Wear analysis and topographical properties of monolithic zirconia and CoCr against human enamel after polishing and glazing procedures

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Abstract: PURPOSE Intraoral adjustments of monolithic zirconia (MZ) necessitate intraoral grinding and polishing procedures, causing surface topography changes. The effect of various polishing and glazing procedures on surface roughness, topographical and phase changes of CoCr compared to zirconia, and assessment of the wear of the opposing dentition has been evaluated in this study. MATERIALS AND METHODS One group of square Cobaltchromium (CoCr) and four groups of sintered and polished zirconia specimens ($12 \times 12 \times 1$ mm) were fabricated ($N = 5$, $n = 8$) using Cobaltchromium or yttria-stabilized zirconia (ZrO_2 , Y_2O_3) blocks (ZEN-TROSTAR Zr Translucent; Wieland Dental + Technik). Each of the four zirconia groups was treated differently, one group was glazed (G), one was left unglazed (UG), two groups were polished, one using silicon carbide polishers (BG) and one with diamond-impregnated ceramic polisher kit (CG). All specimens were thereafter subjected to chewing simulation using enamel cusps ($1'200'000$ cycles, 49N force and 1.67 Hz loading frequency). Topographical changes were evaluated considering (a) weight (digital scale), (b) volume loss (digital microscope), (c) vertical height loss (digital microscope), (d) surface roughness (R_a , profilometer), and (e) mean roughness depth (R_z , profilometer). In addition the volume loss (digital microscope) of the used corresponding enamel cusps was measured. The surface roughness, topographical changes and antagonist wear of enamel cusps was measured. Statistical analysis was performed using the statistical software R and the kruskal-wallis rank sum test and posthoc pairwise comparisons ($\alpha = 0.05$). RESULTS The mean surface roughness (μm) difference (ΔR_a) was lowest for UG (-0.014 ± 0.007) and the highest for CG (-0.806 ± 0.172) ($UG^a < CoCr^b < BG^c < G^{a,d} < CG^e$). UG showed the lowest surface peak roughness (μm) difference (ΔR_z) -0.316 ± 0.084 and CG the highest (-3.691 ± 0.369) ($UG^a < CoCr^b < BG^c < G^{a,d} < CG^e$). Material weight loss (ΔW) ranged between -0.005 ± 0.0001 and -0.000 ± 0.000 g ($CoCr^a < UG^{a,b} < CG^b < BG^b < G^b$) compared to baseline, while the volume loss (ΔV) was between $-21 \pm 52 \times 10^6$ and $58 \pm 36 \times 10^6 \mu m^3$ ($CoCr^a < BG^a < UG^a < CG^a < G^a$). The vertical height loss (ΔVH) was highest for UG (-12.067 ± 11.624) and lowest for G ($-0.033 \pm 0.034 \mu m$) ($G^a < CoCr^{a,b} < CG^c < BG^{a,c,d} < UG^{a,b,d}$). As for the volume loss (ΔV) of the corresponding enamel cusps, no significant differences could be measured ($BG^a < UG^a < G^a < CG^a < CoCr^a$), therefore surface treatment did not affect the wear of the enamel antagonist. CONCLUSION CoCr and highly polished monolithic zirconia produced less surface roughness and similar antagonist wear compared to glazed or unglazed zirconia. CoCr and highly polished monolithic zirconia can be considered as a good choice regarding the mechanical wear behaviour of materials and their corresponding enamel antagonist.

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Wear analysis and topographical properties of monolithic zirconia and CoCr against human enamel after polishing and glazing procedures

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Short title: *Topographical and wear behaviour of zirconia and CorCr against enamel*

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ABSTRACT

Purpose: Intraoral adjustments of monolithic zirconia (MZ) necessitate intraoral grinding and polishing procedures, causing surface topography changes. The effect of various polishing and glazing procedures on surface roughness, topographical and phase changes of CoCr compared to zirconia, and assessment of the wear of the opposing dentition has been evaluated in this study.

