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Progressive Tooth Wear Against Resin-Based Restorative Composites

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ABSTRACT

Purpose: The composition and properties of resin-based composite materials could affect tooth wear and lead to clinical problems. Therefore, the study objective was to characterize human tooth wear behavior against a bulk-fill restorative (BF) compared to a conventional resin composite (RC) and a CAD/CAM resin nano ceramic (RN). Methods: Square-shaped specimens of each material were prepared and sub-divided according to the number of testing cycles (n=8): 100,000, 250,000, and 500,000 cycles. An occlusal wear test was performed using a chewing machine with 49 N, 2 Hz, in 37°C distilled water. Human premolar cusps were used as antagonists. Micro-CT and laser scanner were used to scan antagonists and specimens, respectively. Wear volume was assessed using a software and the wear pattern was examined with SEM. Softening in solvent analysis was performed by measuring the materials' Knoop microhardness (KHN) before and after immersion in ethanol. Wear volume data were analyzed with two-way ANOVA and Student-Neuman-Keuls test ($\alpha=0.05$). Results: For tooth and specimen wear volume, there was statistical significance for material and number of cycles, but not for the interaction between factors. BF resulted in less tooth (p=0.008) and specimen (p=0.030) wear than RN and RC, which were similar (p>0.05). Volume loss increased from 100,000 to 500,000 cycles. BF showed the lowest microhardness (KHN1); and %ΔKHN similar to RC, but greater than RN. Conclusion: BF induced less volume loss to the tooth than RC and RN, while presenting greater wear resistance. The tooth wear pattern and damage progression were mild for all materials. Clinical Significance: Resin composites show favorable wear behavior, leading to low volume loss and mild structural damage of the tooth. Regular bulk-fill resin composite stands out for its efficient restorative technique, low wear susceptibility and reduced capacity to wear down the tooth.

INTRODUCTION

Tooth wear is a clinical problem of great interest in dentistry (1-3). Tooth wear by erosion, abrasion, or attrition may cause loss of vertical dimension and decrease the quality of life of patients. This clinical condition may lead to pain, such as headaches from temporomandibular disorders (TMDs) and tooth sensitivity, opportunistic infections such as angular cheilitis, and esthetic alterations.[1-4] Wear is a complex, cumulative, and irreversible process with a multifactorial etiology. Factors that influence clinical wear include bite force, chewing frequency, diet abrasiveness, liquids' composition, temperature and pH variations, surface roughness, physical and mechanical properties of the materials.[1,3, 5-10] Materials' wear behavior can be associated to their hardness, fracture strength and toughness, and to their composition, microstructure and surface characteristics.[9-13]

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Resin-based composites are indicated to produce direct and indirect restorations, especially for rehabilitating patients with tooth wear.[2,14,15] Bulk-fill resin composites are low-shrinkage restorative materials that can be used in larger increments (4 to 6 mm thick), resulting in a faster and simpler treatment.[16-18] Several strategies have been developed to reduce the polymerization shrinkage and to allow higher depth of cure of bulk-fill restoratives, such as adding monomers that act as modulators in the polymerization reaction, introducing more reactive photoinitiators, and increasing the materials' translucency.[17,19-22] Nevertheless, different manufacturers may use different strategies and these modifications on the materials composition could affect their physical and mechanical properties as well.[19-21,23]

Systematic reviews comparing the longevity of restorations produced with conventional and bulk-fill resin composites reported high survival rates and similar clinical performance.[15,17,24-26] However, most clinical studies are restricted to highly controlled environments, where teeth with extensive coronal destruction and patients with parafunctional habits were not included.[11,24,25] Moreover, the available clinical data was considered inconclusive due to the low effect size and low power, mostly related to small sample sizes.[24] Clinical failure modes included loss of anatomical shape, increase in surface roughness, and discoloration, which can be clinical consequences of wear.[2,14,15,24,26]

Overall, recent laboratory studies showed similar flexural strength, flexural modulus, diametral tensile strength, microhardness, and fatigue survival between regular viscosity bulk-fill and conventional resin composites.[17,18,23,27,28] Few studies investigated the wear behavior of these materials, and existing laboratory methodologies lack standardization.[5-8,13] A study that investigated conventional and bulk-fill low viscosity (flow) resin composites concluded that the wear volume was material-dependent.[8] Another investigation found that bulk-fill flow restoratives have higher wear rates than a conventional nano hybrid composite.[5] On the contrary, when regular viscosity composites were compared, bulk-fill restoratives showed higher wear resistance than the conventional ones.[6,7] Yet, most of the occlusal wear simulations (two-body wear) used stainless steel [5,8] or steatite [6,7] as antagonists. Although a few studies used the human tooth, their findings were mostly focused on the wear behavior of the resin composite materials rather than the tooth.[6,13]

In addition to conventional and bulk-fill resin composites, high-performance polymers, such as resin nano ceramic, are also available to produce indirect restorations with the CAD/CAM technology and can be applied to rehabilitate patients.[2,10,29-32] A study showed that CAD/CAM resin-based composites induced less tooth wear in comparison to glass-ceramics and a hybrid material.[30] Therefore, considering the clinical consequences of wear and the wide range of materials available to produce the restorations, it is important to understand how tooth wear can be influenced by the materials' composition and properties. Thus, the study objective was to characterize the wear behavior of the human tooth against a bulk-fill restorative (BF) compared to a conventional resin composite (RC) and a CAD/CAM resin nano ceramic (RN), through an occlusal wear chewing simulation. The study hypotheses were that: (1) there is no effect of the type of restorative material on the tooth volume loss; (2) there is no influence of the type of restorative material on the specimen volume loss.

