, after 1 million cycles, for the experimental groups were analyzed with Fischer's exact test using the Stata 14.0 software (StataCorp, College Station, TX). For the restoration fracture FDI parameter, survival and success fatigue data were analyzed using the two-parameter Weibull distribution and Maximum Likelihood **Estimation** (MLE). The 90 % confidence intervals (CI) were analyzed using the Likelihood Ratio Method (LRB), **which is a more accurate method when working with smaller sample sizes. Failure and censured data were used in the statistical models.** Fatigue data analysis was performed using Weibull+ + reliability software (Reliasoft).

Gap thickness data failed Shapiro-Wilk normality test ($p > 0.05$). Kruskal-Wallis and Student-Newman-Keuls tests were used to compare the gap thickness (average of all measurement points) between all experimental groups ($\alpha = 0.05$). For restorations produced with the same technique, Wilcoxon Signed Rank test was used to compare the gap thickness at each measurement point before and after fatigue ($\alpha = 0.05$). Kruskal-Wallis and Student-Newman-Keuls tests were used to compare the thickness at different measurement points for the same layering technique ($\alpha = 0.05$).

Time data failed Shapiro-Wilk normality test ($p > 0.05$) and were analyzed with Kruskal-Wallis and Student-Newman-Keuls tests ($\alpha = 0.05$).

3. Results

3.1. Survival and success analysis

The frequency of each score of the FDI parameters tooth integrity, restoration fracture and marginal adaptation for the experimental groups, after fatigue testing for 1 million cycles, are shown in Table 3. There were no differences among groups for tooth integrity, restoration fracture and marginal adaptation ($p > 0.05$). When the independent variable "layering technique" was analyzed separately, there were no differences between the evaluated parameters ($p > 0.05$). When the independent variable "cavity dimension" was analyzed, a lower frequency of clinically excellent restorations was found for no-cusp groups for the FDI parameter restoration fracture ($p = 0.011$).

Fatigue survival (failure = scores 4 and 5) and success (failure = scores 3, 4 and 5) analyses for the restoration fracture parameter are shown in Table 4. The Weibull modulus (β) parameter describes the relative spread of fatigue data in the lifetime distribution. The characteristic lifetime (η) parameter corresponds to the number of cycles for a 63.2 % failure probability [23]. For the survival analysis, β and η values were similar among the experimental groups, as the 90 % confidence intervals (90 % CI) overlapped.

For the success analysis, B-nc group showed the highest β values, since the 90 % CI did not overlap with the other groups, meaning less spread of the fatigue data. Reliability versus time graphs for the success analysis are presented in Fig. 2. When restorations of teeth with all cusps were compared, η value was similar between different layering techniques. Yet, for no-cusp groups, the combined technique resulted in higher η value of restorations than the bulk-fill technique (90 % CI did not overlap). The Weibull parameters of the success analysis were used to predict the probability of failure (P_f) of restorations after 5×10^5 cycles and 1×10^6 cycles at 80 N (Table 4) [23]. The P_f of restorations after 1×10^6 cycles for I-nc and B-nc groups were 41 % and 45 %,

Table 3
Comparison between experimental groups, according to the FDI criteria, after fatigue testing for 1 million cycles (compared by Fisher's exact test at $p < 0.05$).