Materials and Methods: One group of square Cobaltchromium (CoCr) and four groups of sintered and polished zirconia specimens (12x12x1mm) were fabricated (N=5, n=8) using Cobaltchromium or yttria-stabilized zirconia (ZrO₂, Y₂O₃) blocks (ZENTROSTAR Zr Translucent; Wieland Dental + Technik). Each of the four zirconia groups was treated differently, one group was glazed (G), one was left unglazed (UG), two groups were polished, one using silicon carbide polishers (BG) and one with diamond-impregnated ceramic polisher kit (CG). All specimens were thereafter subjected to chewing simulation using enamel cusps (1'200'000 cycles, 49N force and 1.67 Hz loading frequency). Topographical changes were evaluated considering (a) weight(digital scale), (b) volume loss(digital microscope), (c) vertical height loss(digital microscope), (d) surface roughness (Ra, profilometer), and (e) mean roughness depth (Rz, profilometer). In addition the volume loss (digital microscope) of the used corresponding enamel cusps was measured. The surface roughness, topographical changes and antagonist wear of enamel cusps were measured. Statistical analysis was performed using the statical software R and the kruskal-wallis rank sum test and posthoc pairwise comparisons ($\alpha=0.05$).

Results: The mean surface roughness (μm) difference (ΔRa) was lowest for UG (-0.014 ± 0.007) and the highest for CG (-0.806 ± 0.172) ($\text{UG}^a < \text{CoCr}^b < \text{BG}^c < \text{G}^{a,d} < \text{CG}^e$). UG showed the lowest surface peak roughness (μm) difference (ΔRz) -0.316 ± 0.084 and CG the highest (-3.691 ± 0.369) ($\text{UG}^a < \text{CoCr}^b < \text{BG}^c < \text{G}^{a,d} < \text{CG}^e$). Material weight loss (ΔW) ranged between -0.005 ± 0.0001 and -0.000 ± 0.000 g ($\text{CoCr}^a < \text{UG}^{a,b} < \text{CG}^b < \text{BG}^b < \text{G}^b$) compared to baseline, while the volume loss (ΔV) was between $-21 \pm 52 \times 10^6$ and $58 \pm 36 \times 10^6 \mu\text{m}^3$ ($\text{CoCr}^a < \text{BG}^a < \text{UG}^a < \text{CG}^a < \text{G}^a$). The vertical height loss (ΔVH) was highest for UG (-12.067 ± 11.624) and lowest for G $-0.033 \pm 0.034 \mu\text{m}$ ($\text{G}^a < \text{CoCr}^{a,b} < \text{CG}^c < \text{BG}^{a,c,d} < \text{UG}^{a,b,d}$). As for the volume loss (ΔV) of the corresponding enamel cusps, no significant differences could be measured ($\text{BG}^a < \text{UG}^a < \text{G}^a < \text{CG}^a < \text{CoCr}^a$), therefore surface treatment did not affect the wear of the enamel antagonist.

Conclusion: CoCr and highly polished monolithic zirconia produced less surface roughness and similar antagonist wear compared to glazed or unglazed zirconia. CoCr and highly polished monolithic zirconia can be considered as a good choice regarding the mechanical wear behaviour of materials and their corresponding enamel antagonist.

Keywords: CoCr; glazing; monolithic zirconia; surface roughness; tribology; wear; Y-TZP.

1. Introduction

Metal ceramics still represent the gold standard in the dental rehabilitation of prosthodontics patients (Pjetursson et al., 2007). Nevertheless, the introduction and progress of digital computer-aided design/computer-aided manufacturing (CAD/CAM) techniques enabled the widespread of bilayered metal-free material alternatives. Zirconia is used in dentistry since many years, as framework material, due to the excellent mechanical properties, better aesthetic characteristics and excellent biocompatibility (Borba et al., 2011; Coli and Karlsson, 2004). Available long-term clinical data present good zirconia framework resistance in intraoral environment (Studart et al., 2007).

