

ORIGINAL ARTICLE

Two-body wear of monolithic, veneered and glazed zirconia and their corresponding enamel antagonistsBOGNA STAWARCZYK¹, MUTLU ÖZCAN¹, FELIX SCHMUTZ², ALBERT TROTTMANN¹, MALGORZATA ROOS³ & CHRISTOPH H. F. HÄMMERLE¹¹*Clinic of Fixed and Removable Prosthodontics and Dental Material Science, ²Clinic of Preventive Dentistry, Periodontology and Cariology, Center of Dental Medicine, and ³Division of Biostatistics, Institut of Social and Preventive Medicine, University of Zurich, Zurich, Switzerland***Abstract**

Objective. This study tested whether the two-body wear of monolithic zirconia and their corresponding enamel antagonists was higher compared to monolithic alloy and veneered zirconia. **Materials and methods.** Cylindrical specimens ($N=36$, $n=6$) were prepared out of (A) veneered zirconia (VZ), (B) glazed zirconia using a glaze ceramic (GZC), (C) glazed zirconia using a glaze spray (GZS), (D) manually polished monolithic zirconia (MAZ), (E) mechanically polished monolithic zirconia (MEZ) and (F) monolithic base alloy (control group, MA). Wear tests were performed in a chewing simulator (49 N, 1.7 Hz, 5°C/50°C) with enamel antagonists. The wear analysis was performed using a 3D profilometer before and after 120,000, 240,000, 640,000 and 1,200,000 masticatory cycles. SEM images were used for evaluating wear qualitatively. The longitudinal results were analysed using linear mixed models ($\alpha = 0.05$). **Results.** Materials ($p < 0.001$) and number of masticatory cycles ($p < 0.001$) had a significant effect on the wear level. The least enamel antagonist wear was observed for MAZ and MEZ (27.3 ± 15.2 , $28 \pm 11.1 \mu\text{m}$, respectively). GZC ($118 \pm 30.9 \mu\text{m}$) showed the highest wear of enamel antagonists. The highest wear rate in the material was observed in GZS ($91.3 \pm 38.6 \mu\text{m}$). While in the groups of MA, VZ, GZC and GZS 50% of the specimens developed cracks in enamel, it was 100% in MAZ and MEZ groups. **Conclusion.** Polished monolithic zirconia showed lower wear rate on enamel antagonists as well as within the material itself but developed higher rates of enamel cracks.

Key Words: *monolithic zirconia, ceramic, abrasion, enamel, two-body wear***Introduction**

Physical, mechanical and chemical properties make zirconia a material of interest for dental reconstructions [1–4]. Zirconia exhibits polymorphic properties meaning that the same chemical composition exists in its different atomic arrangements [5,6]. Among the crystallographic structures, the monoclinic phase is stable up to 1170°C, which then transforms into the tetragonal phase [5,6]. The tetragonal form for metastable zirconia in biomedical applications could be achieved at room temperature by alloying zirconia with other oxides (stabilizers) [7–10]. Y_2O_3 (3% mol) is the most widely used stabilizer for dental zirconia [6].

A limited number of clinical studies reported seldom zirconia framework fractures but more often

chipping of the veneering ceramic [11–15]. In order to decrease the costs and at the same time overcome the chipping problem, it is possible today to produce zirconia fixed dental prostheses (FDPs) without veneering ceramic, called monolithic zirconia reconstructions. Currently, monolithic zirconia reconstructions could be constructed and subsequently only polished or characterized using a glaze layer in different colours. A glaze layer could be applied using a layering technique or a glaze spray.

To the authors' best knowledge at present there is no information on the clinical performance of the available newly introduced monolithic zirconia reconstructions. Particularly mechanical properties, such as hardness, wear resistance or fracture toughness, are supposed to influence the wear performance of such zirconia ceramics strongly [16–18]. In that

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(Received 8 July 2011; revised 20 September 2011; accepted 7 November 2011)

ISSN 0001-6357 print/ISSN 1502-3850 online © 2013 Informa Healthcare
DOI: 10.3109/00016357.2011.654248

Table I. The test groups, abbreviations, brands, batch numbers and manufacturers of the tested materials.

Test group	Abbreviation	Brand	Batch number	Manufacturer
Monolithic alloy	MA	DentaNEM	Z094348	Wieland Dental + Technik, Pforzheim, Germany
Veneered zirconia	VZ	ZENOTEC Zr Bridge transluzent	405648	Wieland Dental + Technik, Pforzheim, Germany
		Liner A3	1/05	
		Zirox Dentin A3	1/05	
		Zirox Emamel 3	1/05	
		Carving Liquid Standard	30/06	
		Zirox Gaze	02/09	
		X Stain Liquid	10/05	
Glazed zirconia with a glaze ceramic	GZC	ZENOTEC Zr Bridge transluzent	405648	Wieland Dental + Technik, Pforzheim, Germany
		Zirox Glaze	02/09	
		Stain Liquid	10/05	
Glazed zirconia with a glaze spray	GZS	ZENOTEC Zr Bridge transluzent	405648	Wieland Dental + Technik, Pforzheim, Germany
		Glaze Spray	1/09	
		Zenostar Magic Glaze		
Manually polished monolithic zirconia	MAZ	ZENOTEC Zr Bridge transluzent	405648	Wieland Dental + Technik, Pforzheim, Germany
Mechanically polished monolithic zirconia	MEZ	ZENOTEC Zr Bridge transluzent	405648	Wieland Dental + Technik, Pforzheim, Germany

respect, zirconia is expected to demonstrate favourable properties.

