coatings

MDPI

Article

Wear Behavior of Monolithic Zirconia after Staining, Glazing, and Polishing Opposing Dental Restorative Materials: An In Vitro Study

Lívia Fiorin [1], Paulo Eduardo Barros Souza Oliveira [2], Allan Oliveira da Silva [1], Adriana Cláudia Lapria Faria [2], Ana Paula Macedo [2], Ricardo Faria Ribeiro [2] and Renata Cristina Silveira Rodrigues [2,*]

[1] Oral Rehabilitation Graduate Program, Department of Dental Materials and Prosthodontics, Dental School of Ribeirao Preto of University of Sao Paulo, Ribeirao Preto 14040-904, SP, Brazil
[2] Department of Dental Materials and Prosthodontics, Dental School of Ribeirao Preto of University of Sao Paulo, Ribeirao Preto 14040-904, SP, Brazil
* Correspondence: renata@forp.usp.br; Tel.: +55-16-3315-4005

Abstract: The purpose of this in vitro study was to compare the effect of staining, glazing, and polishing on the wear behavior of stabilized zirconia with 5 mol% of yttrium oxide (5Y-TZP) opposing 5Y-TZP, leucite-reinforced ceramic (LC), lithium disilicate (LD), and microhybrid composite resin (MCR). Hemispheres of 5Y-TZP were divided into six groups (n = 10) according to the finishing procedure: C (control), S (staining), G (glazing), P (polishings), SG (staining plus glazing), and SP (staining plus polishing). The two-body wear test (2BW) was performed (20 N load, at 2 Hz, until 300,000 cycles). Vertical height loss of hemispheres (VHL) and wear depth of restorative materials (WD) were analyzed using a profile projector and laser confocal microscope, respectively. Data of VHL and WD were analyzed using a generalized linear model by the Wald test and t post hoc test with the Bonferroni adjustment ($\alpha = 0.05$). The staining, glazing, polishing, and restorative material had a significant effect ($p < 0.05$) on VHL and WD. Polishing reduced VHL opposing MCR, LC, and LD. There was an increase in WD to G opposing LD and SG opposing MCR. The 5Y-TZP presented the highest wear resistance, while MCR presented the lowest. Polishing was recommended to promote staining durability and decrease wear rates opposing MCR and LD.

Keywords: monolithic zirconia; lithium disilicate; leucite-reinforced ceramic; composite resin; abrasion; two-body wear; restorative dental materials; direct and indirect restorations

Citation: Fiorin, L.; Oliveira, P.E.B.S.; Silva, A.O.d.; Faria, A.C.L.; Macedo, A.P.; Ribeiro, R.F.; Rodrigues, R.C.S. Wear Behavior of Monolithic Zirconia after Staining, Glazing, and Polishing Opposing Dental Restorative Materials: An In Vitro Study. *Coatings* **2023**, *13*, 466. https://doi.org/10.3390/coatings13020466

Academic Editors: Devis Bellucci, Ajay Vikram Singh and Christian Mitterer

Received: 16 January 2023
Revised: 2 February 2023
Accepted: 14 February 2023
Published: 18 February 2023

1. Introduction

The increase in patients' demand for highly aesthetic restorations has led to the introduction of high-strength ceramics in dentistry. Zirconia has been widely used to manufacture monolithic or porcelain-veneered restorations. The partially stabilized zirconia with 3 mol% of yttrium oxide (3Y-TZP) is indicated to manufacture frameworks due to its excellent mechanical properties and low translucency, and requires porcelain veneer to present satisfactory aesthetics. However, porcelain-veneered restorations were related to failures, such as porcelain chipping and delamination. To avoid these complications, porcelain-veneered restorations have recently been replaced by monolithic restorations. The zirconia microstructure was modified to be able to the use for monolithic restorations [1,2]. The percentage of yttrium oxide content was increased to 4 mol% (4Y-TZP) and 5 mol% (5Y-TZP) to make these materials more translucent and suitable for manufacturing monolithic restorations on posterior and anterior regions, respectively. The 5Y-TZP presents a mixed cubic/tetragonal structure, in which cubic crystals have a large grain size and isotropic refractive index, and less light scattering at the grain boundaries, making this material more translucent than 3Y-TZP and 4Y-TZP [1–3].

The color of 5Y-TZP is white to ivory; however, preshaded blocks were recently developed, adding metal oxides to zirconia powder [4]. Furthermore, preshaded zirconia can be additionally characterized using extrinsic stains on the 5Y-TZP surface after sintering to mimic the appearance of natural teeth [4,5]. It was related that these stains can affect the surface roughness [6], color stability [5], translucency [5,7], hardness [6], flexural strength [7], and fatigue behavior [8], but the effect of staining on wear behavior is unclear. Additionally, the finishing procedure is recommended to protect the stain layer, improving the staining durability during function [9,10]. The finishing procedures, such as glazing and polishing, present advantages, such as creating a smoothing surface, enhancing surface gloss, and decreasing the wear rate of the antagonist teeth [11]. However, there is no well-established method of finishing procedure to protect the stain layer and decrease wear rates of dental restorative material that can be found as an antagonist.

The 5Y-TZP used to manufacture monolithic restorations will be in direct contact with the opposing teeth or restorative materials, raising concerns about the wear behavior. The wear behavior must be investigated because it is expected that the dental restorative material will not accentuate the wear on natural teeth, and not compromise the longevity of other restorations present in the oral environment [12,13]. Wear can be defined as the loss of substance from a surface as a result of friction between two materials, being affected by their microstructure, roughness, and strength [12–14]. Some authors found that staining and/or finishing procedures increased the surface roughness of 5Y-TZP [6], making it necessary to investigate the effect of these surface treatments on wear behavior using wear tests to predict the clinical wear resistance [15,16]. It was important because excessive wear has been related to clinical complications such as damage to the occlusal surface, marginal gaps, reduced masticatory efficiency, loss of occlusion vertical dimension, and temporomandibular joint remodeling [12,17].

Although the wear behavior of 3Y-TZP has been widely investigated [14–16,18–27], a few studies investigated the wear behavior of 5Y-TZP [23,24,28–31]. Among these studies, some compared the wear behavior of polished 3Y, 4Y, and 5Y-TZP opposing steatite antagonists [23,24], while others investigated the wear behavior of polished 5Y-TZP opposing bovine enamel [28], human enamel [29,30], composite resin [30,31], and lithium disilicate [30,31], but the effects of staining and finishing procedures on the wear behavior of 5Y-TZP opposing dental restorative materials were not evaluated. Therefore, the purpose of this in vitro study was to evaluate the effect of staining, glazing, and polishing on the wear behavior of 5Y-TZP opposing 5Y-TZP, leucite-reinforced ceramic, lithium disilicate, and microhybrid composite resin. The null hypothesis tested was that staining, glazing, and polishing have no influence on the wear behavior of 5Y-TZP opposing different dental restorative materials.