METHODS

Table 1 presents the composition and properties of materials used in the study. Twenty-four specimens of each restorative material were produced: (BF) regular viscosity bulk-fill resin

Table 1. Description of restorative materials used in the study and flexural strength (σ_f), flexural modulus (E_f), diametral tensile strength (DTS), and Knoop (KNH) and Vickers (VHN) hardness values.

Type	Material	Organic composition*	Inorganic composition*	σ_f (MPa)	E_f (GPa)	DTS (MPa)	Hardness	
							KNH	VHN
RC – Conventional resin composite	Filtek Z350XT	Bis-GMA, UDMA, TEGDMA, and bis-EMA	Silica (20 nm) and zirconia (4 to 11 nm) filler: 78.5% wt. (63.3% vol.)	161.0 * 135.2 (27)	11.2*	86.0 * 46.6 (28)	99.9 (28)	
BF - Regular bulk-fill	Filtek One Bulk Fill Restorative	AFM, AUDMA, UDMA, and 1, 12-dodecane-DMA	Silica (20 nm), zirconia (4 to 11 nm), and ytterbium trifluoride (100 nm) filler: 76.5% wt. (58.5% vol.)	159.0 * 144.0 (27) 146.3 (23)	11.5*	56.7 (28)	87.2 (28)	64.9 (23)
RN - Resin nano ceramic	Lava Ultimate	UDMA	Silica (20 nm) and zirconia (4 to 11 nm) filler: 80% wt. (65% vol.).	201.0 (31) 178.0 (32)	10.8 (32)			115 (31)

*** Information provided by 3M Oral Care, St Paul, MN, USA.**
Bis-GMA - bisphenol A-glycidyl methacrylate; UDMA - urethane dimethacrylate; TEGDMA - triethylene glycol dimethacrylate; AFM - addition-fragmentation monomer; bis-EMA - bisphenol A ethoxylated dimethacrylate; AUDMA - aromatic urethane dimethacrylate.

composite (Filtek One Bulk Fill, 3M Oral Care, St Paul, MN, USA); (RC) regular viscosity conventional resin composite (Filtek Z350 XT, 3M Oral Care); and (RN) resin nano ceramic for CAD/CAM (Lava Ultimate, 3M Oral Care). Specimens were subjected to an occlusal wear chewing simulation (two-body wear) against human teeth for 100,000, 250,000, and 500,000 cycles (n=8). In addition, softening in solvent analysis was performed for the three restorative materials by measuring their Knoop microhardness (KHN) before and after immersion in 70% ethanol.

SPECIMEN AND ANTAGONIST PREPARATION

A dentin analog material (NEMA G10, International Paper, Hampton, SC, USA)[33] was cut into 4-mm-thick slices using a metallographic cutter (Struess Minitron, Copenhagen, Denmark) under water refrigeration. The dentin analog material is a fiber-reinforced epoxy resin composite with similar adhesive and elastic properties to human dentin.[33,34] The substrate was manually polished with 220-grit silicon carbide paper and stored in water at 37°C for seven days, for hydration. The cementation surface of the substrate was etched with 10% hydrofluoric acid for one minute, in order to produce microretention for adhesive bonding,[33] washed with water for 30 seconds, and dried by air spray for 30 seconds. Finally, a layer of adhesive (Single Bond Universal Adhesive, 3M Oral Care) was applied to the treated surface using a microbrush, rubbed for 20 seconds, air-dried for 5 seconds, and photoactivated for 10 seconds in the continuous mode of a light-curing unit (LED Emitter Now Duo, Schuster Equipamentos Odontologicos, Brazil; 1,271 mW/cm^2).

BF and RC specimens were fabricated directly on the treated surface of the dentin analog substrate using a silicone matrix (8 mm x 8 mm x 2 mm).[35] Composites were inserted inside the matrix using a spatula, in a single increment. A polyester strip and a glass slide were placed over the material to obtain a flat surface. The glass slide was then removed, and the specimen top surface was divided into two equal parts, each one photoactivated for 20 seconds with a light-curing unit (Emitter Now Duo). Next, specimens were stored in water at 37°C for 48 hours, and the surface polishing protocol was performed with 600-, 800-, and 1200-grit silicon carbide papers.[6,7]

RN specimens were produced by cutting CAD/CAM blocks into 2.0-mm-thick slices (10 mm x 12 mm) using a diamond disc in a metallographic cutter (Minitron; Struers) under refrigeration. Both surfaces were polished with 600-, 800-, and 1200-grit silicon carbide papers. One surface was air-abraded with 45 µm aluminum oxide particles (Biojato, Bio-art, SN 20822, Brazil; 30 psi) prior to cementation, as recommended by the manufacturer. The adhesive (Single Bond Universal Adhesive) was applied to the treated surface, rubbed with a microbrush for 20 seconds, and air-dried for 5 seconds. RN was cemented over the dentin analog substrate using RelyX Ultimate resin cement (3M Oral Care). The bonded specimen was placed in a cementation device with 750g load for 3 minutes to guarantee a uniform cement layer.[31] After removing the excess cement with a microbrush, two lateral sides of the specimen were photoactivated (Radii-cal, SDI, Bayswater, Victoria, Australia; 1200 mW/cm^2) for 20 seconds each, and an additional 20 seconds photoactivation was made perpendicular to RN surface (total 60 seconds). Cemented specimens were stored in distilled water at 37°C for 48 hours prior to the mechanical tests.