One *in vitro* study tested the wear of five zirconia materials vs steatite and human enamel antagonist and found no wear in the zirconia ceramic. In that study, the wear rates of the enamel antagonists were not determined, but it was stated that the enamel generally showed cracks or even fractures at the ridges, in all tested zirconia ceramics [18].

Wear presents loss of material from a surface, caused by mechanical contact, against a solid or liquid body, chemical reactions or simultaneous effect of chemical and mechanical reactions [19]. The hardness and thickness of enamel [18,20], the chewing behaviour in combination with parafunctional habits and neuromuscular forces [18,21–23], as well as the abrasive nature of food and the antagonist material all influence the clinical wear. Zirconia has an elasticity modulus of 210 GPa and hardness of 1200 HV [1]. On the other hand, since veneering glass ceramic has an elasticity modulus of 50–70 GPa and Vickers hardness of 470–600, more wear could be expected in enamel against non-veneered monolithic zirconia.

Wear tests have been performed in the dental literature using the test methods such as Acta, Zurich, Alabama, Freiburg, Minnesota, OHSU or Newcastle [19]. These test methods differ in the antagonist material and design, test medium, force application and mobility of specimens [19]. Among all these test methods, the Zurich wear test method uses human enamel antagonists, making the test more clinically relevant.

The aim of this study was to investigate the two-body wear characteristics of differently polished

monolithic, glazed and veneered zirconia and the wear of their corresponding enamel antagonists. The tested hypotheses were that (a) polished monolithic zirconia would show higher wear of enamel antagonist compared to all other tested groups and (b) polished monolithic zirconia would show similar abrasion resistance compared to veneered zirconia and monolithic alloy.

Materials and methods

This study tested the two-body wear of veneered zirconia (VZ), glazed zirconia using a glaze ceramic (GZC), glazed zirconia using a glaze spray (GZS), manually polished monolithic zirconia (MAZ), mechanically polished monolithic zirconia (MEZ), monolithic base alloy (control group, MA) and their corresponding enamel antagonists using Zurich wear simulation (ISO/TS 14569-2) [19]. For each test group six specimens were fabricated. Table I describes the tested groups.

Specimen preparation

For all test groups one zirconia cylinder in white state (ZENOTEC Zr Bridge transluzent, Wieland Dental + Technik, Pforzheim, Germany) (diameter: 18 mm, length: 50 mm) and for the control group (MA) one wax cylinder (ZENOTE CWax Disc, Wieland Dental + Technik) (diameter: 15 mm, length: 50 mm) were milled using a milling machine (ZENOTEC T1, Wieland Dental + Technik). Subsequently, the zirconia ($N = 30$, $n = 6$) and wax cylinder ($N = 6$) were cut to a thickness of 2 mm with a low-speed diamond saw (Well 3241, Well Diamantdrahtsägen, Mannheim, Germany).

Table II. Firing procedures for the ceramics.

Veneering ceramic	Pre-drying		Heating rate (°C/min)	Firing temperature (°C)	Fusion time (min)
	Temperature (°C)	Time (min)			
Zirox Liner	575	8	45	930	1
Zirox Dentin	575	9	45	900	2
Zirox Enamel	575	8	45	890	1
Zirox Glaze	575	5	45	880	1
Glaze Spray	575	2	45	880	1

The round specimens were ground to the final dimensions using SiC discs P600 (Silicon Carbide Paper, Struers, Ballerup, Denmark) under water-cooling.

The zirconia specimens were sintered in the sintering oven (Thermostar, ZENO Fire, Wieland Dental + Technik, final sintering temperature: 1580°C and holding time: 4 h) according to the manufacturer's instructions.

Thereafter, the surfaces of zirconia ($n = 12$) were air-abraded using 120 μm alumina for 10 s at a pressure of 4.5 bar from an approximate distance of 10 mm (LEMAT NT4; Wassermann; Hamburg, Germany). The zirconia surfaces were treated as follows using the ceramic firing parameters, as described in Table II:

(A) *Veneered zirconia (VZ)*: The zirconia surface was conventionally veneered according to the manufacturer's instructions, where initially a liner was applied (Liner A3 with Liner Liquid Optimix, Wieland Dental + Technik). Then dentin ceramic (Dentin A3, Zirox dentin with Carving Liquid Standard, Wieland Dental + Technik), enamel ceramic (Enamel A3, Zirox enamel with Carving Liquid Standard, Wieland Dental + Technik) and glaze ceramic (Glaze Zirox with Stain Liquid, Wieland Dental + Technik) were added twice.

(B) *Glazed zirconia using a glaze ceramic (GZC)*: The zirconia surface was glazed according to the manufacturer's instructions using glaze ceramic (Glaze Zirox with Stain Liquid, Wieland Dental + Technik) twice.

The remaining specimens ($N = 18$, $n = 6$) were randomly divided into three groups and treated as follows:

(A) *Glazed zirconia using a glaze spray (GZS)*: The zirconia surfaces were manually polished and glazed according to the manufacturer's instructions using glaze spray (ZENOSTar Magic, Wieland Dental + Technik) twice.