2. Materials and Methods

Two types of specimens were obtained: 240 hemispheres of stabilized zirconia with 5 mol% yttrium oxide (5Y-TZP) and 60 square-shaped specimens of each dental restorative material used as antagonist (Table 1).

Table 1. Brand, composition, lot, and manufacturer of materials used in this in vitro study.

Brand	Composition	Lot	Manufacturer
Ceramill Zolid FX Preshade	ZrO_2 + HfO_2 + Y_2O_3: ≥99.0, Y_2O_3: 8.5–9.5, HfO_2: ≤5, Al_2O_3: ≤0.5	1707000	Amann Girrbach, Koblach, Austria
IPS E.max CAD	SiO_2: 57.0–80.0, Li_2O: 11.0–19.0, P_2O_5: 0–11.0, K_2O: 0–13.0, MgO: 0–5.0, Al_2O_3: 0–5.0	Z00ZGP	Ivoclar Vivadent, Barueri, Brazil
IPS Inline POM	SiO_2: 50.0–65.0, Al_2O_3: 8–20.0, Na_2O: 4.0–12.0, K_2O: 7.0–13.0	S15651	Ivoclar Vivadent, Barueri, Brazil
Filtek Z250 XT	Bis-GMA, UDMA, Bis-EMA, zirconia, silica	2104700325	3M Espe, Sumare, Brazil

Hemispheres of 5Y-TZP were manufactured by CAD/CAM (Figure 1), sintered in a furnace (inFire HTC Speed, Dentsply Sirona, Charlotte, NC, USA) with maximum temperature of 1450 °C according to the manufacturer's instructions, and divided into 6 groups (n = 10) according to finishing procedure: C (control), S (staining), G (glazing), P (polishing), SG (staining plus glazing), and SP (staining plus polishing). All finishing procedures were performed by a single trained operator (L.F.).

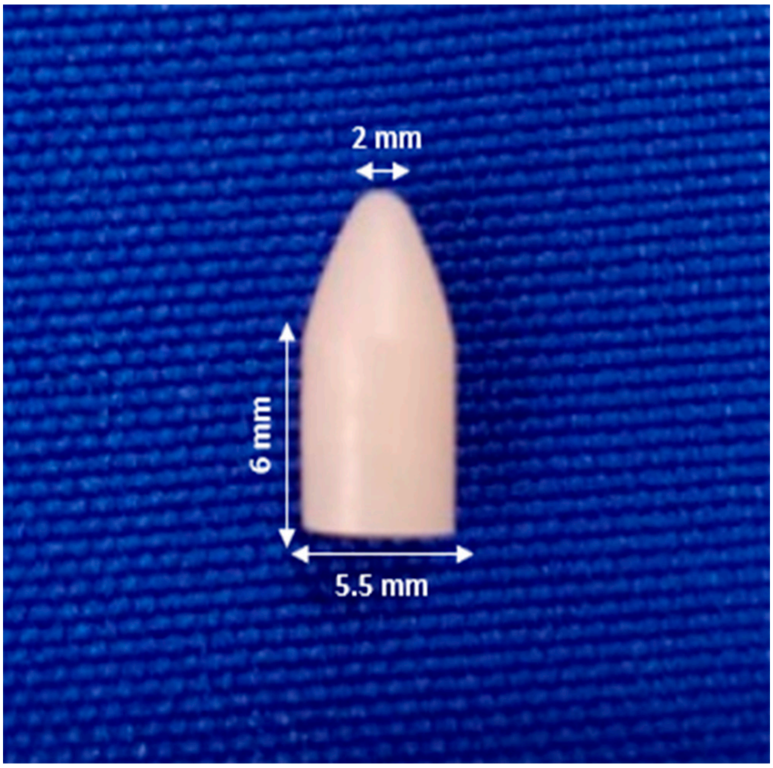
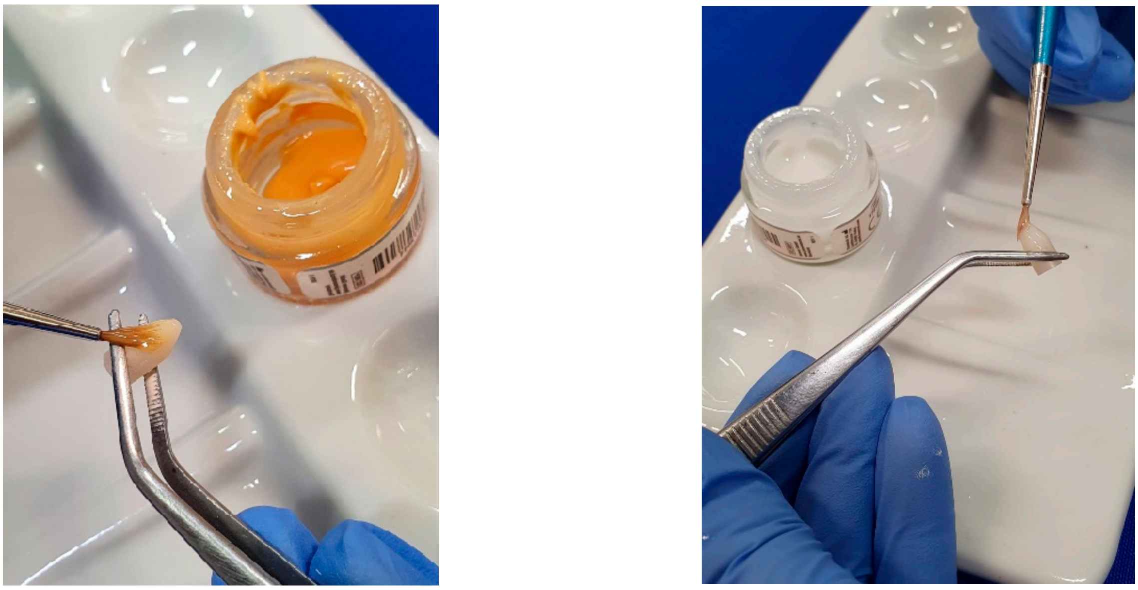


Figure 1. Dimensions of hemispheres.