For the antagonists, seventy-two healthy human upper premolars extracted for orthodontic reasons were selected from a Biobank after approval from the Research Ethics Committee (protocols #2.408.275 and #4.448.780). Teeth with similar anatomy and dimensions, and palatal cusps with round edges and spherical shapes were included. Palatal cusps were cut and included with acrylic resin to testing devices that were attached to the chewing simulator. An alignment apparatus was

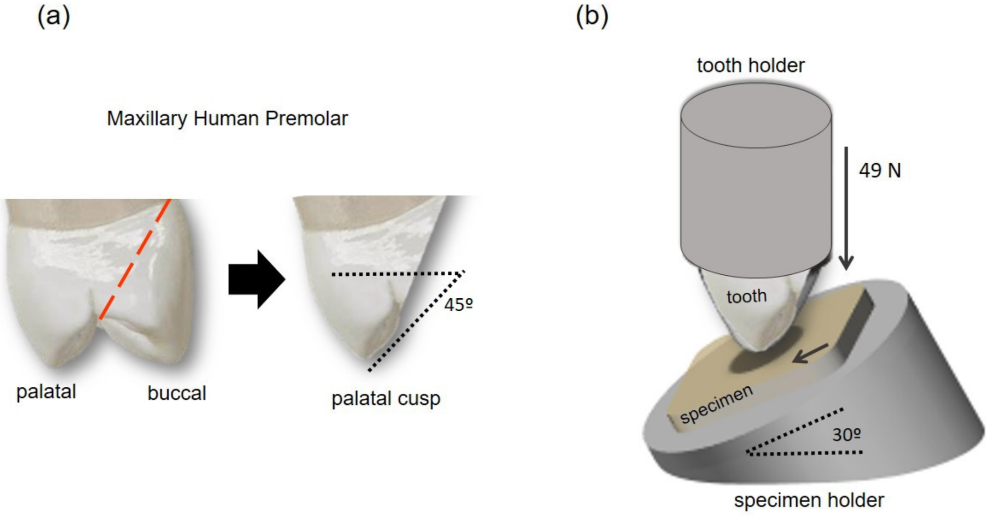


Figure 1: Schematic images showing the occlusal wear chewing simulation. (a) The premolar palatal cusp was cut and assembled with 45° inclination in the machine holder. (b) The specimen was placed in the machine with its surface in a 30° angle. When the cycle begins, the antagonist cusp is in contact with the specimen and the maximum load (49 N) is transferred while sliding down the tilted surface.

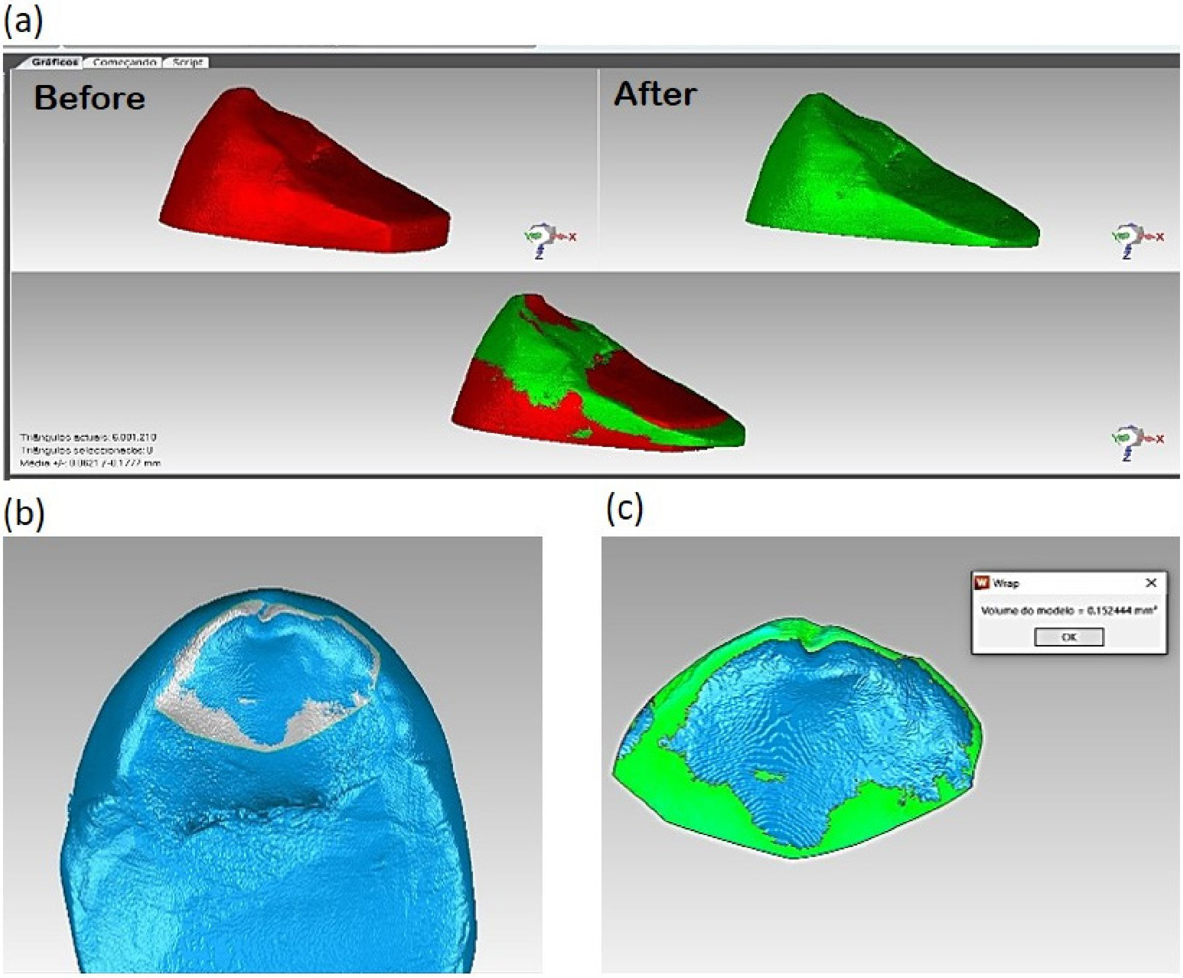
used to guarantee a 45° inclination of the cusp (*Figure 1a*). Teeth were randomly assigned to the experimental groups and the cusp enamel did not undergo previous treatment.