(B) *Manually polished monolithic zirconia (MAZ)*: The zirconia surfaces were polished using a goat hair brush (DT & Shop) and diamond paste (Dia-Glaze, Yeti Dental) for 1 min.

(C) *Mechanically polished monolithic zirconia (MEZ)*: The zirconia surfaces in this group were

polished up to 3 μm using diamond suspensions (Struers, Ballerup, Denmark) in a polishing device (Accutom, Struers).

In the control group, the wax specimens were invested (Wilavest Quick, Wieland Dental + Technik) according to the manufacturer's instructions. After evaporating the wax in a standard oven (EWL Type 5636, KaVo, EWL, Leutkirch am Allgäu, Germany), the alloy (dentaNEM, Wieland Dental + Technik) was casted (Multicast compact, DeguDent, Hanau, Germany). The investment material was removed after cooling in a sandblasting unit (CEMAT NT4, Wassermann, Hamburg, Germany) using 110 μm alumina particles (Renfert, Hilzingen, Germany) at 4 bar pressure. Then, the alloy specimens were polished using a goat hair brush (DT & Shop, Mangelsfeld, Germany) and diamond paste (Dia Glaze, Yeti Dental, Engen, Germany) for 1 min per specimen.

For the two-body wear test, all specimens were fixed and embedded in the middle of a round stainless steel mold using a chemically cured pattern resin (DuraLay, Dental Mfg, Worth, IL). The specimens were aged in a chewing simulator (custom made: University of Zurich), where thermo-mechanical loading was applied during cyclic loading, with a maximum occlusal load of 49 N at 1.67 Hz and simultaneous thermal stress (5°C to 50°C every 120 s). For simulating a typical clinical situation, the mesiobuccal cusp from nearly identical maxillary human molars, fixed in amalgam (Dispersalloy; Dentsply; Konstanz, Germany), acted as antagonists. The tip of the cusps was rounded to a spherical shape. The abraded surfaces were loaded intermittently. The horizontal distance between specimen surface and the enamel antagonist was 2 mm. The profiles of the specimens were measured with a 3D profilometer (custom made: University of Zurich) before aging and after 120,000, 240,000, 640,000 and 1,200,000 masticatory cycles [19]. The vertical material loss (μm) of each specimen and the corresponding enamel antagonist was calculated using the 3DS software (custom made: University of Zurich) by overlapping the profiles with congruent points and subtracting the initial measurements from subsequent measurements.

For the qualitative characterization of wear patterns, all specimens and enamel antagonists were

Table III. Mean (SD), minimum, maximum, 95% confidence intervals (95% CI) of wear of tested reconstruction materials and their enamel antagonists (μm).

Test groups	Masticatory cycles	Material wear				Antagonist enamel wear			
		Mean (SD)	min	max	95% CI	Mean (SD)	min	max	95% CI
MA	MC1	2.8 (2.9)	0	7	(0.24;5.9)	16.3 (12.3)	4	35	(3.4;29.3)
	MC2	5.8 (2.3)	2	8	(3.4;8.3)	24 (14.1)	12	46	(9.2;38.8)
	MC3	10.5 (6.1)	3	19	(4.0;17.0)	34.2 (17.9)	14	56	(15.4;53)
	MC4	13.2 (8.3)	5	27	(4.4;22)	55.3 (38.5)	20	116	(14.9;95.7)
VZ	MC1	12.7 (7.9)	3	24	(4.3;21.0)	26.2 (7.7)	14	34	(18.1;34.2)
	MC2	26.5 (20.8)	7	59	(4.6;48.4)	33 (7.2)	19	39	(25.4;40.7)
	MC3	46.5 (30.6)	17	95	(14.3;78.7)	53.3 (17.6)	37	82	(34.8;71.8)
	MC4	66.8 (47.5)	21	136	(16.9;116.8)	73.5 (32.8)	49	134	(39;108)
GZC	MC1	38.7 (18.1)	15	68	(19.6;57.7)	51.7 (20.6)	22	74	(30;73.3)
	MC2	47.3 (10.9)	37	68	(35.9;58.8)	80 (18.3)	56	112	(60.7;99.3)
	MC3	47.8 (8)	38	62	(39.4;56.3)	97 (26.9)	65	145	(68.6;125.3)
	MC4	49.5 (10.3)	39	69	(38.7;60.3)	118 (30.9)	92	179	(85.5;150.5)
GZS	MC1	30.3 (10.9)	19	48	(18.8;41.8)	24.5 (8.3)	17	39	(15.8;33.2)
	MC2	34 (9)	21	48	(24.5;43.5)	31 (13.2)	21	56	(17;45)
	MC3	58 (20.2)	39	92	(36.7;78)	43.3 (11.6)	33	65	(31.1;55.6)
	MC4	91.3 (38.6)	49	137	(50.8;131.9)	62.2 (16.6)	46	83	(44.7;79.6)
MAZ	MC1	0.3 (0.5)	0	1	(0.2;0.9)	14.3 (5.6)	9	21	(8.4;20.3)
	MC2	0.5 (0.5)	0	1	(0.07;1.1)	17 (7.5)	9	28	(9.1;24.9)
	MC3	0.5 (0.5)	0	1	(0.07;1.1)	19.3 (9.3)	9	32	(9.5;29.2)
	MC4	0.8 (0.8)	0	2	(0.04;1.7)	27.3 (15.2)	12	53	(11.3;43.3)
MEZ	MC1	0.3 (0.5)	0	1	(0.2;0.9)	14.7 (10.1)	7	33	(4;25.3)
	MC2	0.8 (0.8)	0	2	(0.04;1.7)	17 (9.8)	8	33	(6.7;27.3)
	MC3	0.8 (0.8)	0	2	(0.04;1.7)	22 (13)	13	44	(8.3;35.7)
	MC4	0.8 (0.8)	0	2	(0.04;1.7)	28 (11.1)	15	45	(16.3;39.7)

