Wear Characterization of Human Enamel Opposing Dental Ceramics and Resin Composite

ลักษณะการสึกของเคลือบฟันมนุษย์เมื่อสบกับเซรามิกทางทันตกรรมและเรซินคอมโพสิต

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ABSTRACT

Twenty-four test specimens (antagonists) – 6 each of monolithic zirconia, glass ceramic, resin composite, and enamel – were prepared into cylindrical rods. Enamel specimens were prepared from 24 extracted human permanent molars. Using a pin-on-disc wear tester, enamel specimens were abraded against each type of antagonist under a constant load of 25 N, at 20 rpm for 4,800 cycles. Maximum depth of wear (D_{max}), mean depth of wear (D_a), and mean surface roughness (R_a) of enamel specimens were measured with a profilometer. SEM pictures were used for evaluating wear qualitatively of both enamel and antagonists. Within the limitations of this study, monolithic zirconia and resin composite caused less wear depth to human enamel compared to glass ceramic and enamel. All test materials except resin composite similarly increased enamel surface roughness after wear testing.

บทคัดย่อ

ชิ้นงานทดสอบจำนวนทั้งหมด 24 ชิ้นงาน ได้แก่ โมโนลิธิคเซอร์โคเนียร์ กลาสส์เซรามิก เรซินคอมโพสิต และเคลือบฟันมนุษย์ เตรียมเป็นรูปทรงกระบอกชนิดละ 6 ชิ้นงาน เพื่อเป็นคู่สบกับชิ้นงานเคลือบฟันจำนวน 24 ชิ้นงานซึ่งเตรียมจากฟันกรามแท้มนุษย์ นำมาทดสอบการสึกกับคู่สบแต่ละชนิดโดยใช้เครื่องมือศึกษาการสึกกร่อนแบบพินออนดิสก์ ที่น้ำหนักกดคงที่ 25 นิวตัน ความเร็ว 20 รอบต่อนาที จำนวน 4,800 รอบ วัดความลึกของการสึกสูงสุด ความลึกของการสึกเฉลี่ย และความหยาบผิวเฉลี่ยของชิ้นงานเคลือบฟันโดยใช้เครื่องโปรไฟโลมิเตอร์ ประเมินลักษณะการสึกในเชิงคุณภาพของผิวเคลือบฟันและผิวคู่สบด้วยภาพถ่ายจากกล้องจุลทรรศน์อิเลคตรอนชนิดส่องกราด ภายใต้เงื่อนไขและข้อจำกัดของการศึกษานี้ โมโนลิธิคเซอร์โคเนียร์และเรซินคอมโพสิตทำให้เกิดการสึกบนเคลือบฟันน้อยกว่ากลาสส์เซรามิกและเคลือบฟัน และความหยาบผิวเคลือบฟันที่เกิดขึ้นหลังการทดสอบการสึกมีค่าเพิ่มขึ้นในวัสดุบูรณะทุกกลุ่ม ยกเว้นกลุ่มเรซินคอมโพสิต

Key Words: Abrasive wear, Dental ceramic, Enamel wear

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Introduction

Nowadays, all-ceramic materials and resin composite are commonly used for posterior tooth-colored restorations. Their utilization has increased following the demand for non-metallic dental prostheses. The superiority of ceramic substrate is renowned for its high biocompatibility, strength and, especially, excellent esthetics as it could naturally mimic the characteristic of human tooth structure (DeLong et al., 1989; Kelly et al., 1996). However, the abrasiveness of these materials against enamel antagonist is still a clinical concern. Several investigators have demonstrated that, in general, ceramic material cause greater enamel wear compared with any other restorative materials or enamel (Kelly et al., 1996; Ratledge et al., 1994; Hudson et al., 1995; Jagger and Harrison, 1995).

Since wear of a material is influenced by numerous factors, include contact geometry, surface roughness, microstructural features, grain size, fracture toughness, speed, load, temperature, duration, environment and lubrication (Hsu and Ming, 2004), enamel wear by ceramic or composite is also the multi-factorial condition. In many decades, there were a lot of studies trying to find out which factors affect wear of human enamel by these materials (Kelly et al., 1996, Anusavice, 2013).