Groups	FDI criteria[a]							
	Restoration Fracture		Tooth integrity		Marginal adaptation		Total restoration evaluation	
	% of restorations within each score (1/2/3/4/5)	p-value*	% of restorations within each score (1/2/3/4/5)	p-value*	% of restorations within each score (1/2/3/4/5)	p-Value*	Success[b] Without small fractures	Survival[c] Clinically Acceptable
I-c	75.0/0.0/0.0/8.3/16.7	0.656	0.0/75.0/0.0/8.3/16.7	0.656	58.3/0.0/16.7/8.3/16.7	0.544	75.0 %	75.0 %
C-c	75.0/0.0/0.0/0.0/25.0		0.0/75.0/0.0/0.0/25.0		66.7/8.3/0.0/0.0/25.0		75.0 %	75.0 %
B-c	91.7/0.0/0.0/0.0/8.3		0.0/91.7/0.0/0.0/8.3		83.3/0.0/8.3/0.0/8.3		91.7 %	91.7 %
I-nc	41.7/16.7/16.7/0.0/25.0	0.412	0.0/75.0/0.0/0.0/25.5	0.656	41.6/16.7/16.7/0.0/25.0	0.134	58.3 %	75.0 %
C-nc	75.0/8.4/0.0/8.3/8.3		0.0/83.4/0.0/8.3/8.3		83.4/0.0/0.0/8.3/8.3		83.3 %	83.3 %
B-nc	41.7/8.3/25.0/0.0/25.0		0.0/75.0/0.0/0.0/25.0		50.0/0.0/25.0/0.0/25.0		50.0 %	75.0 %
Cusp	80.6/0.0/0.0/2.8/16.6	0.011	0.0/80.6/0.0/2.8/16.6	0.954	69.4/2.7/8.3/2.8/16.6	0.866	80.6 %	80.6 %
No cusp	52.8/11.1/13.9/2.8/19.4		0.0/77.8/0.0/2.8/19.4		58.3/5.6/13.9/2.8/19.4		63.9 %	77.8 %
Incremental	58.3/8.3/8.3/4.2/20.8	0.770	0.0/75.0/0.0/4.2/20.8	0.953	50.0/8.3/16.7/4.2/20.8	0.257	66.7 %	75.0 %
Combined	75.0/4.2/0.0/4.2/16.6		0.0/79.2/0.0/4.2/16.6		75.0/4.2/0.0/4.2/16.6		79.2 %	79.2 %
Bulk	66.7/4.2/12.5/0.0/16.6		0.0/83.4/0.0/0.0/16.6		66.7/0.0/16.7/0.0/16.6		70.8 %	83.3 %

[a] Numbers separated by slashes represent the percentage of evaluated restorations for each score, according to the FDI criteria. Only parameters relevant for the fatigue test were evaluated.
[b] Scores 1 and 2 represent restorations without small fractures/defects (FDI criteria) at the time of evaluation.
[c] Scores 1, 2 and 3 represent restorations that are clinically acceptable (FDI criteria) at the time of evaluation.
* Fisher's exact test.

Table 4
Weibull's modulus (β) and characteristic lifetime (η) parameters of the fatigue survival and success analysis, with their respective 90 % confidence intervals (90 % CI), for the experimental groups. Probability of failure (P_f) for 500,000 and 1,000,000 cycles estimated in the success analysis, with their respective 90 % confidence intervals (90 % CI).

Group	Survival Analysis - Parameters				Success Analysis - Parameters				Success Analysis - Probability of Failure (P_f)			
									500,000 cycles		1,000,000 cycles	
	β*	β - 90 % CI	η*(n. cycles)	η - 90 % CI	β*	β - 90 % IC	η*(n. cycles)	η - 90 % CI	P_f (%)	90 % CI	P_f (%)	90 % CI
I – c	1.1 a	0.4; 2.5	3.2×10^6 a	1.4×10^6; 6.6×10^7	1.1 b	0.4; 2.5	3.0×10^6 a	1.3×10^6; 5.3×10^7	12	0.3; 30	25	8.9; 48
C – c	1.5 a	0.5; 3.4	2.3×10^6 a	1.2×10^6; 2.0×10^7	1.0 b	0.5; 3.6	3.6×10^6 ab	1.2×10^6; 2.8×10^7	12	0.2; 28	23	8.0; 50
B – c	0.7 a	0.1; 2.7	2.6×10^7 a	2.1×10^6; 1.6×10^{18}	0.7 b	0.1; 2.7	2.6×10^7 a	2.1×10^6; 1.6×10^{18}	5.1	0.1; 20	8.4	1.0; 28
I – nc	1.0 a	0.3; 2.1	3.5×10^6 a	1.4×10^6; 1.2×10^8	1.6 b	0.7; 2.9	1.5×10^6 ab	9.9×10^5; 4.0×10^6	16	5.4; 35	41	20; 64
C – nc	0.8 a	0.2; 2.0	8.8×10^6 a	1.8×10^6; 3.2×10^{10}	0.8 b	0.2; 2.0	8.8×10^6 a	1.8×10^6; 3.2×10^{10}	10	2.3; 28	17	4.3; 39
B - nc	5.5 a	1.9; 12	1.3×10^6 a	1.1×10^6; 2.3×10^6	10.7 a	5.2; 19	1.1×10^6 b	9.9×10^5; 1.2×10^6	0.0	0.0; 0.0	45	24; 66

*Values followed by similar letters in the same column are statistically similar as the 90 % CI did not overlap.

respectively; while for C-nc group the P_f was 17 %.