MC1 = after 120,000 masticatory cycles, MC2 = after 240,000 masticatory cycles, MC3 = after 640,000 masticatory cycles, MC4 = after 1,200,000 masticatory cycles.

evaluated under scanning electron microscopy (SEM) (Carl Zeiss Supra 50 VP FESEM, Carl Zeiss, Oberkochen, Germany).

Statistics

The data set were analyzed with statistical software (SPSS Version 19, SPSS Inc, Chicago, IL). Descriptive statistics were computed. Linear mixed models were applied to investigate the influence of the number of masticatory cycles, reconstruction materials/enamel and the interaction between them. All results with p -values smaller than 5% were considered as statistically significant.

Results

The descriptive statistics of the wear results belonging to the reconstruction materials and their corresponding enamel antagonists are summarized in Table III. Reconstruction materials ($p < 0.001$) and number of

masticatory cycles ($p < 0.001$) had a significant effect on the wear.

Material wear

GZC ($p < 0.001$) and GZS ($p = 0.033$) showed higher wear rates compared to the control group (MA). No statistical differences were observed between the control group (MA) and VZ ($p = 0.314$), MAZ ($p = 0.751$) and MEZ ($p = 0.771$) (Table IV, Figure 1).

VZ ($p < 0.001$) and GZS ($p < 0.001$) showed significantly higher increases in the material wear itself dependent on the number of masticatory cycles compared to the control group. Between MA, GZC ($p = 0.824$), MAZ ($p = 0.290$) and MEZ ($p = 0.285$) no differences were found (Table IV, Figure 1).

Antagonist enamel wear

GZC ($p < 0.001$) showed a higher wear rate of enamel antagonists than the control group, MA. No differences

Table IV. Estimates of regression coefficients for wear of reconstruction materials (linear mixed models analysis).

Parameter	Estimate (standard error)	Significance <i>p</i> -values	95% CI
Constant term	3.0 (6)	0.617	(-9.0;15.1)
MA	0 (0)	—	—
VZ	8.6 (8.5)	0.314	(-8.3;25.7)
GZC	38.8 (8.5)	< 0.001	(21.7;55.8)
GZS	18.5 (8.5)	0.033	(1.5;35.6)
MAZ	-2.7 (8.5)	0.751	(-19.7;14.4)
MEZ	-2.5 (8.5)	0.771	(-19.4;14.6)
Masticatory cycles (MC)	9.1E-6 (5.8E-6)	0.119	(-2.3E-6;2.1E-5)
MA * MC	0 (0)	—	—
VZ * MC	3.9E-5 (8.2E-6)	< 0.001	(2.2E-5;5.5E-5)
GZC * MC	-1.8E-6 (8.2E-6)	0.824	(-1.8E-5;1.5E-5)
GZS * MC	4.8E-5 (8.2E-6)	< 0.001	(3.2E-5;6.5E-5)
MAZ * MC	-8.7E-6 (8.2E-6)	0.290	(-2.4E-5;7.6E-6)
MEZ * MC	-8.8E-6 (8.2E-6)	0.285	(-2.5E-5;7.5E-6)

italics data: significant difference to test group MA.

between MA and other tested groups ($p > 0.369$) were found in wear values of enamel antagonists (Table V, Figure 2).

GZC ($p = 0.007$) showed a significantly higher increase than MA in loss of enamel antagonist dependent on the number of masticatory cycles. In contrast,

the increase of wear of enamel antagonists was lower for MAZ ($p = 0.001$) and MEZ ($p = 0.002$) compared to the control group dependent on aging time. Between MA, VZ ($p = 0.193$) and GZS ($p = 0.939$) no differences were found in terms of enamel wear increase (Table V, Figure 2).