Recently, monolithic zirconia (so-called "full zirconia") has been used for posterior fixed partial dentures in order to eliminate the problem from chipping of veneering porcelain (Stawarczyk et al., 2013). Because of its high fracture resistance and ability to withstand high force by only 0.5 mm occlusal thickness, the monolithic zirconia was suggested to use with patient with limited inter-occlusal space (Jang et al., 2011). These advantages make the full zirconia become a promising substitute of metal, apart from the predominance in esthetics.

Objectives of the study

The purpose of this study was to investigate wear of enamel when opposed to dental ceramics (monolithic zirconia, glass ceramic) and resin composite.

Methodology

Preparation of test specimens (antagonists)

Materials used in this study are presented in Table 1. Twenty-four test specimens separated into 4 types of test material with 6 pieces for each group were fabricated into cylindrical rods (3 mm in diameter and 10 mm in length). A flat circular surface of any test material was finished with a polishing kit (Jota All Ceramic Kit 1369, Jota AG, Rüthi SG, Switzerland). A mean radius of 1.5 mm was selected for the test due to the pin-on-disc wear tester used in this study (Model TE 79; Plint & Partners Ltd., Berkshire, England) (Fig 1) could accept this size of material, following ASTM G99 (Standard test method for wear testing with a pin-on-disc apparatus).

Table 1 List of material selected for wear tests and some of their properties

Materials	Product	Fracture toughness (MPa.m1/2)	Vicker hardness (GPa)	Manufacturer
Monolithic zirconia	Lava All Zirconia	8-10.3[a]	8.8-11.8[a]	3M ESPE, Seefeld, Germany
Lithium-disilicate glass-ceramic	IPS e.max Press	2.2-3.3[a]	6.3[a]	Ivoclar Vivadent, Amherst, NY
Resin composite	Premise	1.32[b]	0.55-0.58[b]	Kerr, Orange, CA
Human occlusal enamel	-	0.77[a]	3.23-3.62[a]	-

[a]From Anusavice KJ. Phillips' science of dental materials. 12[th] ed. St Louis: Elsevier; 2013. p66, 284, 453

[b]From manufacturer's data

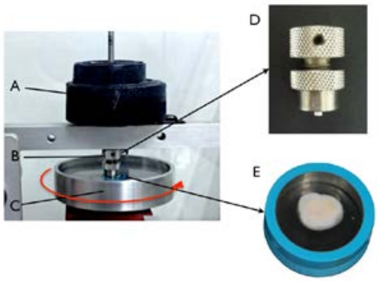

Fig 1 A pin-on-disc wear tester: (A) constant load; (B) upper specimen holder; (C) lower specimen holder; (D) ceramic pin inserted into the upper specimen holder; (E) Enamel specimen.

Preparation of enamel specimens

Twenty-four freshly extracted unrestored non-carious human permanent molars were cleaned with ultrasonic scaler and stored in 0.1% thymol solution. All teeth were randomly divided into each group of antagonists.

To prepare enamel specimen, occlusal surface was ground down using rotary cutting instrument in the presence of water until obtaining flat circular area entirely of enamel with a diameter of at least 8 mm in order to enable it to undergo wear testing by pin-on-disc apparatus. The enamel surface was confirmed by viewing through a stereomicroscope (ML 9300, Meiji Techno, Saitama, Japan).

The enamel specimen was embedded in the middle of a cylindrical tube using epoxy resin (Huntsman, Woodlands, Texas) (Fig 1E). Only wide pit(s) or fossa(e) presenting on the occlusal surface after flattening were filled with flowable composite (Premise Flowable; Kerr) and light-cured with a LED light curing unit (450–470 nm) in order to avoid errors from macroscopic roughness during the test. Afterward, all prepared enamel specimens were finished with silicon carbide abrasive papers (400, 800 and 1,200 grit, respectively) under running water for 2 min each with a revolving polishing machine (Nano 2000 grinder-polisher; Pace Technologies, Tucson AZ).