However, one major problem, mentioned in the literature observed in zirconia-ceramic reconstructions concerns the link between the two substrates and results in delaminations and chippings of ceramic veneer with or without zirconia exposure. This phenomena is due to different coefficients of thermal expansion (Studart et al., 2007), grinding damages produced during laboratory procedures (Fischer et al., 2009) and resulting residual stress and strain inside the ceramic material created during the firing of feldspathic ceramic coating, in terms of the speed of heating of the ceramic oven and the next sequence of cooling (Aboushelib et al., 2006; Luthardt et al., 2004). This most frequent cause of failures of zirconia ceramic bridges (Aboushelib et al., 2008) occurs in 15% of cases after 24 months (Vigolo et al., 2012), 13% after 36 months (Vult von Steyern et al., 2005) and 15 % after 60 (Sailer et al., 2006). Therefore, to manufacture single crowns, veneers and bridges, with more than three elements, zirconia can be effectively used, for the framework structure or, in the recent more translucent formulation, as monolithic solution (Wolfart et al., 2007; Tinschert et al., 2001).

Since monolithic zirconia (MZ) does not necessitate the use of any veneering ceramic, less tooth preparation is required, while CAD-CAM technology can be used to produce both the anatomically shaped ceramic veneering material and the framework from ceramic blocks,

characterized by high mechanical properties lacking the veneering ceramic and thereby avoiding veneer-chipping type of failures (Nakamura et al., 2015; Fischer et al., 2009; Beuer et al., 2008; Studart et al., 2007; Wolfart et al., 2007; Luthardt et al., 2004; Tinschert et al., 2001).

Zirconia is an oxide ceramic consisting of a pure crystalline matrix having 3 allotropes: monoclinic, tetragonal, and cubic (Ludovichetti et al., 2018; Manicone et al., 2014; Gupta et al., 1978; Garvie et al., 1975). 3Y-, 4Y- and 5Y- Y₂O₃ tetragonal zirconia polycrystals (Y-TZP) differ in strength (500-1200 MPa) and translucency (<50%), but show comparable hardness (HV: 1200-1300). Hardness and other material properties that vary between zirconia (HV: 1200-1300), CoCr (6.1GPa) and human tooth enamel (HV: 300-400) influence the wear performance (Hayashi et al., 2019; Li et al., 2016).

Because of its hardness zirconia is very difficult to polish or re-polish after clinical adjustment following laboratories final polish. Furthermore depending on the CAD/CAM system, grooves are produced on the surface in the range of 60 to 300 µm and are associated with the cutting tool (Estagan et al., 2003) Hardness of the material coupled with a rough surface texture may later produce wear of opposing enamel or reconstruction materials. Dental technicians should polish the grooves on the outer surface and clinicians should polish adjustments made to the restorations chairside. Enamel wear of 10 µm within an observation period of only 6 months and an approximately 42 µm wear in premolars and 127 µm in molars after 1 year of function were reported in different studies (Mundhe et al., 2015; Stober et al., 2014).

Polishing ceramic materials decreases the surface roughness and thereby causes less wear of opposing enamel (Elmaria et al., 2006). Polished zirconia was even reported to cause less wear of opposing enamel than enamel opposing itself (Olivera et al., 2006). Hence, polishing systems and protocols are urgently needed for determining which method and materials deliver the best surface on zirconia.

Aging also reduces the strength of zirconia significantly with monolithic phase formation (Basilio et al., 2016). The resistance to fracture and the phase stability are susceptible to hydrothermal and mechanical conditions (Basilio et al., 2016). Thus, the final surface roughness of the zirconia is important as it affects antagonist wear. High-luster polishing has been preferred over glazing of zirconia because it produces less surface roughness and less antagonist wear (Janyavula et al., 2014; Preis et al., 2013; Preis et al., 2012; Stawarczyk et al., 2012; Kern et al., 1998). Cobalt chromium (CoCr), which has become increasingly prevalent due to its superior physical properties and low cost compared to other restorative materials (Wataha, 2002).

The purpose of this study was to evaluate the effect of polishing and glazing procedures on surface roughness, topographical and phase changes of CoCr compared to zirconia, and to assess the wear of the opposing dentition. The null hypothesis of this study was that the choice of the material and aging method has no effect on the wear behaviour of the material and opposing enamel measured.