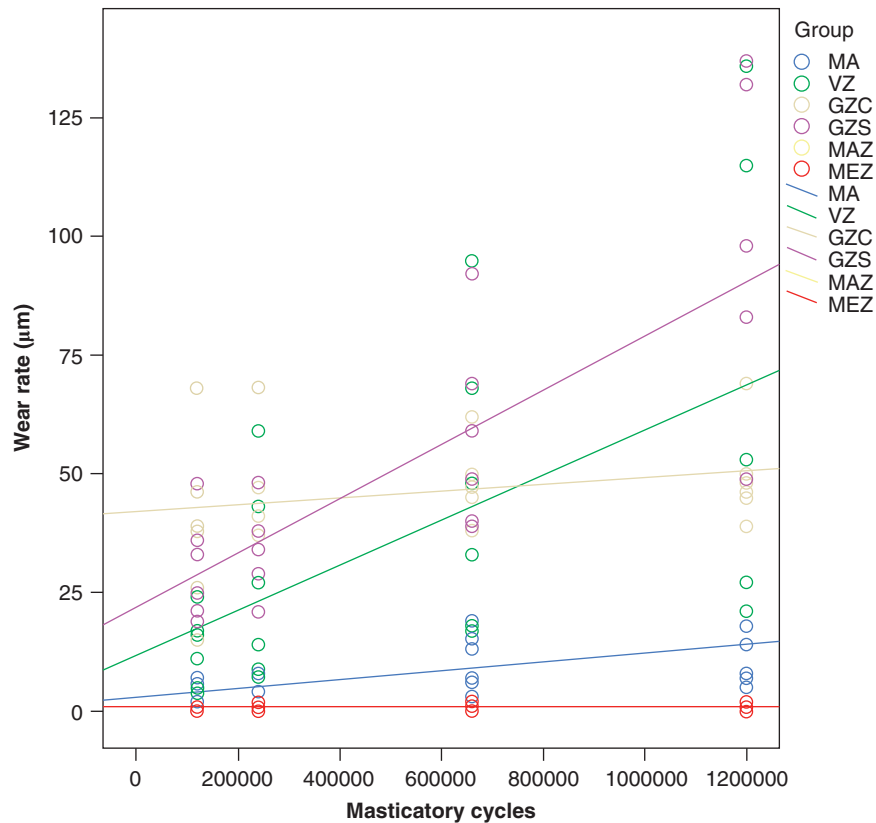


Figure 1. Linear mixed models diagram of reconstruction materials wear.

Table V. Estimates of regression coefficients for wear of enamel antagonists (linear mixed models analysis).

Parameter	Estimate (standard error)	Significance <i>p</i> -values	95% CI
Constant term	13.4 (6.9)	0.061	(-0.6;27.4)
MA	0 (0)	—	—
VZ	8.9 (9.8)	0.369	(-10.8;28.7)
GZC	43.3 (9.8)	< 0.001	(23.5;63.2)
GZS	8.1 (9.8)	0.414	(-11.6;27.9)
MAZ	-0.1 (9.8)	0.990	(-19.9;19.7)
MEZ	0.4 (9.8)	0.972	(-19.4;20.2)
Masticatory cycles (MC)	3.4E-5 (5E-6)	< 0.001	(2.4E-5;4.5E-5)
MA * MC	0 (0)	—	—
VZ * MC	9.2E-6 (7.1E-6)	0.193	(-4.7E-6;2.4E-5)
GZC * MC	2.0E-5 (7.1E-6)	0.007	(5.5E-6;3.4E-5)
GZS * MC	-5.4E-7 (7.1E-6)	0.939	(-1.4E-5;1.4E-5)
MAZ * MC	-2.3E-5 (7.1E-6)	0.001	(-3.7E-5;-9.2E-6)
MEZ * MC	-2.2E-5 (7.1E-6)	0.002	(-3.6E-5;-8.4E-6)

italics data: significant difference to test group MA.

The qualitative characterization of wear of all reconstruction materials and their enamel antagonists are summarized in Figures 3 and 4.

Evaluation of the enamel antagonists with SEM showed damage in the form of cracks on the worn enamel surface. While in the MA, VZ, GZC and GZS groups 50% of specimens developed cracks in the

enamel, it was 100% in both the MAZ and MEZ groups.

Discussion

This study showed that the wear rate in the material and on enamel antagonists was strongly dependent on

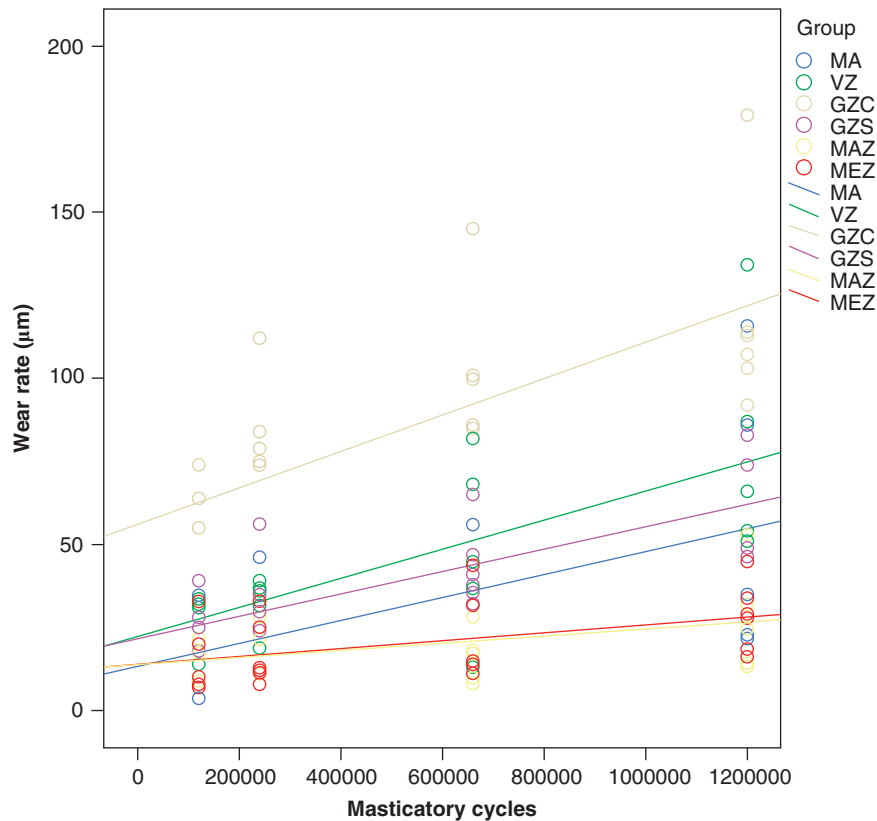


Figure 2. Linear mixed models diagram of enamel antagonists wear.