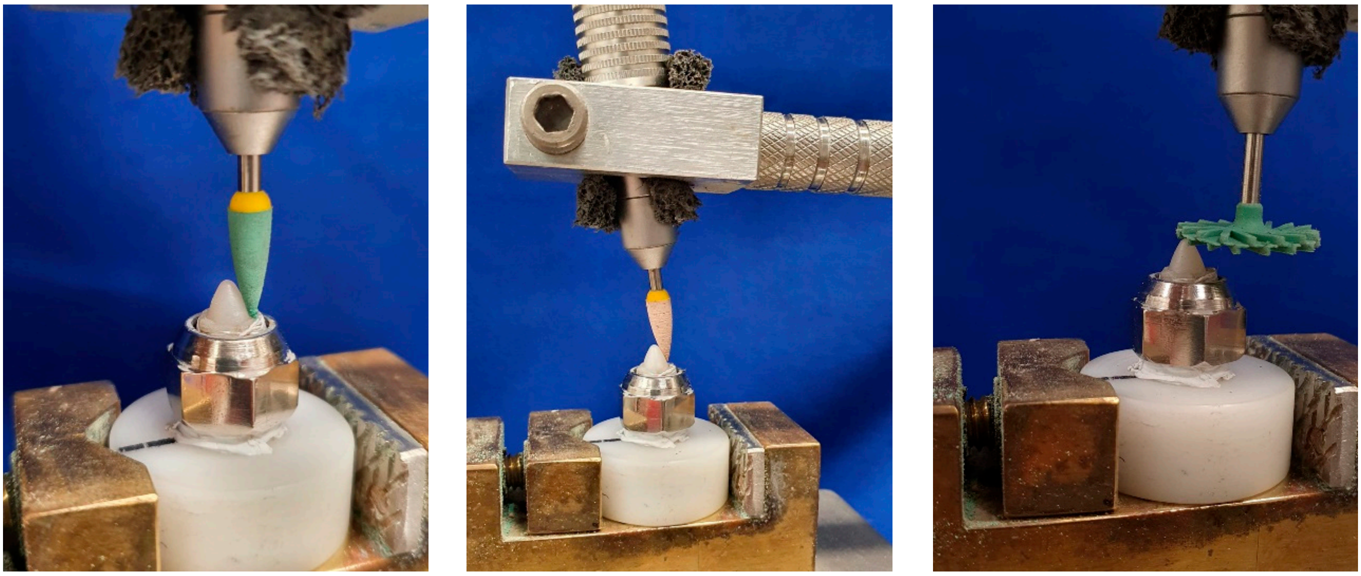
Staining and glazing were performed after sintering, applying a single layer of stain (Stain Orange InSync, Jensen GmbH, Harsum, Germany) or glaze paste (Glaze InSync, Jensen GmbH, Harsum, Germany) using a brush, after being fired in a furnace (Sinter Press Alumini, EDG, Sao Carlos, Brazil) [6] (Figure 2). The thickness of this layer was approximately 100 µm [9]. SG received glaze layer after staining, and it was fired two times [6].

Polishing was performed using a device for standardizing [6]. This device consisted of a modified parallelometer, which allowed the positioning of the specimen, diamond polisher, and rotary instrument, ensuring standardization of the load applied to specimens during polishing. The polishing was performed in two steps. In the first, medium (W16DC Diacera, Eve Ernst Vetter GmbH, Keltern, Germany) and fine (W16DCmf Diacera, Eve Ernst Vetter GmbH, Keltern, Germany) diamond polishers with point shapes were used to polish conical surface of hemisphere for 30 s [32–34]. In the second, medium (DT-H17DCmf Diacera, Eve Ernst Vetter GmbH, Keltern, Germany) and fine (DT-H17DC Diacera, Eve Ernst Vetter GmbH, Keltern, Germany) diamond polishers with twist shapes were used to polish the apex of hemisphere for 10 s. Both steps used slow-speed dental handpiece (Micromotor, Dabi Atlante, Ribeirao Preto, Brazil) at 10,000 rpm. Diamond polisher was replaced after polishing five specimens [33]. SP received polishing after staining [6] (Figure 3).



(**A**) (**B**)

Figure 2. (**A**) Staining; (**B**) glazing.



(**A**) (**B**) (**C**)

Figure 3. Polishing. (**A**) Medium diamond polisher with point shape; (**B**) fine diamond polisher with point shape; (**C**) medium diamond polisher with twist shape.

Square-shaped specimens (10 mm × 8 mm × 3 mm) were obtained from 5Y-TZP, lithium disilicate, leucite-reinforced ceramic, and microhybrid composite resin. The 5Y-TZP and lithium disilicate specimens were sectioned from their blocks with a diamond disk (Diamond Wafering Blade, Allied High Tech Products Inc, Compton, CA, USA) in a high precision cut (Isomet 1000 Precision Saw, Buehler, Uzwil, Switzerland) under water cooling. The 5Y-TZP was sintered (inFire HTC Speed, Dentsply Sirona, Charlotte, NC, USA), and the lithium disilicate was crystallized (Sinter Press Alumini, EDG, Sao Carlos, Brazil) according to their respective manufacturer's instructions. One specimen of 5Y-TZP was molded in order to obtain a silicon matrix that was used to obtain leucite-reinforced ceramic and microhybrid composite resin specimens. For leucite-reinforced ceramic specimens, wax patterns were made using a silicon matrix; then, they were invested, submitted to the investment heating cycle, and heat-pressed according to the manufacturer's instructions. The microhybrid composite resin specimens were built into the silicone matrix in incremental process followed by light-curing for 40 s to each increment. All square-shaped specimens were embedded in PVC rings using auto-polymerizing acrylic resin to be positioned on the wear testing machine and polished with sequential sandpaper (grit: 320, 400, 600, 1200) (211Q, 3M Espe, St. Paul, MN, USA).

The two-body wear (2BW) test was performed using a chewing simulator developed by Department of Dental Materials and Prosthodontics of Dental School of Ribeirao Preto of University of São Paulo [35]. Hemispheres were fixed in vertical loading poles under a 20 N load and 2 Hz frequency, and plane specimens were positioned in a recipient that performed sliding motion in a 5 mm linear course. Specimens were tested immersed in distilled water at 37 °C. It was performed for 300,000 cycles, where each cycle included a downward vertical movement (occlusion), 5 mm of sliding motion (eccentric loading), and an upward vertical movement (disocclusion), simulating 18 months of clinical service [27,36–38]. After testing, the specimens were ultrasonically cleaned in distilled water for 5 min.

The vertical height loss of hemispheres (VHL) (n = 10) was measured using a profile projector (Profile Projector, Nikon, Tokyo, Japan) at 10× magnification. The initial and final profiles were traced on transparent paper, and the difference between them was measured using 0.01 mm digital pachymeter (Absolute Digital Pachymeter, Mitutoyo South American, Suzano, Sao Paulo, Brazil) [35]. The laser confocal microscopy (LEXT OLS4000, Olympus, Tokyo, Japan) and its respective software (LEXT 3D Measuring Laser Microscope OLS4000, Olympus, Tokyo, Japan) were used to analyze the surface topography of all groups and wear depth of restorative material used as antagonist (WD) (n = 10).

Statistical analyses were performed using IBM SPSS Statistics (SPSS v20.0, IBM). The VHL and WD were analyzed using generalized linear model by Wald test and t post hoc test. All paired comparisons were performed with the Bonferroni adjustment ($\alpha = 0.05$).