2. Material and methods

2.1 Specimen preparation

8 CoCr specimens were (12x12x1mm) fabricated through the lost-wax casting method. Using a phosphate-bonded investment (Ceramvest; Protechno) wax patterns (S-U Green wax, 60 000 11; Schuler-Dental) were invested in 3 silicone rings. After application of a surface tension reducing agent (Waxit; Evonik Degussa GmbH), the investment was mechanically spatulated under vacuum for 30 seconds at 425 rpm in a mixer (Iris 2; Mestra). 15 minutes later, the investment rings were heated in an oven (Model 5635; KaVo GmbH) to 900°C for 30 minutes for wax elimination. Afterwards, they were cast with a Co-Cr alloy (Colado CC; Ivoclar Vivadent) in air with a centrifugal-vacuum casting machine (Galloni Okay Plus Centrifugal Caster). Finally, the castings were devested and airborne particle abraded (DuoStar Z blaster; Bego) using 50 mm

aluminum oxide at 0.2 MPa for 10 seconds at a distance of 8 cm until all traces of investment were removed. 32 zirconia Specimens were cut out zirconia blocks (ZENTROSTAR Zr Translucent; Wieland Dental + Technik, Pfortzheim, Germany) with a small grain size of $<0.1 \mu\text{m}^2$, fracture toughness of $5 \text{ MPa}\cdot\text{m}^{1/2}$ and flexural strength of $>900 \text{ MPa}$. A water-cooled electrical precision diamond wire saw (Well; Walter Ebner) with blade diameter of 0.17 mm and 30 mm roughness was used to cut the specimens. The surfaces of the sectioned specimens were polished manually under water cooling using P2400 grit silicon carbide paper (Struers) until the thickness was obtained and verified using a digital micrometer (Mitutoyo). The specimens were then sintered in a high-temperature furnace (LHT02L16; Nabertherm) at 1500°C for 7 hours at a heating rate of 10 degrees per min according to the manufacturer's instructions.

2.2 Surface treatment

The five resulting groups, 1 CoCr and 4 zirconia groups were each treated individually. While the CoCr specimens (CoCr) and one zirconia specimen group (UG) were not further treated, one zirconia group was glazed (G) using a powder-liquid mix applied by brush (Vita Akzent; Vita Zahnfabrik). The other two zirconia groups were ground and polished using a constructed custom-made device (The Dhriller; University of Zurich, Switzerland, Designer: MÖ) (Fig1). High- and slow-speed handpieces (Intramatic Lux 700KL; KaVo Dental AG, Brugg, Germany) could be connected to the dental unit (KaVo ESTHETICA Comfort 1065; KaVo Dental AG). The device allowed controlled bidirectional and horizontal movement of the handpiece on the specimen. Load ranging from 120 to 750 g could be applied on the handpiece. Throughout the finishing procedures, the grinding and polishing instruments were positioned parallel to the specimen surfaces.

The obtained zirconia specimens were ground with $220 \mu\text{m}$ grit diamond rotatory burs with a shoulder edge (diameter: 0.13 mm; length: 12 mm; FG 5410L/6; Intensiv, Montagnola, Switzerland) at 160,000 rpm using the high-speed handpiece for 10 seconds. After the grinding

procedures, the specimens were ultrasonically cleaned (Branson Ultrasonic Cleaner 3510; Branson, Danbury, CT) in isopropanol for 10 minutes. The grinding procedure of both groups was followed by a polishing procedure performed using different polishing systems, each step was performed for 10 seconds using a slow-speed handpiece. One group (BG) was polished using silicon carbide polishers under water coolant (50ml/min); while the group (CG) was polished urethane-coated paper with aluminum oxide grits. All grinding and polishing procedures were performed under 7.5 N load with rpm ranging between 5000 and 30,000 depending on the manufacturer's instructions. After each step the specimens were ultrasonically cleaned for 10 minutes in isopropanol.