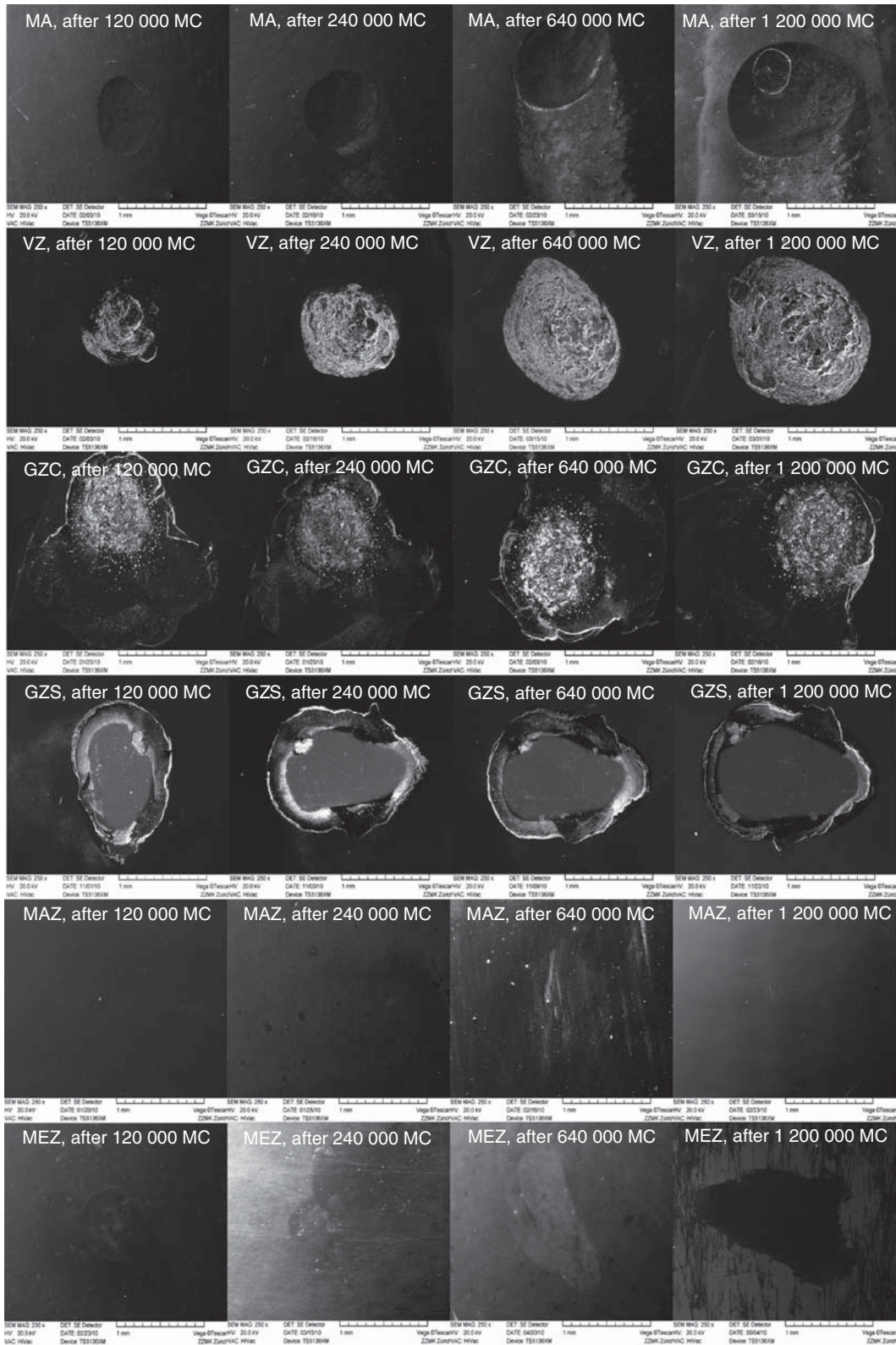


Figure 3. SEM images of the abraded reconstruction materials after different masticatory cycles (MC). Note that the control group (MA) showed little deformation of alloy on the contact surface; the veneered and glazed groups VZ, GZC and GZS presented the highest wear and MAZ and MEZ showed practically no wear.

the reconstruction material. Polished monolithic zirconia (MAZ, MEZ) showed the lowest wear rate on enamel antagonists of all tested groups. Sandblasted and subsequently glazed zirconia using a glaze

ceramic gave the highest wear on enamel antagonists compared to all other test groups. Therefore, the first hypotheses that polished monolithic zirconia would present higher enamel antagonistic wear is rejected.