The restoration failure modes identified during the fatigue teste were: intact restoration (score 1); presence of cracks (score 2 - Fig. 3a); restoration chipping (score 3 - Fig. 3b); restoration partial fracture involving the marginal ridge and/or the cusp (score 4 – Fig. 3c); catastrophic fracture involving the restoration and the tooth (score 5 - Fig. 3d).

3.2. Marginal Gap

The average of the gap thickness collected at all measurement points was used to compare the adaptation of restorations produced with the three different techniques (Table 5). Combined technique resulted in statistically smaller gap thickness than incremental and bulk-fill techniques. Additionally, the gap thickness of restorations produced with incremental and bulk-fill techniques increased after fatigue.

For each technique separately, the gap thickness at each measurement point was compared (Table 5). For the incremental and bulk-fill techniques, there were significant differences between regions. Overall, regions B and D, which corresponded to the cavity angles, showed greater gaps. For these regions, there was also statistical difference before and after fatigue. For the combined technique, the gap thickness was similar among measurement regions.

3.3. Time evaluation

There were significant differences between the groups for the time required to produce the restoration ($p < 0.001$), as shown in Fig. 4. Group I-nc resulted in the highest values, while groups B-c and B-nc had statistically similar and lower values.

4. Discussion

Both dentists and patients seek for restorative treatments that are conservative, have a good cost-effectiveness and great clinical longevity. Therefore, the present in vitro study focused on investigating variables that could help predicting the clinical behavior of endodontically treated teeth rehabilitated with direct restorations, produced with different layering techniques and restorative materials. Moreover, considering the difficulties of restoring extensively **damaged** teeth, bulk fill (BF) restoratives were investigated as they could simplify the treatment and reduce the clinical time [8,9,14,26].

The type of layering technique had no influence on the survival of restorations subjected to fatigue, but affected the success of restorations on extensively **damaged** teeth without a cusp, partially accepting the first study hypothesis. In the present investigation, data on restoration fracture over time was used in the fatigue analysis, considering that clinical studies have shown that fracture of the restoration is one of the most frequent type of failure for posterior teeth [1,2,12,25,28]. Minor fractures, such as chipping, are likely to be repaired. However, major fractures require restoration replacement and, depending on the extension, could lead to the loss of the tooth [2,3]. Therefore, for the fatigue survival analysis, restoration fracture involving the marginal ridge and/or the cusp (FDI score 4) and catastrophic fracture of the restorations/tooth (FDI score 5) were considered failures. For the fatigue success analysis, the restoration was ranked as success when it was free of technical complications, meaning that restoration chipping (FDI score 3) was included as failure [20].

For the success analysis, restorations on no-cusp teeth produced with the bulk fill technique had higher Weibull modulus, indicating less spread of fatigue data in the lifetime distribution [22,23]. Bulk fill technique involves a lower number of clinical steps, which could reduce the incorporation of air voids, producing a more homogeneous structure and resulting in a more predictable treatment [10,14]. In addition, for both fatigue survival and success analysis, when the incremental and bulk fill techniques were compared, the characteristic lifetime of the restorations was similar. For example, the probability of failure for restorations subjected to 1 million cycles at 80 N load was predicted to be 41 %, 45 % and 17 % for I-nc, B-nc and C-nc groups, respectively. These results could be partially explained by the fact that the mechanical properties of the regular bulk fill (BFR) restorative evaluated in the present study are in the same range of the conventional RC [34,35]. Besides the differences in the polymeric matrix, both materials have similar type and content of inorganic fillers, as described by the manufacturer (Table 1). Moreover, a study reported similar reliability and strength degradation over time for BF in comparison to RC, using a dynamic fatigue method [22].

For no-cusp teeth, the combined technique resulted in high number of cycles to **failure**, being superior to the bulk fill technique, but statistically similar to incremental technique. The low filler content, low elastic modulus, flowable bulk fill (BFF) restorative may improve the absorption and dissipation of the compressive forces, while the conventional RC in the occlusal surface could provide fracture strength and wear resistance, resulting in greater survival of the restoration in fatigue [6,8,13,15,16]. A 3-year follow-up study reported good clinical performance and absence of fractures for endodontic treated teeth restored with the combined technique, corroborating with our findings [16]. As for the time required to produce the restoration, the combined technique is more time-consuming than the bulk fill technique, but it is faster than the incremental one, accepting the study hypothesis.