2.3 Wear testing

After the glazing and polishing procedures, all specimens of each group and material, namely CoCr, UG, G, BG and CG were mounted into a custom-made chewing simulator (1'200'000 cycles, 49N force and 1.67 Hz loading frequency) (Krejci et al., 2018). The antagonist was a enamel cusp, force was applied perpendicular to the centre of the square specimens.

2.4 Measurement

Surface topographical and material changes were evaluated considering (a) weight loss (ΔW), (b) volume loss (ΔV), (c) vertical height loss (ΔVH), (d) mean surface roughness (ΔRa), and (e) mean roughness depth (Rz). For each parameter, measurements from the final non-treated, glazed or polished specimen were subtracted from baseline measurements.

The weight loss ΔW was measured after specimen drying by subtraction of surface modified specimen from initial manufactured (baseline) specimen using a digital balance (Adventurer Pro AV264C; Ohaus, Pine Brook, NJ). For each specimen, ΔV and ΔVH were calculated by subtracting the scans of the final non-treated, glazed and polished surfaces from baseline using a digital microscope (VHX-2000D; Keyence, Osaka, Japan). Scans were obtained from a pre-

established reference point in the middle of each specimen, where the force of the enamel cusp was applied at 200x using a custom-made holder to remeasure the same area.

ΔRa and ΔRz was measured using a contact profilometer (Profilometer; PerthometerS2, Mahr, Göttingen, Germany) and the corresponding software program (MarSurfXR 20, Mahr). Measurements were conducted using a probe with a diameter of 2 μm perpendicular to the polishing direction with a cutoff length of 0.4 mm, at the following settings: traverse length: 2.4 mm; standard critical wavelength: 0.25 mm; velocity: 0.1 mm/s. Scans and the mean volume loss (ΔV) of the corresponding enamel cusps was measured using silicone duplicates (Affinis, Coltene, Altstätten, Switzerland) of the enamel cusps at pre-established reference points in the middle of each obtained duplicate (Figs 2a-b).

2.5 Statistical Analysis

All statistical analyses and plots were performed using the statistical software R (R Core Team R, 2015) and the PMCMR package for multiple comparisons (Pohlert, 2014). Krus-Wallis rank sum test and posthoc pairwise Conover's test for multiple comparisons were conducted ($p \leq 0.05$).

3. Results

The results of the study showed different wear behaviour considering the parameters weight, surface roughness, volume and vertical height loss of the different materials and surface treatments and their corresponding volume loss of the antagonistic enamel cusps.

The mean volume loss (ΔV) of the corresponding enamel cusps ranged between $9.3 \pm 1.4 \times 10^9 \mu m^3$ for BG and $70 \pm 77 \times 10^9 \mu m^3$ for CoCr with similar non significant differences ($BG^a < UG^a < G^a < CG^a < CoCr^a$). For all materials and surface treatments the volume loss of the enamel cusps decreased after the wear procedure.

Compared to baseline the mean material weight loss (ΔW) from the surface after polishing

ranged between -0.005 ± 0.0001 and -0.000 ± 0.000 g in ascending order as follows $\text{CoCr}^a < \text{UG}^{a,b} < \text{CG}^b < \text{BG}^b < \text{G}^b$ (one-way ANOVA Scheffé). The mean volume loss (ΔV) was highest for G ($58 \pm 36 \times 10^6$) and lowest for CoCr ($-21 \pm 52 \times 10^6$) μm^3 ($\text{CoCr}^a < \text{BG}^a < \text{UG}^a < \text{CG}^a < \text{G}^a$). As for the groups CoCr and BG the volume loss decreased, while it increased for the groups UG, CG and G.

Regardless of the chosen material and conducted surface treatment the mean vertical height loss (ΔVH) decreased ranging between -12.067 ± 11.624 μm for UG and -0.033 ± 0.034 μm for G ($\text{G}^a < \text{CoCr}^{a,b} < \text{CG}^c < \text{BG}^{a,c,d} < \text{UG}^{a,b,d}$).