3. Results

Figure 4 illustrates the surface morphology of 5Y-TZP after staining, glazing, and polishing. The C and P groups showed a more regular surface morphology. The G, S, and SG groups showed large irregularities, while polishing regularized the surface after staining (SP group).

Mean values and standard deviations of VHL and WD after 2BW are shown in Tables 2 and 3, respectively. The Wald test (Table 3) showed that the use of stains, finishing procedure, and restorative material used as the antagonist (all $p < 0.001$) had a significant effect on VHL. Polishing reduced VHL for 5Y-TZP (C = G > P), microhybrid composite resin (C = G > P), leucite-reinforced ceramic (C = G > P), and lithium disilicate (G > C > P), while glazing increased VHL for lithium disilicate (G > C = P). In the presence of staining, the finishing procedure had no influence on VHL for microhybrid composite resin (S = SG = SP) and leucite-reinforced ceramic (S = SG = SP), while polishing reduced VHL for 5Y-TZP (S = SG > SP) and lithium disilicate (S = SG > SP). The 5Y-TZP used as an antagonist was responsible for the high mean values of VHL.

All restorative materials used as antagonists were abraded by 2BW. The presence of staining ($p = 0.042$), finishing procedure ($p < 0.001$), and restorative material used as the antagonist ($p < 0.001$) had a significant effect on WD. Polishing reduced the WD of microhybrid composite resin (C = G > P), while glazing increased the WD of lithium disilicate (G > C = P). In the presence of staining, glazing increased the WD of microhybrid composite resin (SG > S = SP), while it had no influence on the WD of 5Y-TZP (S = SG = SP), leucite-reinforced ceramic (S = SG = SP), and lithium disilicate (S = SG = SP). The highest mean values of WD were found for microhybrid composite resin, and were the lowest for 5Y-TZP (Table 4). For all groups, leucite-reinforced ceramic, and lithium disilicate presented similar and intermediate wear behavior.

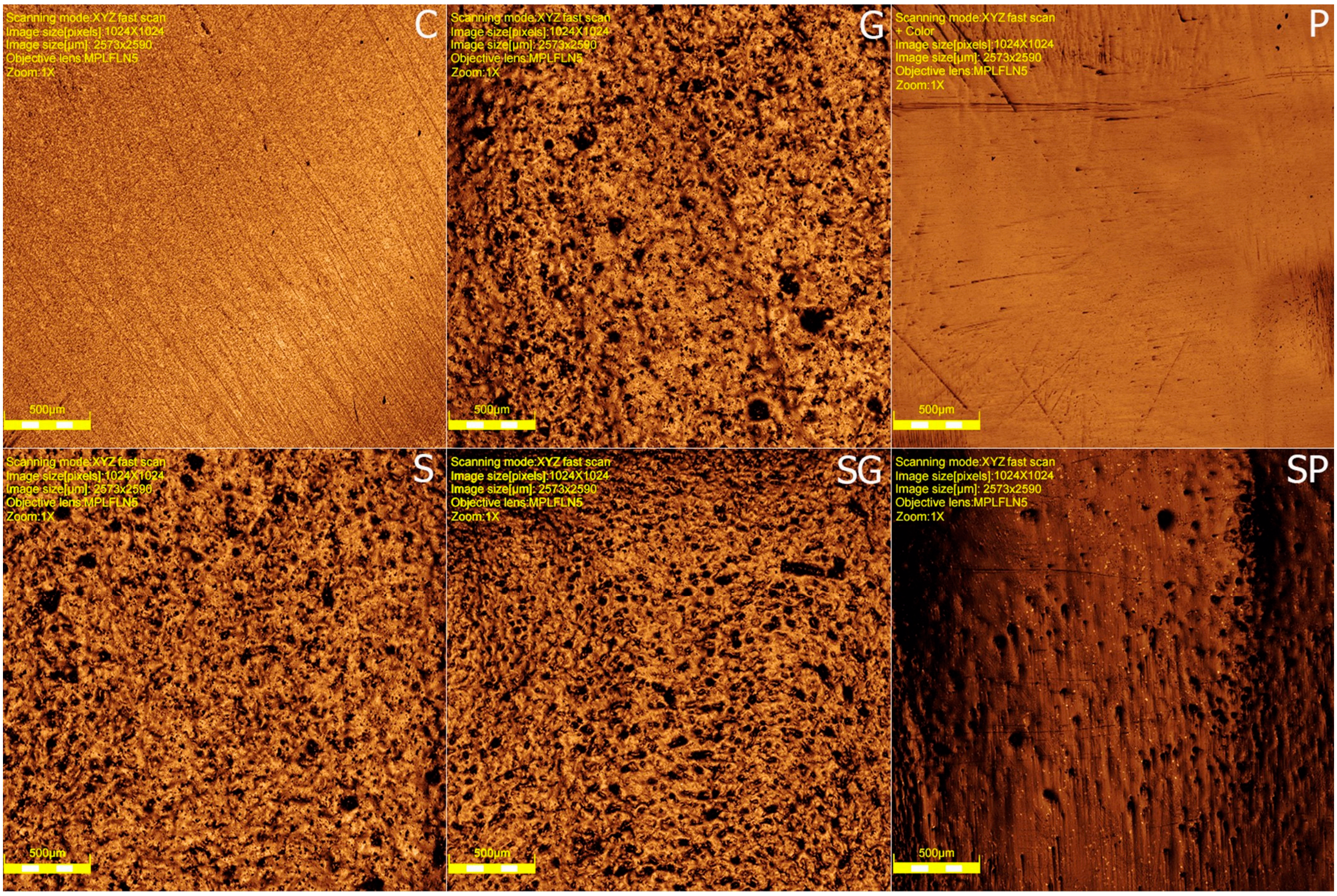


Figure 4. Laser confocal microscopy images showing the different surface morphology for all groups, including C (control), G (glazing), P (polishing), S (staining), SG (staining plus glazing), and SP (staining plus polishing).

Table 2. The vertical height loss (VHL) of hemispheres (µm) opposing stabilized zirconia with 5 mol% of yttrium oxide (5Y-TZP), lithium disilicate, leucite-reinforced ceramic, and microhybrid composite resin for all groups.