In the present investigation, teeth that had 1/3 of the palatal cusp removed showed a lower frequency of clinically excellent restorations, partially accepting the second study hypothesis. In addition, as already discussed, the fatigue success of restorations on no-cusp teeth was dependent on the type of layering technique, while for teeth with all cusps this effect was not observed. Literature has shown that the presence of endodontic treatment and a greater number of restored surfaces increases the risk of restoration failure [1–3]. As the restorative challenge of no-cusp groups was greater, the restoration success was more dependent on the properties of the restorative materials and more

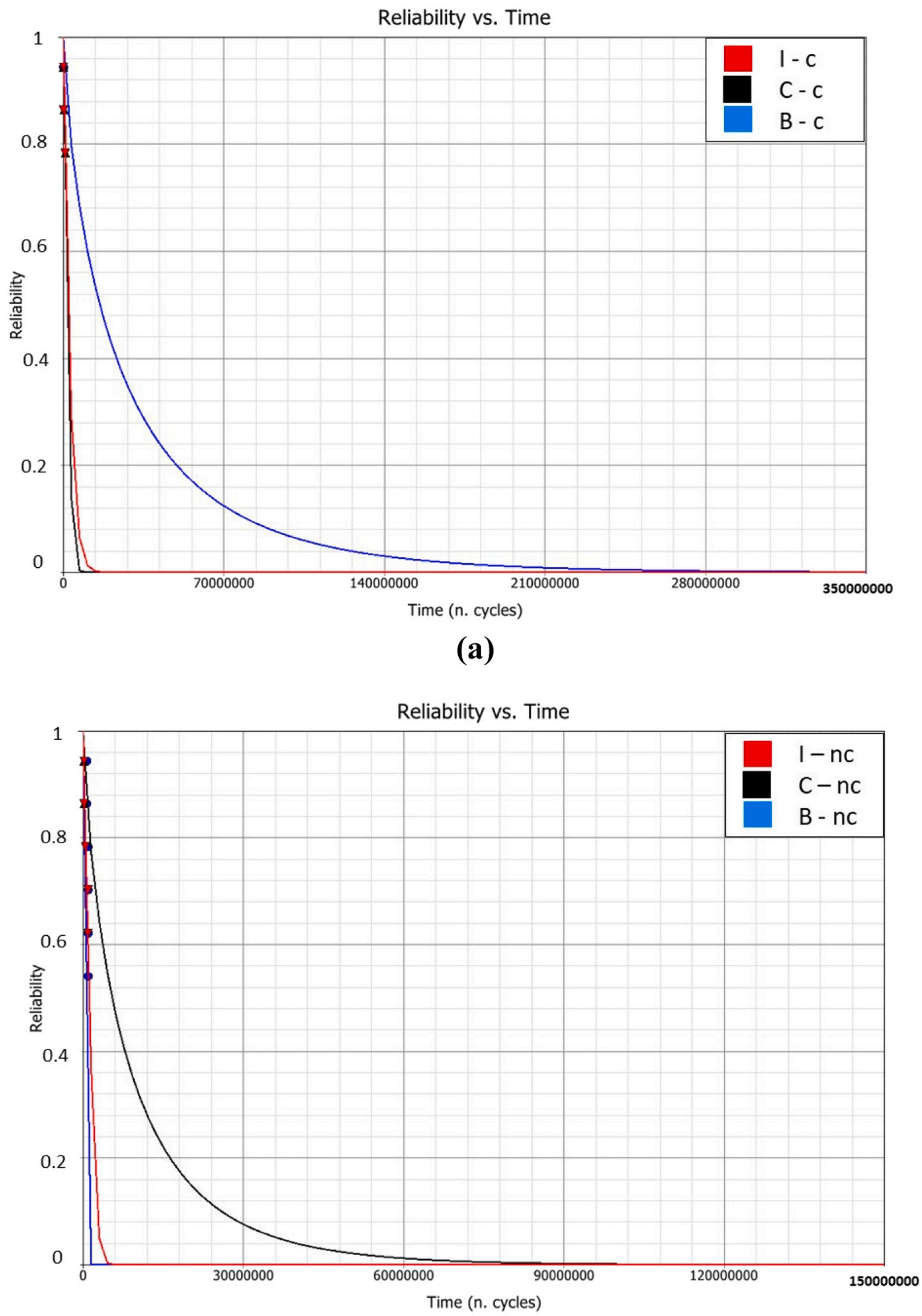

Fig. 2. Reliability versus time graphs for the success analysis of cusp and no-cusp groups. (a) For teeth with cusp, bulk fill technique (B-c) resulted in high number of cycles to failure (blue curve), but not statistically different than combined (C-c) and incremental (I-c) techniques. (b) For teeth without the palatal cusp, the combined technique (C-nc) led to greater number of cycles to failure (black curve) than bulk fill (B-nc), but statistically similar to the incremental technique (I-nc).

sensitive to differences in the layering technique.