The mean surface roughness (μm) difference (ΔRa) was lowest for UG (-0.014 ± 0.007) and the highest for CG (-0.806 ± 0.172) ($\text{UG}^a < \text{BG}^b < \text{CoCr}^c < \text{G}^{a,d} < \text{CG}^e$). CG showed the highest surface peak roughness (μm) difference (ΔRz) -0.316 ± 0.084 and UG the lowest (-3.691 ± 0.369) ($\text{UG}^a < \text{CoCr}^b < \text{BG}^c < \text{G}^{a,d} < \text{CG}^e$).

All groups presented significant differences regarding mean surface roughness and peak roughness compared to each other except for the groups UG and G. Boxplots of the measured parameters are shown in (Figs. 3a-f).

Correlation Coefficients of all parameters: Weight (ΔW), Volume loss (ΔV), Vertical height loss (ΔVH), Volume loss (ΔV), Volume loss (ΔV) for all five different groups (CoCr, UG, G, BG, CG) and the Volume loss (ΔV) of the corresponding enamel cusps are shown in Figure 4. Linear and monoton correlations were shown between the Parameters ΔRa and ΔRz (0.980), a correlation tendency could be shown between ΔRz and ΔV of the specimens (-0.308) (Fig 4).

Digital microscope images presented smoothest surfaces G, while polishing grooves are the deepest in CG, followed by BG, CoCr and UG specimens (Figs. 5a-e).

4. Discussion

This study was conducted to evaluate the effect of polishing and glazing procedures on surface roughness and topographical changes of CoCr compared to zirconia, and to assess the wear of the opposing dentition. The null hypothesis that the choice of the material and aging method had no effect on the wear behaviour of the material and opposing enamel using surface roughness, weight, volume loss and vertical height loss parameters was not rejected for the material choice regarding Ra and Rz values and for the wear of the opposing enamel cusps. However, it could be rejected for all other materials and topographical and wear comparisons.

The similar amount of wear of the enamel cusps caused by CoCr and zirconia specimens and measured using volume loss values of the enamel cusps can be attributed to similar high mechanical properties of the materials such as hardness (HV values: CoCr: 6100 MPa; Zirconia: 1200-1300 MPa) and flexural strength (CoCr: 1945 ± 308 ; Zirconia: 1200 ± 200) (Gustavsen et al., 1989). The materials, their mechanical properties, the chewing simulation and the different glazing and polishing procedures did not result in significant differences of the wear of the enamel cusps. However, the highest volume loss and thereby least associated wear of the enamel cusps could be observed in the BG group. Monolithic zirconia was reported to cause less wear of opposing enamel than enamel itself (Elmaria et al., 2006), in case it is highly polished. BG polishing systems on the other hand were reported to cause least material loss while producing low surface roughness values (Gustavsen et al., 1989).

After fabrication of the Cobaltchromium and the four monolithic zirconia groups, one zirconia group was left untreated, while one was glazed and two were polished. Roughness measurements were determined by the parameters Ra and Rz as recommended by ISO:4287–1997. Both parameters showed similar tendencies as shown in the correlation diagrams. The polished monolithic zirconia specimens were prior treated using grinding procedures, which introduced surface defects and is assumed to induce inherent increase in the monoclinic phase.

On the other hand glazing was shown to induce phase transformation reversion by removing the compression layer and keeping the defects and negatively influencing the fatigue strength.

The afterwards performed cyclic loading using a chewing simulator promotes tetragonal to monoclinic phase changes and induces further crack propagation and low temperature degradation (LTD) of zirconia, which may influence mechanical properties and wear (Ramos et al., 2016). Results suggest that after wear specimens polished with BG show lower surface roughnesses than the ones polished with CG (Al-Haj Husain and Özcan, 2018). Once the glaze is harmed the surface roughness showed higher roughness than the unglazed specimens. This might be due to included flaws in the interior of the glaze layer, caused by inherent imprisonment of air during mixing of the liquid (Cazzato et al., 1997). Stress concentration during chewing simulation is very dependent on the size of preexisting cracks/defects (Mecholsky, 1995), as a consequence to the applied force glaze ceramic dissolves and thereby might roughen the surface, which wears easily. Unglazed monolithic zirconia specimens show the lowest surface roughnesses and the CoCr specimens the second least. This could be explained by the chosen conventional casting techniques including shrinkage and an increased risk of defects due to poor control of the flow of molten alloy (Yamanaka et al., 2013), and less possible control of composition during fabrication of CoCr structures (Li et al., 2015).