WEAR ANALYSIS

The test was performed using a pneumatic mechanical cycling machine (Biopid, Biocycle, São Carlos, São Paulo, Brazil) in water at 37°C, with 2 Hz frequency, and 49 N vertical load.[35] The chewing simulator was limited to vertical movement only. The specimen was placed in the machine with its surface in a 30° angle, while the tooth cusp was at 45° angle, aiming to reproduce the premolar occlusion (*Figure 1b*). When the cycle begins, the antagonist cusp is in contact with the specimen (to reduce the impact) and the maximum load is transferred while sliding down the tilted surface for, approximately, 1 mm; then the antagonist lifts out of contact while returning to its original position, to begin a new cycle. Each specimen was tested against a new antagonist. Groups were subdivided according to the number of cycles used in the chewing simulation (n=8): 100,000, 250,000, and 500,000.

The tooth cusps were scanned with computed X-ray microtomography (Micro-CT, inspeXio, SMX-90CT Plus, Shimadzu, Japan) before and after the wear test. The used parameters were SID (Source to Image Distance) 300 mm, SOD (Source to Object Distance) 44.6 mm, CT-Z (z-axis position) 22 mm, and a voxel size of 0.012 mm/Pix, totaling 540 slices per cusp. The files were saved in DICON format and converted to STL with a 3D slicer free open-source software (www.slicer.org). Specimens were scanned only after the wear test using a laser scanner (SD Mechatronic Laser Scanner LAS-20) and 10 μm resolution.[9]

Quantitative analysis of the wear volume loss of the antagonists and the specimens were performed with a 3D reconstruction software (3D System Geomagic Wrap). For the antagonist, images obtained before and after the wear test were first overlapped (*Figure 2a and 2b*) and then subtracted, in order to isolate the scar and calculate the volume loss (*Figure 2c*). For the specimen wear volume analysis, there was no need for scanning before the wear test as the original flat surface could be reconstructed using the 3D image software. Therefore, specimen volume loss was calculate using the same methodology described for the antagonist analysis but comparing reconstructed (original surface) and test (after wear test) models.[9]



Triângulos actuais: 6.001.210
Triângulos seleccionados: 0
Media +/-: 0.0621 / -0.1777 mm

Volume do modelo = 0.152444 mm³

Figure 2: Image processing software for volume analysis. (a) Tooth images before and after the wear test and image overlapping to identify wear volume. (b) Delimited wear scar for analysis. (c) Volume loss analysis.

Qualitative analysis of the wear scars for the antagonists and the specimens were performed using optical and scanning electron microscopy (SEM Vega3 model, Tescan). Teeth did not receive a layer of a conductive material as the wear scars were analyzed in the SEM with a Back-Scatter Detector (BSE).

Tooth volume loss data obtained in a pilot test was used to calculate the sample size with G*Power 3.1.9.4 software. The parameters used were effect size = 0.70, α = 0.05 and power = 0.80, which resulted in a sample size of 8 per group. Wear scar volume data passed the Shapiro-Wilk normality test ($p>0.05$) and similar variance test ($p>0.05$) and were analyzed with two-way ANOVA (factor 1: material; factor 2: number of cycles) and the Student-Newman-Keuls test ($\alpha=0.05$).

SOFTENING IN SOLVENT ANALYSIS

Disc-shaped specimens of the three restorative materials (4 mm diameter x 1 mm height) were prepared for the softening in solvent analysis (n = 5).[36] Knoop microhardness (KHN1) was measured using a microhardness tester (HMV 2, Shimadzu, Japan) with a 10 g load for 5 seconds, with three indentations in each specimen. Specimens were then immersed in 70% ethanol solution for 2 hours, and a new KHN measurement was performed (KHN2). The difference between KHN1 and KHN2 was used to calculate de ΔKHN % for softening solvent analysis.