FDI World Dental Federation criteria is a standard criterion used to assess dental restorations in clinical trials, proposed by Hickel et al. and approved by the Science Committee of the FDI World Dental Federation. FDI criteria was used to evaluate the tooth integrity, restoration fracture and marginal adaptation aiming to improve the correlation among clinical and laboratory findings [33]. Nevertheless, when adaptation was accessed using FDI criteria, there were no statistical differences among groups. On the contrary, when images of the interface between tooth and restoration at the proximal surfaces were obtained with an esteromicroscope and measured using a software, it was possible to observe that the combined technique produces more homogeneous and smaller gap thickness. Thus, the third study hypothesis was accepted. Multiple factors are related to marginal

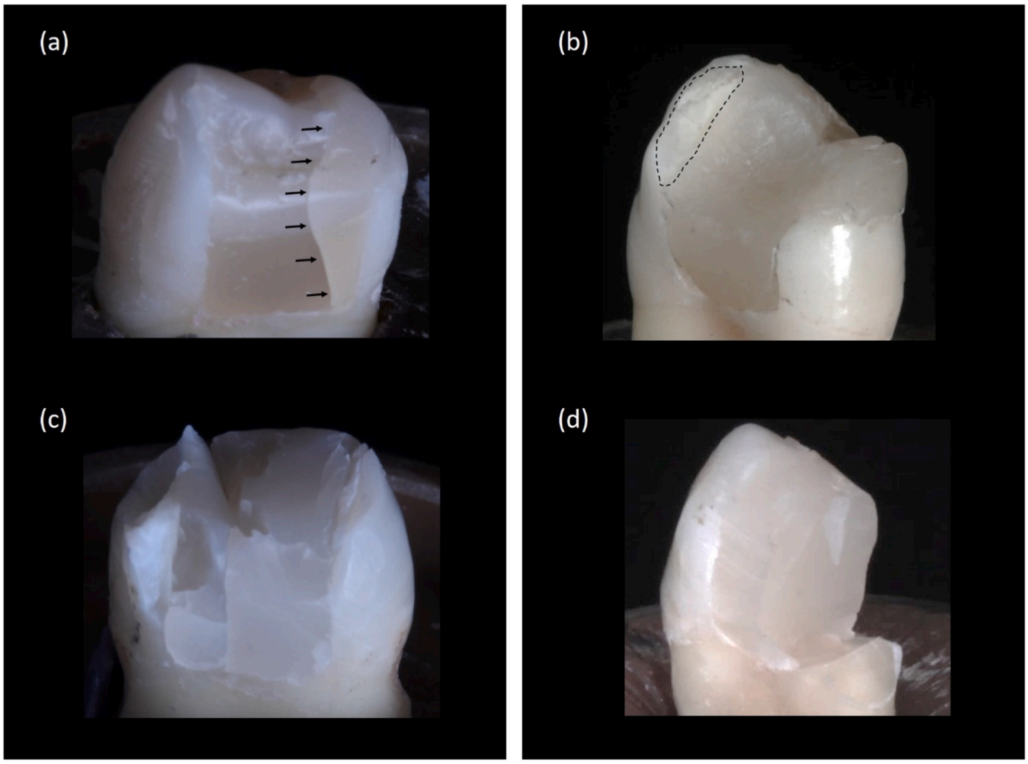

Fig. 3. Representative failure modes observed during the fatigue test for FDI restoration fracture criteria: (a) score 2 – presence of cracks as shown by the black arrows; (b) score 3 – restoration chipping (delimited by the black dots); (c) score 4 - restoration partial fracture involving the marginal ridge and the cusp (d) score 5 - catastrophic fracture involving the restoration and the tooth.

Table 5
Mean gap thickness (μm) of restorations produced with different techniques and at different measurement points, before and after fatigue testing.