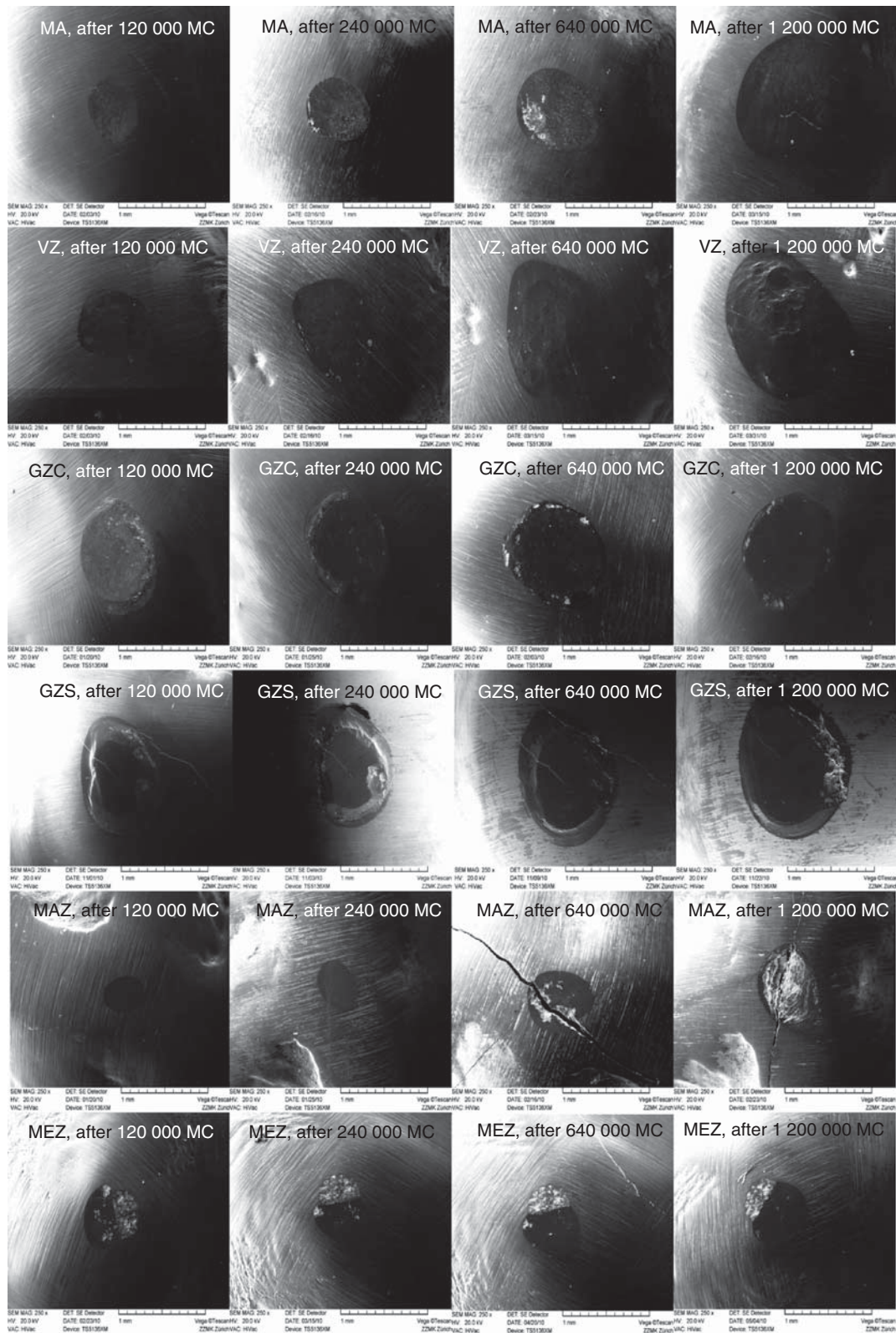


Figure 4. SEM images of the abraded enamel antagonists after different masticatory cycles (MC). Note that VZ, GZC and GZS showed the highest wear in enamel. The group images of VZ, GZS and MAZ indicate crack formation in enamel.

The highest wear rate was observed for veneered and both glazed zirconia groups. On the other hand, the polished zirconia showed no wear in the material. No differences in zirconia and enamel wear were found between polished zirconia regardless of the

polishing method. Hence, the second hypothesis that monolithic zirconia would show similar wear resistance compared to veneered, glazed zirconia and monolithic alloy, is also rejected. One other study tested the wear performance of polished hip and

presintered zirconia using steatite balls and human enamel as an antagonist. Similar to our results, in that study none of the tested zirconia ceramics showed any wear after the simulation tests, neither with steatite nor with enamel [18].

Glazing of zirconia may be required for aesthetic improvement of reconstructions. Under clinical conditions, glaze layers have shown to be worn after 6 months [24], which may require polishing of the zirconia surfaces after glazing (18). In this study, we tested the wear of two different glazing methods. The first method tested the wear of air-abraded zirconia that was glazed using a layering technique with glaze ceramic. This group showed the highest wear on enamel antagonist with 118 μm after 1.2 Million masticatory cycles. The wear rate for enamel per year has been reported to range between 30–40 μm [24]. In this study, the glaze layer was observed to abrade already in the first masticatory cycle (120,000). Most probably, the increase in wear rate of the enamel antagonist was due to the continuous loading of rough sandblasted surface. On the other hand, polished zirconia that were glazed using a glaze spray showed the highest loss of glaze layer, but less enamel wear with 62 μm after 1.2 Million masticatory cycles. These results were comparable with the veneered group. The reason for the low wear rate of enamel compared to air-abraded and glazed zirconia could be due to the polished and smooth zirconia surface in the GZS. Since dental materials should ideally present wear behaviour similar to that of enamel, the wear of dental materials is usually characterized in relation to that of dental tissues. These considerations imply that restorative materials, such as ceramics, should not damage natural antagonistic teeth [18,25].