KHN1 and ΔKHN % data passed the Shapiro-Wilk normality test ($p>0.05$) and similar variance test ($p>0.05$) and were analyzed with one-way ANOVA and Tukey's test ($\alpha=0.05$). For each material, separately, KHN1 and KHN2 values were compared using t-test ($\alpha=0.05$).

RESULTS

QUANTITATIVE WEAR ANALYSIS

For tooth volume loss, there was statistical significance for the factor restorative material (p = 0.008; power = 0.724) and for the factor number of cycles (p = 0.049; power = 0.420), but there was no significance for the interaction between factors (p=0.451; power = 0.050) *(Table 2)*. BF resulted in significantly lower tooth wear than RC and RN, which were statistically similar. Volume loss significantly increased between 100,000 and 500,000 testing cycles.

For the specimen wear analysis, the factors material (p=0.030; power = 0.519) and number of cycles (p=0.016; power = 0.640) significantly affected volume loss, while the interaction between factors was not significant (p=0.161; power = 0.213) *(Table 3)*. BF presented the lowest volume loss. RC and RN showed the highest wear values, which were statistically similar. Wear volume was higher after 500,000 cycles than 100,000 cycles.

QUALITATIVE WEAR ANALYSIS

Figure 3 shows representative images of the tooth wear surface after 100,000 testing cycles, for the three experimental groups. The tooth wear pattern was similar among groups, showing a rough surface *(Figures 3a, 3b, 3d, 3e, 4d)* and plough marks *(Figures 3f, 4a, 4b, 4c)* that indicate microplasticity and may be caused by the dislodgment of the composites' filler particles. Less frequently, it was also possible to identify microcracks and exposure of the enamel prisms due to structural loss *(Figures 3c, 3f, 4c)*. As the number of cycles increased from 100,000 to 500,000 cycles, these wear marks became slightly more prominent, as described in Figure 4.

Table 2. Mean (standard deviation) tooth volume loss (mm^3) for the experimental groups.

Factor 1: Restorative Material

BF	RC	RN	p
0.17 (0.06) b	0.24 (0.12) a	0.28 (0.15) a	0.008*

Factor 2: Time

100,000 cycles	250,000 cycles	500,000 cycles	p
0.18 (0.09) b	0.23 (0.12) ab	0.28 (0.15) a	0.049*

Interaction: Material vs. Time

BF			RC			RN			p
100,000	250,000	500,000	100,000	250,000	500,000	100,000	250,000	500,000	
0.17 (0.07)	0.14 (0.04)	0.19 (0.07)	0.20 (0.10)	0.25 (0.10)	0.29 (0.15)	0.19 (0.11)	0.30 (0.15)	0.36 (0.17)	0.451

***Values followed by different letters in the same row are statistically different ($p<0.05$).**

Table 3. Mean (standard deviation) specimen wear volume (mm³) for the experimental groups.

Factor 1: Restorative Material

BF	RC	RN	p
0.46 (0.29) b	1.17 (1.26) a	1.06 (0.80) a	0.030*

Factor 2: Time

100,000 cycles	250,000 cycles	500,000 cycles	p
0.43 (0.23) b	0.94 (1.14) ab	1.32 (0.85) a	0.016*

Interaction: Material vs. Time

BF			RC			RN			p
100,000	250,000	500,000	100,000	250,000	500,000	100,000	250,000	500,000	
0.25 (0.09)	0.43 (0.27)	0.70 (0.28)	0.45 (0.27)	1.72 (1.85)	1.32 (0.92)	0.57 (0.22)	0.67 (0.19)	1.93 (0.84)	0.161