Group	Restorative Materials			
	5Y-TZP	Lithium Disilicate	Leucite-Reinforced Ceramic	Microhybrid Composite Resin
C	506.1 (139.0) $^{A\ a\ \alpha}$	227.9 (48.2) $^{A\ b\ \alpha}$	227.4 (48.9) $^{A\ b\ \alpha}$	215.9 (24.8) $^{A\ b\ \alpha}$
G	440.5 (60.5) $^{A\ a\ \alpha}$	332.4 (118.4) $^{B\ b\ \alpha}$	212.4 (38.1) $^{A\ c\ \alpha}$	189.9 (59.0) $^{A\ c\ \alpha}$
P	361.2 (67.5) $^{B\ a\ \alpha}$	83.4 (59.8) $^{C\ b\ \alpha}$	10.7 (33.8) $^{B\ b\ \alpha}$	0.0 (-) $^{B\ b\ \alpha}$
S	441.9 (85.0) $^{A\ a\ \alpha}$	160.4 (28.4) $^{A\ b\ \alpha}$	79.4 (55.6) $^{A\ b\ \beta}$	94.3 (24.4) $^{A\ b\ \beta}$
SG	394.6 (61.7) $^{A\ a\ \alpha}$	194.1 (48.7) $^{A\ b\ \beta}$	0.0 (-) $^{A\ c\ \beta}$	60.8 (67.7) $^{A\ c\ \beta}$
SP	286.8 (64.8) $^{B\ a\ \alpha}$	27.3 (58.3) $^{B\ b\ \alpha}$	0.0 (-) $^{A\ b\ \alpha}$	0.0 (-) $^{A\ b\ \alpha}$

$^{A,\ B}$ Different uppercase letters indicate statistical difference between subgroups in the column ($p < 0.05$), $^{a,\ b,\ c}$ different lowercase letters indicate statistical difference between subgroups in the line ($p < 0.05$), and $^{\alpha,\ \beta}$ different greek letters indicate statistical difference between different subgroups with the same restorative material and finishing procedure, and presence or not of staining ($p < 0.05$).

Table 3. The wear depth (WD) of dental restorative materials (µm), including stabilized zirconia with 5 mol% of yttrium oxide (5Y-TZP), lithium disilicate, leucite-reinforced ceramic, and microhybrid composite resin for all groups.

Group	Restorative Materials			
	5Y-TZP	**Lithium Disilicate**	**Leucite-Reinforced Ceramic**	**Microhybrid Composite Resin**
C	127.5 (22.0) $^{A\,a\,\alpha}$	467.9 (115.0) $^{A\,b\,\alpha}$	655.6 (85.6) $^{A\,b\,\alpha}$	1248.4 (169.0) $^{A\,c\,\alpha}$
G	112.98 (28.5) $^{A\,a\,\alpha}$	693.0 (153.6) $^{B\,b\,\alpha}$	662.9 (128.7) $^{A\,b\,\alpha}$	1085.3 (387.0) $^{A\,c\,\alpha}$
P	97.5 (37.2) $^{A\,a\,\alpha}$	498.1 (88.5) $^{A\,b\,\alpha}$	541.0 (114.1) $^{A\,b\,\alpha}$	709.1 (114.8) $^{B\,b\,\alpha}$
S	143.6 (18.9) $^{A\,a\,\alpha}$	526.9 (85.4) $^{A\,b\,\alpha}$	562.0 (66.5) $^{A\,b\,\alpha}$	932.2 (157.7) $^{A\,c\,\beta}$
SG	181.4 (75.7) $^{A\,a\,\alpha}$	523.3 (117.8) $^{A\,b\,\alpha}$	730.4 (140.2) $^{A\,b\,\alpha}$	1514.6 (129.2) $^{B\,c\,\beta}$
SP	159.8 (39.2) $^{A\,a\,\alpha}$	472.7 (93.7) $^{A\,b\,\alpha}$	616.6 (137.9) $^{A\,b\,\alpha}$	947.4 (110.4) $^{A\,c\,\beta}$

$^{A,\,B}$ Different uppercase letters indicate statistical difference between subgroups in the column ($p < 0.05$), $^{a,\,b,\,c}$ different lowercase letters indicate statistical difference between subgroups in the line ($p < 0.05$), and $^{\alpha,\,\beta}$ different greek letters indicate statistical difference between different subgroups with the same restorative material and finishing procedure, and presence or not of staining ($p < 0.05$).

Table 4. Data of Wald test for vertical height loss (VHL) and wear depth (WD).

Source	VHL			WD		
	Wald Chi-Square	**DF**	**P**	**Wald Chi-Square**	**DF**	**P**
(Intercept)	2387.674	1	0.000	4920.898	1	0.000
Restorative material	1102.728	3	0.000	1555.076	3	0.000
Finishing procedure	292.335	2	0.000	78.643	2	0.000
Staining	131.751	1	0.000	4.131	1	0.042
Restorative material X Finishing procedure	34.055	6	0.000	71.696	6	0.000
Restorative material X Staining	8.283	3	0.041	12.041	3	0.007
Finishing procedure X Staining	26.669	2	0.000	24.490	2	0.000
Restorative material X Finishing procedure X Staining	23.370	6	0.001	76.821	6	0.000

4. Discussion

The results of the current investigation support the rejection of the null hypothesis. The staining, glazing, and polishing influenced the wear behavior of 5Y-TZP opposing different dental restorative materials. Polishing reduced the VHL of 5Y-TZP opposing 5Y-TZP, microhybrid composite resin, leucite-reinforced ceramic, and lithium disilicate, and reduced the WD of microhybrid composite resin, while glazing increased the WD of G opposing lithium disilicate and SG opposing microhybrid composite resin. The presence of staining and finishing procedures were chosen in this study to represent different scenarios of monolithic zirconia restoration.

Previous studies investigated the wear behavior of polished 3Y, 4Y, and 5Y-TZP opposing steatite antagonists and found no difference among them [23,24], but the effect of staining and glazing was not considered. For 3Y-TZP, studies have shown that polishing reduces the wear of human enamel compared with glazing [18–20,22]. However, the results found for 3Y-TZP cannot be considered for 5Y-TZP, because these materials present significant differences in crystalline phase content, microstructure, and mechanical properties, which affect wear behavior [12].

The VHL mean values represent the loss of glaze (for G and SG groups) and/or stain layer (for S, SG, and SP groups), considering that each layer measures approximately 100 µm [8]. The G group presented VHL above 100 µm, demonstrating that the glaze layer was lost after 2BW, corroborating with other studies [18–20,39]. This fact can be explained by potential chemical incompatibility [40,41] and differences in thermal expansion coefficients [42] of zirconia and glaze paste, resulting in a weak interface between them. This weak interface is considered the greatest problem of glazed zirconia and creates a fragile region that can give rise to delamination and production of critical defects, increasing the antagonist wear [20]. This study found that the G group increased the VHL and WD opposing LD, and the SG group increased the WD of microhybrid composite resin. It is possible that delamination of the glaze layer exposed a rough zirconia substructure [19,25], and delaminated glaze particles acted as a third abrasion agent, justifying these results.

In view of the need to select a finishing procedure for non-stained monolithic zirconia restorations, the results of this study suggest that polishing is better than glazing, because decreased VHL opposed all dental restorative materials investigated and also decreased WD of microhybrid composite resin. This fact can be attributed to zirconia's ability to retain the initial surface smoothness after polishing for the P group, and the weak interface between zirconia and glaze paste related to the G group. Additionally, polishing offers the dental clinician the advantage of finishing the restoration chairside without the need for an expensive firing furnace or glazing cycles [29].