Intervention

Wear tests were conducted using a pin-on-disc wear tester. The test specimen (antagonist) was inserted into the upper specimen holder. The test specimen was controlled to project at 5 mm length from the opening of the holder (Fig 1D). The upper specimen holder could be inserted and tightened to the lever arm of the device. The enamel specimen was also attached to the lower specimen holder, which could be run in rotational movement (counter-clockwise direction).

Wear tests were performed with a load of 25 N, 20 cycles/min for 240 min (4,800 cycles). These control parameters were determined from the pilot study of this research together with the manufacturer's recommendations for the wear tester according to ASTM G99. The center of the upper specimen surface was set at 2 mm from the center of rotation. The samples were tested in distilled water, which was renewed after each test.

Data collection

Maximum depth of wear (D_{max}) and mean depth of wear (D_a) of human enamel specimens were evaluated using a profilometer (Talyscan 150; Taylor Hobson, Leicester, England). Five measurements of wear track depth were made on each specimen (speed = 1,500 μm/s, spacing = 1 μm).

Mean surface roughness (R_a) before (baseline) and after testing of the enamel specimens were determined using the same profilometer with a 0.008 mm Gaussian filter. The transverse length was set at 1 mm. Five measurements per specimen were made for each R_a value. Baseline measurements were made on unworn portions of enamel adjacent to the worn areas (Metzler et al., 1999).

For the qualitative characterization of wear patterns, all test materials and enamel specimens were evaluated under scanning electron microscopy (JSM - 5410 LV; JEOL, Tokyo, Japan). The surfaces were examined at a magnification of 50-350 at 15 keV.

Results

The results of enamel wear depth (D_{max}, D_a) are recorded in Tables 2 and 3. For both D_{max} and D_a, no statistically significant differences were found between those of resin composite and monolithic zirconia (subset 1) and those of lithium-disilicate glass-ceramic and human enamel (subset 2); however, a significant difference was revealed between these two subsets ($P < 0.001$).

Table 2 Distribution of maximum depth of wear (D_{max}) of enamel for all test specimens.

Enamel wear depth	Test specimens				Significance (one-way ANOVA)
	Monolithic zirconia	Lithium-disilicate glass-ceramic	Resin composite	Human enamel	
D_{max} (µm) (mean ± sd)	2.17 ± 0.80^a	8.54 ± 2.31^b	1.70 ± 0.92^a	10.72 ± 6.31^b	<0.001

Values with the same lowercase letter are not significantly different at $P < 0.05$

Table 3 Distribution of mean depth of wear (D_a) of enamel for all test specimens.

Enamel wear depth	Test specimens				Significance (one-way ANOVA)
	Monolithic zirconia	Lithium-disilicate glass-ceramic	Resin composite	Human enamel	
D_a (µm) (mean ± sd)	1.83 ± 0.75^a	7.32 ± 2.06^b	1.37 ± 0.81^a	8.81 ± 5.16^b	<0.001

Values with the same lowercase letter are not significantly different at $P < 0.05$

To compare R_a of enamel in each material group before and after wear testing, paired t-tests were conducted; the results are shown in Table 4. R_a of enamel specimens increased significantly after wear tests with monolithic zirconia (P = 0.005), glass-ceramic (P = 0.001) and enamel ($P < 0.001$); however, no difference was found among these materials (Table 5). Resin composite was the only material that produced no significant difference in R_a of the enamel specimen before and after wear testing (P = 0.354).

Table 4 Comparison of mean surface roughness (R_a) of enamel between baseline and after wear testing for all test specimens.