***Values followed by different letters in the same row are statistically different (p<0.05).**

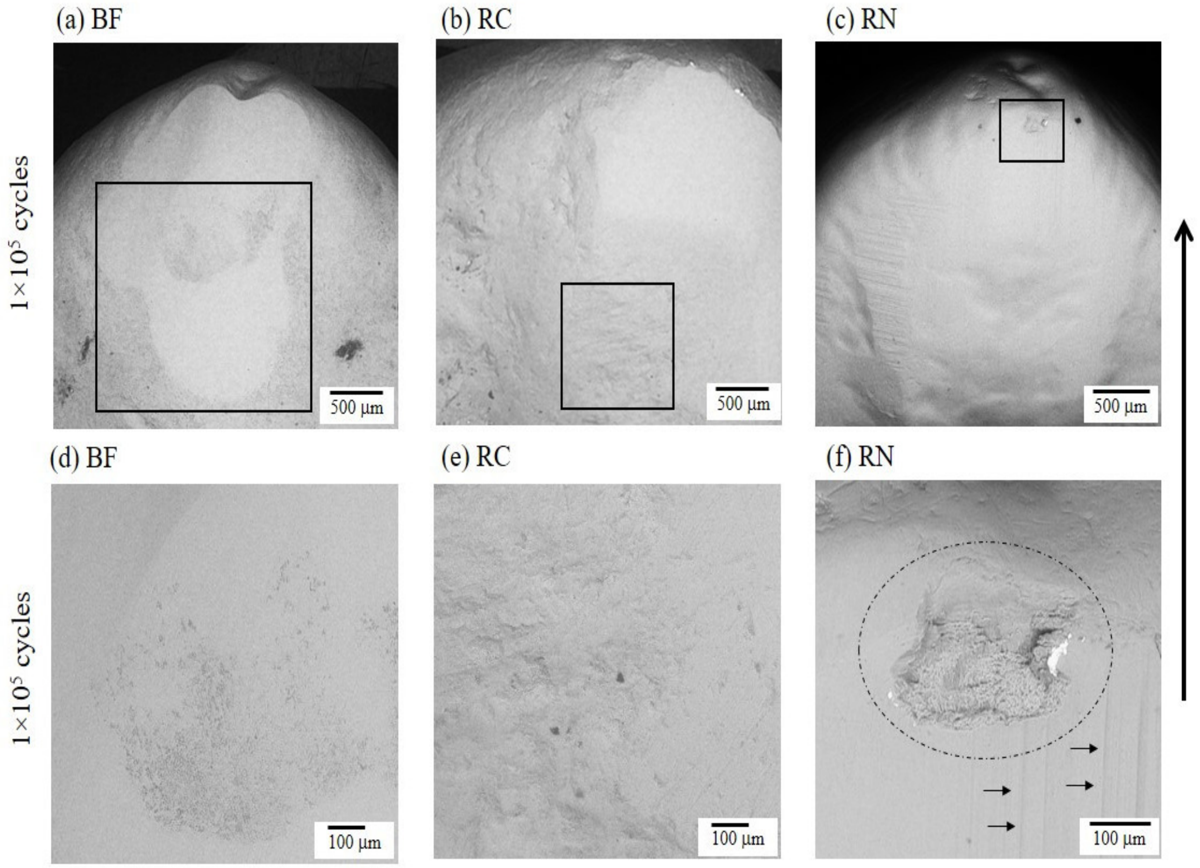


Figure 3: SEM representative images of the antagonist tooth surface after the wear test for 100,000 cycles against (a) BF, (b) RC, and (c) RN. Images (d), (e), and (f) correspond to the region determined by the black box in figures (a), (b), and (c), respectively. Wear resulted in increased surface roughness, as observed in images (d) and (e); plough marks, as pointed by the black arrows in image (f); and, enamel prism exposure, delimited by the doted circle in image (f). The sliding direction is from the bottom to the top (black arrow to the right).