Layering Techniques – average of all regions						
Incremental		**Bulk-fill**		**Combined**		**p-value**
Before	**After**	**Before**	**After**	**Before**	**After**	
117 C	170 A	93.6 C	126 B	41.3 D	52.1 D	< 0.001
	Incremental – measurement regions					
	A	**B**	**C**	**D**	**E**	**p-value**
Before	48.7 aA	195 bA	96.3 aA	179 bA	63.4 aA	0.022
After	86.3 aB	281 aA	129 aB	257 aA	95.8 aB	< 0.001
p-value	0.219	0.004	0.164	0.012	0.094	
	Bulk-fill – measurement regions					
	A	**B**	**C**	**D**	**E**	**p**
Before	83.6 aA	166 bA	74.3 aA	128 bA	16.7 bB	0.001
After	82.1 aB	209 aA	113 aA	183 aA	42.4 aB	0.001
p-value	1.00	0.021	0.125	0.012	0.016	
	Combined - – measurement regions					
	A	**B**	**C**	**D**	**E**	**p-value**
Before	38.5 aA	41.1 aA	51.1 aA	37.8 aA	37.8 aA	0.780
After	47.2 aA	43.3 aA	81.7 aA	53.7 aA	34.6 aA	0.694
p-value	0.250	0.813	0.188	0.250	1.00	

*Values followed by the same capital letter in the same line are statistically similar ($p > 0.05$).
**Values followed by the same small letter in the same column are statistically similar ($p > 0.05$).

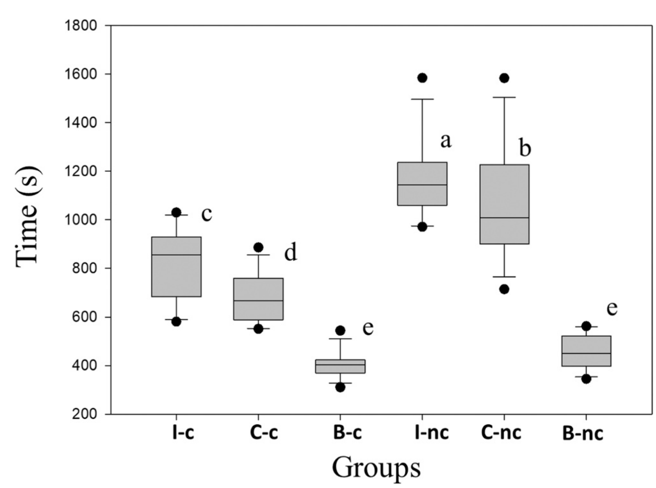

Fig. 4. Box-plot showing data on the time required to produce the restorations for the experimental groups. Groups followed by the same small letter are statistically similar ($p > 0.05$).

gap formation, including the type of **resin composite**, the restorative technique, and cavity characteristics [5,9,10,29]. The viscosity of both BFR and conventional RC is similar and greater than the BFF, which could impair the material adaptation at the cavity angles. Gap thickness also increased after 1 million cycles of fatigue testing in humid environment, indicating degradation of the interface over time [29]. Clinically, it is not possible to directly analyze the proximal surfaces of the restoration with a microscope. An alternative to obtain a more reliable clinical characterization is to produce replicas of the restoration's margins for further microscopy analysis.

The fatigue test was designed to closely simulate the conditions of the oral environment [19], including: (1) restorations produced in prepared and endodotically treated extracted human teeth [15]; (2) simulation of the periodontal ligament [32]; (3) **load applied by a piston with a tripoidism design produced with a glass-fiber reinforced epoxy resin material that can simulate the behavior of the human tooth in fatigue tests** [20,23]; (4) load level in the same range of the masticatory force at the posterior region; (5) masticatory frequency simulated at **2 Hz**; (6) humid environment at the body temperature (37° C distilled water) [19,21]. The test was also performed for a total of 1 million cycles as to reproduce, approximately, 1 year of clinical use [21]. The absence of contact sliding during the fatigue test is a study limitation. **Human teeth cannot be completely standardized and some variability in the stress distribution is expected in the fatigue test.** In addition, there are individual factors that affect the longevity of the restoration and cannot be properly reproduced in a laboratory study, such as the patient age, economic status, caries incidence, and parafunctional habits [2,3].

5. Conclusion

The effect of the layering technique on the success of restorations was dependent on the cavity extension. The combined technique favors the adaptation and the longevity of extensively **damaged** teeth, while the bulk fill technique produces restorations with more predictable fatigue behavior.

Restorations produced with the bulk fill technique had similar performance to the conventional incremental technique regarding fatigue survival and success, and marginal adaptation. In addition, a shorter time is required to produce the restoration with the bulk fill technique.

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