In simulation tests, enamel antagonists are required to present clinical conditions. However, morphological and structural differences of enamel complicate standardized wear testing that may cause high variations in the wear data. In this study, the wear results varied highly within each group. This variation could be attributed to the inhomogeneity in the antagonists, namely human tooth tissues may show variations in geometry or thickness of enamel layers, and may become brittle due to storage conditions (18).

In summary, monolithic zirconia groups showed the lowest wear rate on enamel and in the material itself compared to all other test groups. However, the evaluation of the enamel antagonists with SEM showed damages in the form of cracks on the worn enamel surface. Both monolithic zirconia groups developed 100% cracks in enamel, while all other tested groups had only 50%. Obviously, sliding of the enamel antagonists on a hard zirconia surface caused added cracks of the enamel. Future studies should clarify whether this problem is clinically relevant or happened as a possible consequence of

dehydration of the dental tissues under vacuum during SEM analysis. Until this is classified, as a clinical alternative to monolithic zirconia the monolithic lithium disilicate ceramic can be used. Early clinical reports show predicable results with lithium disilicate ceramics [26–28].

Most wear tests provide only limited or no correlation with the clinical data [29], even though they allow a comparative evaluation and ranking of different materials under standardized testing conditions. Therefore, testing conditions close to the clinical situations are preferable. A chewing force of 50 N, applied with a frequency of $\sim 1\text{--}1.6$ Hz, presents the average mastication load [18,30] and is commonly used for oral simulation [18,31,32]. In this method, it is expected that permanent thermal cycling with water removes wear debris from the specimens surface, but specimens are kept wet during the whole course of the test and may have caused additional aging of the specimens [33].

Monolithic zirconia FDPs require higher translucency when they are to be used in the anterior region with superior mechanical properties especially. For this reason, many zirconia manufacturers tend to increase the final sintering temperature with the expectation of increasing the translucency. One must consider the fact that the flexural strength and stability of zirconia above the sintering temperature of 1550°C decreases [34]. According to the manufacturer's instructions the zirconia material used in this study was sintered at 1580°C. The grain size of Y-TZP increased with the rise in final sintering temperature, which may result in grain pull out and, thereby, decreased mechanical properties [34]. The increased grain size may yield to crack propagation since applied stress intensity factor may affect the transformation change [35]. When tetragonal zirconia is subjected to tension, it minimizes this perturbation by expanding its dimensions and transforming to monoclinic zirconia, as this expansion decreases the initially applied tensile stress [5]. The phase transformation is combined with the aging effect of zirconia and decreases the mechanical properties [5]. In this study, however, none of the monolithic zirconia specimens were broken. The long-term mechanical stability of the monolithic zirconia needs to be verified in future studies.

Many studies reported that the major disadvantage of Y-TZP is its reduced stability against low temperature degradation (LTD) [36–40]. LTD is defined as the spontaneous tetragonal to monoclinic transformation occurring over time at low temperatures, when the transformation is not triggered by the local stress produced at the tip of the advancing crack [6]. Under hydrothermal changes, an undesired phase transformation from tetragonal phase to the weaker monoclinic zirconia can occur on the surface of the monolithic zirconia FDPs. This is combined with

an increase in the surface roughness [39], resulting possibly in high abrasion of the antagonist enamel. Future studies should clarify whether wear rate is associated with grain pull out due to LTD.

In this study, the tested specimens were repeatedly used and longitudinal data were therefore available. Consequently, the measurements from one particular specimen were correlated with one another. Thus, linear mixed models with random intercept were applied to investigate the influence of different wear times. Linear mixed models allow for correlated responses by including random effects in the linear predictor.

Heintze [29] compared the ACTA, Zurich, Alabama, MTS and OHSU wear simulation devices for direct resin composites. The wear of 10 direct resin composites with the five wear simulations methods showed no comparable results; as all methods follow different wear testing concepts. For characterizing the complex oral wear situation, clinical tests are essential. However, *in vitro* studies for wear measurement show only little correlation with clinical data [29], but present a comparative evaluation of different materials under standardized conditions [18]. Since no clinical study looked at wear rate of enamel against zirconia with and without veneering ceramic, the results of this study with the monolithic zirconia and their corresponding enamel antagonists require clinical verification.

Conclusions

Within the limitations of this study, the following conclusions can be drawn:

- (1) Polished monolithic zirconia showed the lowest wear rate on enamel antagonists of all tested groups.
- (2) Glazed zirconia showed a higher material wear rate than those of polished monolithic zirconia or monolithic alloy surface due to the abrasion of the glaze layer.
- (3) Polished zirconia surface showed similar wear rate compared to monolithic alloy.
- (4) Sandblasted, glazed zirconia using a glaze ceramic showed the highest wear of enamel antagonists due to the rough zirconia surface after wear of the glaze layer.
- (5) While in the groups of monolithic alloy, veneered and both glazed zirconia groups 50% of the specimens developed cracks in enamel, it was 100% in both monolithic zirconia groups.

Acknowledgements

The authors are grateful to Mrs Jacqueline Hofmann, Center of Dental Medicine, University of Zurich, for performing the scanning electron microscopy. Special thanks go to Wieland Dental + Technik, Pforzheim, Germany for support this study.

Declaration of interest: The authors report no conflicts of interest.

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