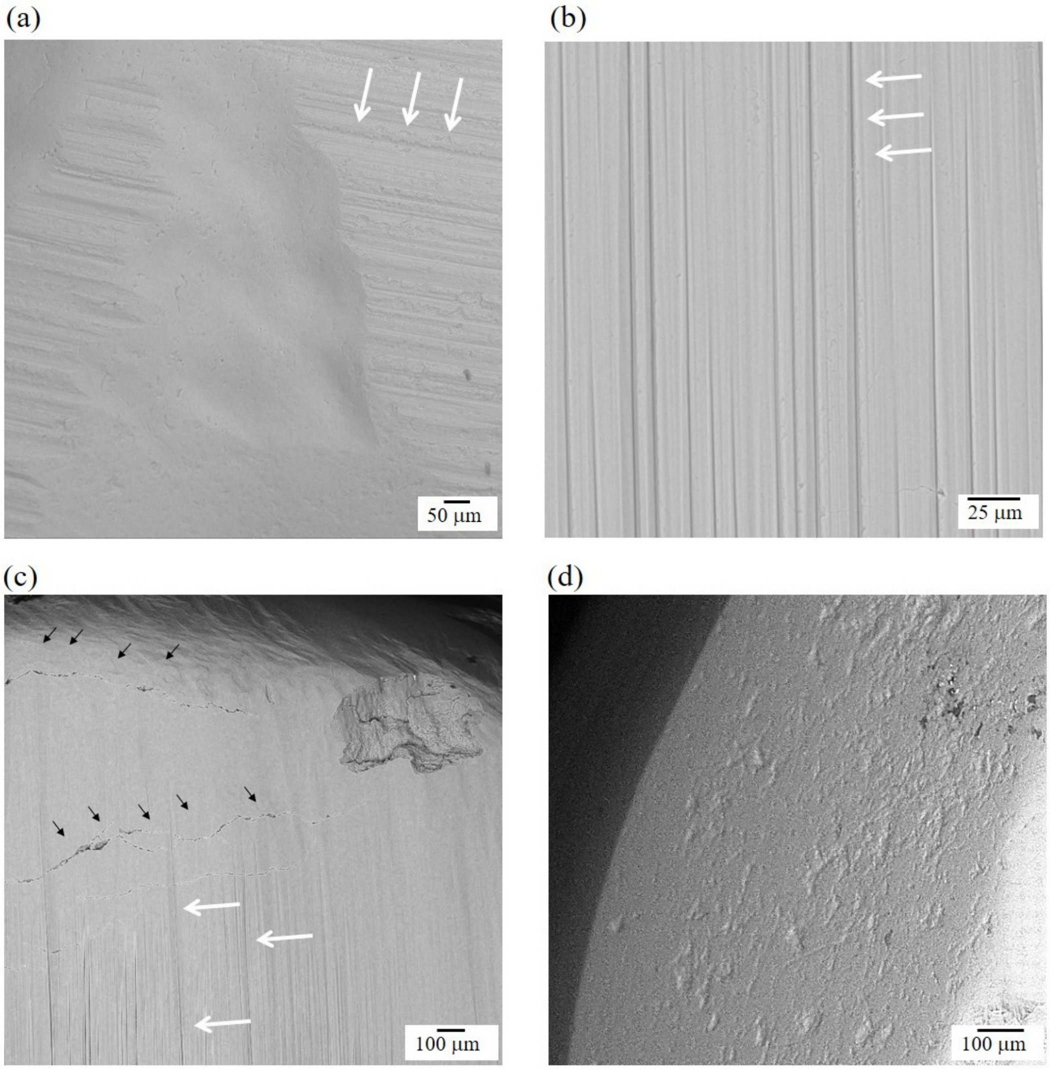


Figure 4: SEM representative images of the tooth surface damage after 250,000 and 500,000 cycles. Damages observed were enamel grooves (plough marks) (a) perpendicular and (b) parallel to the sliding direction, as shown by the white arrows (c) small cracks indicated by the black arrows, and (d) increased surface roughness due to the removal of wear particles.

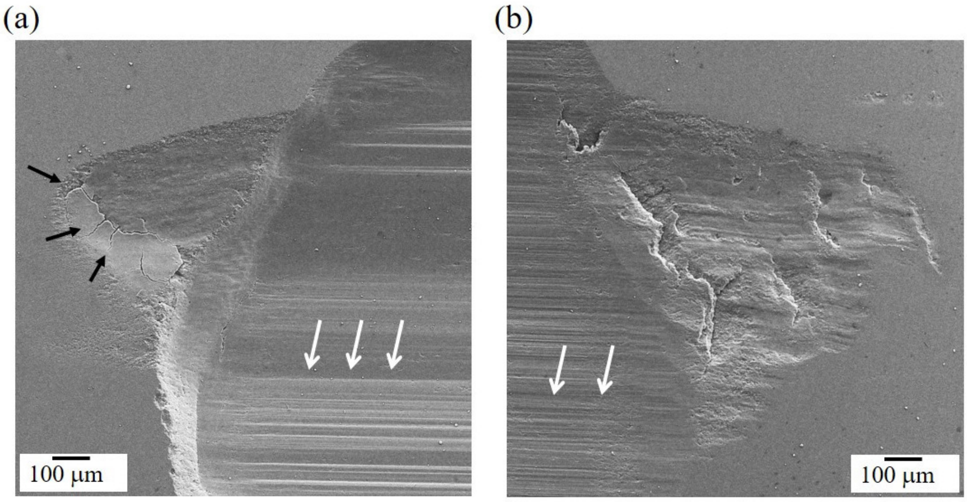


Figure 5: SEM representative images of the restorative material surface showing damage caused by the antagonist teeth during the wear test. Images (a) and (b) show plough marks (white arrows), microcracks (black arrows), and material loss on the RN surface, with signs of plastic deformation.

Table 4. Mean (standard-deviation) values of Knoop microhardness for the restorative materials before (KHN1) and after (KHN2) immersion in ethanol, and difference between KHN1 and KHN2 (%ΔKHN).

Materials	KHN1	KHN2	p***	%ΔKHN
BF	70.66 (4.72) C a	55.06 (3.61) b	0.003	21.84 (6.60) B
RC	85.27 (5.65) B a	72.80 (4.88) b	0.006	14.46 (5.72) AB
RN	107.29 (2.3) A a	94.21 (4.65) b	0.003	12.17 (4.39) A
p**	<0.001			0.047

***Values followed by different lowercase letters in the same row are statistically different (p<0.05). Values followed by different uppercase letters in the same column are statistically different (p<0.05).**
****p-values obtained from One-Way ANOVA.**
*****p-values obtained from t-test.**

Figure 5 shows a representative image of the surface damage observed for RN specimen. The three different materials presented a similar pattern with smooth surfaces, plough marks (as observed in the surface of the respective antagonist teeth), and microcracks.

SOFTENING IN SOLVENT ANALYSIS

BF presented the lowest initial Knoop microhardness (KHN1), followed by RC and RN, which had the highest value (p<0.001) *(Table 4)*. The three restorative materials showed a significant decrease in microhardness after immersion in ethanol (p<0.050). BF had greater % ΔKHN than RN, and statistically similar to RC (p=0.047).

DISCUSSION

Several factors can affect tooth wear, including the composition, surface characteristics and properties of the restorative materials.[1,3,11,12] In the present investigation, a regular bulk fill restorative induced less volume loss to the antagonist tooth than the conventional resin composite and a CAD/CAM resin nano ceramic material, rejecting the first study hypothesis. The wear behavior of resin-based composites can be associated to the filler type, size, shape, and content.[5-7,9,11,12,21] Yet, the three restorative materials evaluated have similar inorganic composition, with zirconia and silica nanoparticles, ranging from 76.5 wt% to 80 wt% *(Table 1)*. Therefore, the distinct behavior among materials does not seem to be associated with their inorganic content.