Regarding staining durability, previous studies found that glaze can protect the stain layer on glass ceramics [9,10]. Dal Piva et al. [16] investigated the stain durability (stain plus glaze) after a three-body wear test without an antagonist, and found that stain and glaze layers were removed from 4Y-TZP after 600,000 cycles. In this study, the glaze protected the stain layer of the SG group opposing microhybrid composite resin and leucite-reinforced ceramic. However, it is possible that the glaze and stain layer was removed after more than 300,000 cycles. Furthermore, polishing after staining reduced VHL and protected the stain layer for the SP group opposing lithium disilicate, leucite-reinforced ceramic, and microhybrid composite resin. The stain layer was removed for all groups opposing 5Y-TZP, regardless of the finishing procedure that was used. Therefore, the results of this study suggest that polishing is recommended to protect the stain layer instead of glazing, and stain durability was related to the abrasiveness of dental restorative material used as an antagonist.

The relationship between surface roughness and wear behavior is expounded by the literature. Many studies correlated rougher surfaces with the increase in the attrition coefficient and consequently increased the wear on the antagonist [20,43]. The most uniform and smooth surfaces found in the C, P, and SP groups on laser confocal microscopy can justify the lowest VHL opposing all dental restorative materials investigated and the lowest WD opposing lithium disilicate and microhybrid composite resin.

The wear behavior of dental restorative materials differs significantly according to microstructure, fracture toughness, and fatigue strength. Wear occurs during crack formation and propagation, explaining the high wear resistance for materials with high fracture toughness and fatigue strength [12,20,44]. The 5Y-TZP showed the highest wear resistance, according to previous studies [27,29–31]. Its high wear resistance could be explained by the difficulty for cracks to propagate in a polycrystalline microstructure, and the high values of fracture toughness [6]. The effect of hardness on wear resistance has been discussed. Some authors argued that hardness is related to wear resistance [14,28], while others claim that there is no correlation between them [17,31].

Glass ceramics (leucite-reinforced ceramic and lithium disilicate) presented intermediate and similar wear behavior after 2BW, in line with another study [27]. The wear on glass ceramics occurs from crack formation and propagation. During the wear process, the edge of individual crystals of the crystalline phase may have been exposed, increasing surface roughness and intensifying wear [12]. Some authors related that polished 5Y-TZP caused high wear rates on lithium disilicate due to the presence of microfractures and grain dislodgment, which increased the wear during 2BW [30].

Resin composite is widely used in dentistry, and is a common antagonist. The MCR was the dental restorative material that showed the lowest wear resistance. This wear occurs preferentially in the resin matrix, exposing filler particles that may have acted as a third abrasive agent [12]. The high values of WD suggest that the exposure of filler particles favored wear, and the 2BW promoted crack propagation in the subsurface of the material [12,31]. Although some authors suggested that the manufacturing method of composite resins could influence wear behavior [26], others investigated the wear behavior of polished 5Y-TZP opposing six brands of direct and indirect composite resin and found that the increase in polymerization degree for indirect composite resin did not improve the wear resistance of the composite resin opposing monolithic zirconia [31]. An additional concern for composite resin restorations is margin failure and gap propagation due to cyclic loading superimposed on the interfacial stresses caused by polymerization shrinkage of the resin during curing. The marginal gaps can enable secondary caries formation, leading to a need to composite resin restoration replacement [12].

The in vivo methods represent a more accurate progression of wear, but it was related to high cost, long time duration, and ethical issues. In addition, it is difficult to control and isolate the main factors that influence wear in vivo. In contrast, in vitro methods allow the control over exposure time, temperature, and other variables, has a high level of standardization, and the results indicate trends regarding the true extent of wear, which should not be extrapolated to the oral environment because it is not possible to reproduce all its particularities [45]. The results of in vitro studies are affected by the applied load, number of cycles, and experimental design, such as the two-body or three-body wear test [15,30,43,45]. This in vitro study evaluated the wear behavior of dental restorative materials using the two-body wear test with a clinically relevant load (20 N) [29,38,43,45], frequency close to human chewing function (2 Hz) [43,45], and a number of cycles equivalent to 18 months of clinical service [27,36–38].

The present study demonstrated that polishing is able to reduce the wear rates of dental restorative material used as the antagonist, especially to microhybrid composite resin. The glaze layer was lost after 2BW and led to the increase in wear rates to lithium disilicate used as the antagonist. The selection of polishing as a finishing procedure after staining is important to preserve staining. However, the limitations of this study included the use of non-anatomic specimens, the difficulty of reproducing the oral environment's complexity, such as occlusal contacts, pH variations, and chewing pattern individual variations, which depend on multiple factors such as muscle tone and the presence of temporomandibular disorders (Tables S1 and S2).

5. Conclusions

Based on the findings of this in vitro study, the following conclusions were drawn:

- Polishing is recommended to reduce the wear rates of microhybrid composite resin used as the antagonist and allow the dental clinician to finish the restoration chairside without the need for an expensive firing furnace or glazing cycles.
- When staining is necessary to characterize restorations, polishing improved staining durability opposing microhybrid composite resin, leucite-reinforced ceramic, and lithium disilicate;
- Glazing increased wear rates opposing lithium disilicate;
- Among restorative materials used as antagonists, 5Y-TZP presented the highest wear resistance; leucite-reinforced ceramic and lithium disilicate presented similar wear behavior with intermediate wear rates, and microhybrid composite resin presented the lowest wear resistance.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/coatings13020466/s1. Table S1: Pairwise comparations to vertical height loss of hemispheres; Table S2: Pairwise comparations to wear depth of dental restorative materials.

Author Contributions: Conceptualization, R.C.S.R.; Methodology, R.C.S.R.; Validation, L.F., A.O.d.S., A.C.L.F., R.F.R. and R.C.S.R.; Formal Analysis, A.C.L.F., A.P.M. and R.C.S.R.; Investigation, L.F., P.E.B.S.O. and A.O.d.S.; Resources, R.F.R. and R.C.S.R.; Data Curation, R.C.S.R.; Writing—Original Draft Preparation, L.F., P.E.B.S.O., A.O.d.S., A.C.L.F., A.P.M. and R.C.S.R.; Writing—Review & Editing, L.F., A.C.L.F., R.F.R. and R.C.S.R.; Visualization, L.F., P.E.B.S.O., A.O.d.S., A.C.L.F., A.P.M., R.F.R. and R.C.S.R.; Supervision, R.C.S.R.; Project Administration, R.C.S.R.; Funding Acquisition, R.C.S.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the São Paulo Research Foundation—FAPESP, grant number 2019/18367-4; L.F. received a PhD scholarship from the Agency for the High-Standard Promotion of Graduate Courses—CAPES, which also supports the Oral Rehabilitation Graduate Program—code

001; P.E.B.S.O. received a Scientific Initiation scholarship from the São Paulo Research Foundation—FAPESP, grant number 2020/05467-8.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data supporting the results of this study are available in the article and can be requested from the corresponding author.