Regarding the material weight loss (ΔW) the groups CG, BG and G showed significantly higher values compared to CoCr and higher non-significant ones compared to CoCr.

Obtained digital images showed that both polishing systems could not completely eliminate the baseline grooves, while CG treated specimens showed deeper irregularities and grooves. All tested materials and surface treatments resulted in similar high volume loss (ΔV) values, with the least volume loss was observed in the CoCr group and the highest in G, the hereby related vertical height loss (ΔVH) was therefore least for the specimens in group G. CG was comparable with BG and significantly differed from all other groups.

This study showed that CoCr is a good choice considering wear behaviour of materials and their corresponding enamel antagonist, while high-luster polishing is preferable over glazing of monolithic zirconia because it produces less surface roughness and similar antagonist wear.

One limitation of the study might be the use of only the volume loss parameter to measure the wear of the enamel cusps. However, as no profilometry measurements could be conducted on the silicone duplicate and digital microscope has been showed to be an acceptable tool for measuring tribiological parameters, the results can still be seen as validated (Al-Haj Husain and Özcan, 2018).

As the wear behavior of cobaltchromium or zirconia reconstructions materials might differ compared to the natural teeth and have an influence on occlusion and jaw position or even result in craniomandibular dysfunctions, the clinician should adjust a correct occlusion at delivery and to control wear behavior and occlusion and make adjustments if required during regular recall sessions.

Long-term in vivo studies should therefore focus on the investigation of wear behavior of newer materials, especially the hard monolithic zirconia and antagonistic teeth or reconstruction materials.

5. Conclusions

Based on this in vitro study, the following could be concluded:

1. CoCr exhibited the best results for the parameters ΔW , ΔV and similar good results for ΔVH compared to G, while causing similar high wear behaviour to opposed enamel antagonist.
2. CoCr resulted regarding mean surface roughness and mean roughness depth in significant higher values compared to unglazed zirconia, yet significantly better than polished BG, CG monolithic zirconia specimens.

3. Once monolithic zirconia needs intraoral adjustment after cementation, BG could be recommended, as it resulted in lower surface roughness values and better results for ΔW , ΔV compared to CG.

Clinical Relevance

CoCr and highly polished monolithic zirconia can be recommended for dental restoration regarding mechanical wear and tribological behaviour of the materials and the wear of THE antagonistic enamel.

Conflict of interest

The authors declare that they have no conflict of interest.

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Captions to tables and figures:

Figures:

Fig. 1. MZ specimen in the holder of the custom-made grinding and polishing device with controllable force and rpm values.

Figs. 2ab. Silicon duplicate of the enamel cusps a) before and b) after wear.

Figs. 3af. Boxplot of **a)** Weight (ΔW), **b)** Volume loss (ΔV), **c)** Vertical height loss (ΔVH), **d)** Surface roughness (ΔRa), **e)** Mean roughness depth (ΔRz) for all five different groups (CoCr, UG, G, BG, CG) and the **f)** Volume loss (ΔV) of the corresponding enamel cusps.

Fig. 4. Correlation Coefficients of all parameters: Weight (ΔW), Volume loss (ΔV), Vertical height loss (ΔVH), Surface roughness (ΔRa), Mean roughness depth (ΔRz) for all five different groups (CoCr, UG, G, BG, CG) and the Volume loss (ΔV) of the corresponding enamel cusps.

Figs. 5ae. Digital microscope images of **a)** Cobalt-Chromium (CoCr), **b)** Unglazed (UG), **c)** Glazed (G), and polished **d)** BG, and **e)** CG specimens.

Figs. 6ae. Digital microscope images of wear of enamel cusps against **a)** Cobalt-Chromium (CoCr), **b)** Unglazed (UG), **c)** Glazed (G), and polished **d)** BG, and **e)** CG specimens. Slots, grooves and fractures were observed.

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