Factors related to the organic matrix composition, such as monomer type and ratio, photoinitiators, and degree of polymer crosslinking, may also affect the properties of resin-based composites.[11,23,37] The resin matrix of bulk-fill restoratives was modified to reduce stresses during polymerization.[16,17] The organic matrix of the tested BF has a high molecular weight AUDMA monomer, which reduces the number of reactive groups, leading to lower polymerization shrinkage and stress, and reducing the stiffness of the final matrix. An addition-fragmentation monomer (AFM) was also added to relieve stress.[23,27] The organic matrix of the conventional RC has bis-GMA, BISEMA, TEGDMA, and UDMA monomers,[27,28] while RN has a high-density cross-linked UDMA matrix.[10,30]

As these differences in the materials' organic matrix composition could be associated to its wear behavior, a softening in solvent analysis was performed.[37,38] The degree of polymer cross-linking may affect the structural stability of the materials and could be indirectly assessed by measuring the degree of softening in ethanol.[38] Polymer networks with high cross-linking density have limited space and pathways available for solvent molecules to diffuse within the structure, being more resistant to degradative reactions.[36,37] RN experiences an industrial polymerization process involving high temperatures (>100°C) and high pressure (>150 MPa), achieving a high degree of conversion and crosslink density which could explain its higher microhardness and chemical stability.[29,31] On the contrary, a greater degree of softening for BF could indicate a more linear and less cross-linked polymer structure.[38]

Although BF lead to reduced tooth wear, qualitative analyses of the surface damage showed similar wear pattern for the different restorative materials. Overall, the surface characteristics suggest the presence of mild wear, with increased enamel roughness due to removal of wear particles and presence of plough marks (surface grooves), as seen in more details in Figure 4. These marks may be caused by the dislodgment of the composites' filler particles, resulting in abrasive wear.[1,10] Yet, as the occlusal wear chewing simulation progresses, higher frequency of small cracks could be identified and suggest the presence of fatigue damage, that lead to gradual loss of structure due to delamination.[3] Intact human teeth with similar characteristics were used to properly characterize the conditions of the oral environment.[1] Yet, it is not possible to completely standardize the contact area and pressure during the test, especially as the contact area may change as the wear process advances, which is a study limitation.

In addition to inducing less wear to the tooth, BF also showed less volume loss in comparison to the other restorative materials, rejecting the second study hypothesis. Studies that evaluated the same BF material against a steatite antagonist also reported lower volume loss than conventional RC and attributed the differences to the polymer matrix composition.[6,7] Yet, the wear pattern of the three restorative materials was similar and volume loss progressively increased over time, corroborating previous studies.[10] For occlusal wear simulations, the wear pattern of resin composites is usually a combination of attrition, abrasion, and micro-fatigue mechanisms.[1] A high filler content with dispersed and agglomerated nanoparticles reduces resin matrix exposure to the antagonist tooth and promotes wear resistance.[10-12] It also provides a more homogeneous surface, considering that particle nano-agglomerates break into small fragments.[10] The resin-based composite viscoelastic behavior results in zones of plastic deformation that were similar to the pattern seen for the antagonist enamel. Fatigue mechanisms are also present as cyclic loading can lead to the initiation of microcracks in the plastically deformed regions, as observed in Figure 5. Moreover, as the wear process progresses, exposure and detachment of filler particles may lead to an abrasive wear mechanism (three-body abrasive wear) as evidenced by the presence of plough marks in the wear surface of the materials and antagonist teeth.[10,11]

The materials' physical and mechanical properties, which are defined by their composition, may influence the wear of the resin composites.[1,12] For the materials investigated in the present study, the values of flexural strength, flexural modulus, and diametral tensile strength found in the literature are in a similar range,[23,27,28,31,32] as seen in Table 1. Yet, differences in the surface microhardness were found between the materials. Nevertheless, its relationship with wear is not always straightforward, as it is usually material-dependent.[12] Moreover, the presence of abrasive wear mechanisms also highlights the importance of a high-quality bond between fillers and polymer matrix.[1]

The wear test was an adaptation of the Zürich wear method described in ISO 14569-2 and intended to simulate occlusal wear (attrition) between the restorative material and an antagonist tooth.[1,35] Moreover, clinical parameters were added to the methodology, including testing in a humid environment at 37°C, using load (49 N) and frequency (2 Hz) values in the same range of the ones found in service.[1,35] Nevertheless, the lack of controlled horizontal movement and artificial saliva are methodology limitations. It is important to emphasize that the wear mechanisms are complex and involve several factors that cannot be properly reproduced in a laboratory setup, such as the patients individual conditions.[1,3,12] Moreover, it is not possible to directly correlate the number of cycles used in the wear test with time in service as the testing conditions are more aggressive. Therefore, the wear analysis was performed at different number of cycles aiming to characterize the progressive wear of the tooth and restorative material in different scenarios.

The specimen thickness (2 mm) and polishing protocol was also based on the Zürich wear method and it is a simplification of the clinical scenario.[35] Clinically, the surface quality will be affected by the different finishing protocols available and by difficulties imposed by the restoration geometry. Additionally, bulk fill resin composite restorations are produced using larger increments (4 to 6 mm thick).[16,18] Nevertheless, as the direct resin composites evaluated in the present study have similar degree of conversion,[22] the effect of the specimens' thickness in the materials surface properties is expected to be low.

CONCLUSION

Within the limitations of this current study, it was concluded that bulk-fill restorative resulted in less volume loss of the tooth and the specimen than conventional direct and indirect composites. Yet, the tooth wear pattern and damage progression were mild for all investigated materials.

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