Acknowledgments: The authors acknowledge, the Digital Center CAD-CAM Lab, Regina Guenka Palma-Dibb for access to the confocal laser microscope, and Juliana Jendiroba Faraoni for technical support.

Conflicts of Interest: The authors declare that they have no financial or personal interest that could have influenced the work reported in this paper.

References

1. Stawarczyk, B.; Keul, C.; Eichberger, M.; Figge, D.; Edelhoff, D.; Lümkemann, N. Three generations of zirconia: From veneered to monolithic. Part I. *Quintessence Int.* **2017**, *48*, 369–380. [CrossRef] [PubMed]
2. Zhang, Y.; Lawn, B.R. Novel Zirconia Materials in Dentistry. *J. Dent. Res.* **2018**, *97*, 140–147. [CrossRef] [PubMed]
3. Carrabba, M.; Keeling, A.J.; Aziz, A.; Vichi, A.; Fonzar, R.F.; Wood, D.; Ferrari, M. Translucent zirconia in the ceramic scenario for monolithic restorations: A flexural strength and translucency comparison test. *J. Dent.* **2017**, *60*, 70–76. [CrossRef] [PubMed]
4. Tabatabaian, F. Color in Zirconia-Based Restorations and Related Factors: A Literature Review. *J. Prosthodont.* **2019**, *27*, 201–211. [CrossRef]
5. Farzin, M.; Ansarifard, E.; Taghva, M.; Imanpour, R. Effect of external staining on the optical properties and surface roughness of monolithic zirconia of different thicknesses. *J. Prosthet. Dent.* **2021**, *126*, 687.e1–687.e8. [CrossRef]
6. Silva, A.O.; Fiorin, L.; Faria, A.C.L.; Ribeiro, R.F.; Rodrigues, R.C.S. Translucency and mechanical behavior of partially stabilized monolithic zirconia after staining, finishing procedures and artificial aging. *Sci. Rep.* **2022**, *12*, 16094. [CrossRef] [PubMed]
7. Sulaiman, T.A.; Abdulmajeed, A.A.; Donovan, T.E.; Vallittu, P.K.; Närhi, T.O.; Lassila, L.V. The effect of staining and vacuum sintering on optical and mechanical properties of partially and fully stabilized monolithic zirconia. *Dent. Mater. J.* **2015**, *34*, 605–610. [CrossRef]
8. Souza, L.F.B.; Soares, P.M.; Chiapinotto, G.F.; Ribeiro, V.F.; Daudt, N.F.; Valandro, L.F.; Pereira, G.K.R. Effect of pigmentation techniques on the fatigue mechanical behavior of a translucent zirconia for monolithic restorations. *J. Mech. Behav. Biomed. Mater.* **2022**, *134*, 105362. [CrossRef] [PubMed]
9. Garza, L.A.; Thompson, G.; Cho, S.H.; Berzins, D.W. Effect of toothbrushing on shade and surface roughness of extrinsically stained pressable ceramics. *J. Prosthet. Dent.* **2016**, *115*, 489–494. [CrossRef]
10. Kanat-Ertürk, B. Color stability of CAD/CAM ceramics prepared with different surface finishing procedures. *J. Prosthodont.* **2020**, *29*, 166–172. [CrossRef]
11. Aljomard, Y.R.M.; Altunok, E.Ç.; Kara, H.B. Enamel wear against monolithic zirconia restorations: A meta-analysis and systematic review of in vitro studies. *J. Esthet. Restor. Dent.* **2022**, *34*, 473–489. [CrossRef]
12. Kruzic, J.J.; Arsecularatne, J.A.; Tanaka, C.B.; Hoffman, M.J.; Cesar, P.F. Recent advances in understanding the fatigue and wear behavior of dental composites and ceramics. *J. Mech. Behav. Biomed. Mater.* **2018**, *88*, 504–533. [CrossRef] [PubMed]
13. Kruzic, J.J.; Hoffman, M.; Arsecularatne, J.A. Fatigue and wear of human tooth enamel: A review. *J. Mech. Behav. Biomed. Mater.* **2023**, *138*, 105574. [CrossRef]
14. Mörmann, W.H.; Stawarczyk, B.; Ender, A.; Sener, B.; Attin, T.; Mehl, A. Wear characteristics of current aesthetic dental restorative CAD/CAM materials: Two-body wear, gloss retention, roughness and Martens hardness. *J. Mech. Behav. Biomed. Mater.* **2013**, *20*, 113–125. [CrossRef] [PubMed]
15. Pereira, G.K.R.; Dutra, D.M.; Werner, A.; Prochnow, C.; Valandro, L.F.; Kleverlaan, C.J. Effect of zirconia polycrystal and stainless steel on the wear of resin composites, dentin and enamel. *J. Mech. Behav. Biomed. Mater.* **2019**, *91*, 287–293. [CrossRef]
16. Dal Piva, A.M.O.; Tribst, J.P.M.; Werner, A.; Anami, L.C.; Bottino, M.A.; Kleverlaan, C.J. Three-body wear effect on different CAD/CAM ceramics staining durability. *J. Mech. Behav. Biomed. Mater.* **2020**, *103*, 103579. [CrossRef]
17. Oh, W.S.; Delong, R.; Anusavice, K.J. Factors affecting enamel and ceramic wear: A literature review. *J. Prosthet. Dent.* **2002**, *87*, 451–459. [CrossRef] [PubMed]
18. Mitov, G.; Heintze, S.D.; Walz, S.; Woll, K.; Muecklich, F.; Pospiech, P. Wear behavior of dental Y-TZP ceramic against natural enamel after different finishing procedures. *Dent. Mater.* **2012**, *28*, 909–918. [CrossRef]
19. Preis, V.; Behr, M.; Handel, G.; Schneider-Feyrer, S.; Hahnel, S.; Rosentritt, M. Wear performance of dental ceramics after grinding and polishing treatments. *J. Mech. Behav. Biomed. Mater.* **2012**, *10*, 13–22. [CrossRef]
20. Janyavula, S.; Lawson, N.; Cakir, D.; Beck, P.; Ramp, L.C.; Burgess, J.O. The wear of polished and glazed zirconia against enamel. *J. Prosthet. Dent.* **2013**, *109*, 22–29. [CrossRef]

21. Lawson, N.C.; Janyavula, S.; Syklawer, S.; McLaren, E.A.; Burgess, J.O. Wear of enamel opposing zirconia and lithium disilicate after adjustment, polishing and glazing. *J. Dent.* **2014**, *42*, 1586–1591. [CrossRef] [PubMed]
22. Park, J.H.; Park, S.; Lee, K.; Yun, K.D.; Lim, H.P. Antagonist wear of three CAD/CAM anatomic contour zirconia ceramics. *J. Prosthet. Dent.* **2014**, *111*, 20–29. [CrossRef] [PubMed]
23. Zhang, F.; Spies, B.C.; Vleugels, J.; Reveron, H.; Wesemann, C.; Müller, W.D.; van Meerbeek, B.; Chevalier, J. High-translucent yttria-stabilized zirconia ceramics are wear-resistant and antagonist-friendly. *Dent. Mater.* **2019**, *35*, 1776–1790. [CrossRef] [PubMed]
24. Rosentritt, M.; Preis, V.; Behr, M.; Strasser, T. Fatigue and wear behavior of zirconia materials. *J. Mech. Behav. Biomed. Mater.* **2020**, *110*, 103970. [CrossRef] [PubMed]
25. Çakmak, G.; Subaşı, M.G.; Sert, M.; Yilmaz, B. Effect of surface treatments on wear and surface properties of different CAD-CAM materials and their enamel antagonists. *J. Prosthet. Dent.* **2021**, *20*, S0022-3913(21)00340-1. [CrossRef] [PubMed]
26. Ozkir, S.E.; Bicer, M.; Deste, G.; Karakus, E.; Yilmaz, B. Wear of monolithic zirconia against different CAD-CAM and indirect restorative materials. *J. Prosthet. Dent.* **2021**, *28*, S0022-3913(21)00198-0. [CrossRef] [PubMed]
27. Albashaireh, Z.S.; Ghazal, M.; Kern, M. Two-body wear of different ceramic materials opposed to zirconia ceramic. *J. Prosthet. Dent.* **2010**, *104*, 105–113. [CrossRef]
28. Hatanaka, A.; Sawada, T.; Sen, K.; Saito, T.; Sasaki, K.; Someya, T.; Hattori, M.; Takemoto, S. Wear behavior between aesthetic restorative materials and bovine tooth enamel. *Materials* **2022**, *15*, 5234. [CrossRef] [PubMed]
29. Fouda, A.M.; Atta, O.; Kassem, A.S.; Desoky, M.; Bourauel, C. Wear behavior and abrasiveness of monolithic CAD/CAM ceramics after simulated mastication. *Clin. Oral Investig.* **2022**, *26*, 6593–6605. [CrossRef]
30. Jia-Mahasap, W.; Jitwirachot, K.; Holloway, J.A.; Rangsri, W.; Rungsiyakull, P. Wear of various restorative materials against 5Y-ZP zirconia. *J. Prosthet. Dent.* **2022**, *128*, 814.e1–814.e10. [CrossRef]
31. Maier, E.; Grottschreiber, C.; Knepper, I.; Opdam, N.; Petschelt, A.; Loomans, B.; Lohbauer, U. Evaluation of wear behavior of dental restorative materials against zirconia in vitro. *Dent. Mater.* **2022**, *38*, 778–788. [CrossRef] [PubMed]
32. Khayat, W.; Chebib, N.; Finkelman, M.; Khayat, S.; Ali, A. Effect of grinding and polishing on roughness and strength of zirconia. *J. Prosthet. Dent.* **2018**, *119*, 626–631. [CrossRef] [PubMed]
33. Incesu, E.; Yanikoglu, N. Evaluation of the effect of different polishing systems on the surface roughness of dental ceramics. *J. Prosthet. Dent.* **2020**, *124*, 100–109. [CrossRef] [PubMed]
34. Ozen, F.; Demirkol, N.; Parlar, O.O. Effect of surface finishing treatments on the color stability of CAD/CAM materials. *J. Adv. Prosthodont.* **2020**, *12*, 150–156. [CrossRef] [PubMed]
35. Theodoro, G.T.; Fiorin, L.; Moris, I.C.M.; Rodrigues, R.C.S.; Ribeiro, R.F.; Faria, A.C.L. Wear resistance and compression strength of ceramics tested in fluoride environments. *J. Mech. Behav. Biomed. Mater.* **2017**, *65*, 609–615. [CrossRef] [PubMed]
36. Kern, M.; Strub, J.R.; Lu, X.Y. Wear of composite resin veneering materials in a dual axis chewing simulator. *J. Oral Rehabil.* **1999**, *26*, 372–378. [CrossRef] [PubMed]
37. Ghazal, M.; Kern, M. The influence of antagonistic surface roughness on the wear of human enamel and nanofilled composite resin artificial teeth. *J. Prosthet. Dent.* **2009**, *101*, 342–349. [CrossRef] [PubMed]
38. Kwon, S.J.; Lawson, N.C.; McLaren, E.E.; Nejat, A.H.; Burgess, J.O. Comparison of the mechanical properties of translucent zirconia and lithium disilicate. *J. Prosthet. Dent.* **2018**, *120*, 132–137. [CrossRef]
39. Badarneh, A.; Eun Choi, J.J.; Lyons, K.; Porter, G.; Waddell, N.; Chun Li, K. The effect of aging on the wear performance of monolithic zirconia. *Dent. Mater.* **2022**, *38*, e136–e146. [CrossRef] [PubMed]
40. Aboushelib, M.N.; Kleverlaan, C.J.; Feilzer, A.J. Effect of zirconia type on its bond strength with different veneer ceramics. *J. Prosthodont.* **2008**, *17*, 401–408. [CrossRef]
41. Yamamoto, L.T.; Rodrigues, V.A.; Dornelles, L.S.; Bottino, M.A.; Valandro, L.F.; Melo, R.M. Low-Fusing Porcelain Glaze Application on 3Y-TZP Surfaces can Enhance Zirconia-Porcelain Adhesion. *Braz. Dent. J.* **2016**, *27*, 543–547. [CrossRef] [PubMed]
42. Aboushelib, M.N.; Wang, H. Effect of surface treatment on flexural strength of zirconia bars. *J. Prosthet. Dent.* **2010**, *104*, 98–104. [CrossRef] [PubMed]
43. Kaizer, M.R.; Moraes, R.R.; Cava, S.S.; Zhang, Y. The progressive wear and abrasiveness of novel graded glass/zirconia materials relative to their dental ceramic counterparts. *Dent. Mater.* **2019**, *35*, 763–771. [CrossRef]
44. Heintze, S.D.; Reichl, F.X.; Hickel, R. Wear of dental materials: Clinical significance and laboratory wear simulation methods. A review. *Dent. Mater. J.* **2019**, *38*, 343–353. [CrossRef]
45. Lambrechts, P.; Debels, E.; Van Landuyt, K.; Peumans, M.; Van Meerbeek, B. How to simulate wear? Overview of existing methods. *Dent. Mater.* **2006**, *22*, 693–701. [CrossRef] [PubMed]