Test specimen	R_a (nm) (mean ± sd)		Significance (two-tailed)
	At baseline	After test	
Monolithic zirconia	1.64 ± 0.98	3.02 ± 0.68	0.005
Lithium-disilicate glass-ceramic	1.63 ± 0.08	3.19 ± 0.56	0.001
Resin composite	1.66 ± 0.15	1.51 ± 0.22	0.354
Human enamel	1.64 ± 0.15	3.38 ± 0.54	<0.001

Table 5 Distribution of mean surface roughness (R_a) of enamel after abrasion against test specimens.

Enamel surface roughness	Test specimens				Significance (one-way ANOVA)
	Monolithic zirconia	Lithium-disilicate glass-ceramic	Resin composite	Human enamel	
R_a (nm) (mean ± sd)	3.02 ± 0.68^a	3.19 ± 0.56^a	1.51 ± 0.22^b	3.38 ± 0.54^a	<0.001

Values with the same lowercase letter are not significantly different at $P < 0.05$

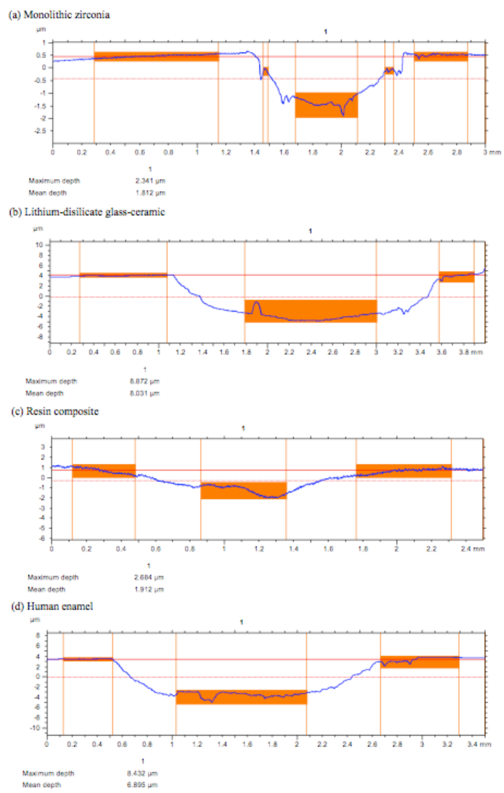

Fig 2 Examples of enamel wear profiles of each type of antagonists obtained after wear testing.

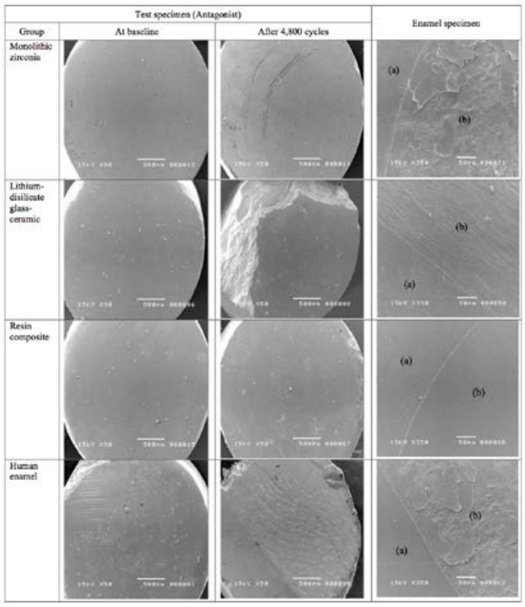

Fig 3 SEM pictures of surfaces of test specimens at baseline and after 4,800 cycles of wear testing and their enamel surfaces at unworn (a) and worn (b) areas.

The qualitative characterizations of wear of all test specimens and their enamel specimens are illustrated in Fig 3. After the wear test, monolithic zirconia showed some scratches on its abraded surface, lithium-disilicate glass-ceramic showed some cracks and chipping, resin composite showed slightly different surface compared to its beginning, and human enamel showed rough plowed surface with craze line. It was noticed that enamel specimen of resin composite group showed little to no wear on the worn zone.

Discussion

The outcomes of this study revealed significant differences in enamel wear depth (D_{max}, D_a) and R_a of enamel among all materials after wear testing. Within the limitations of this study, the results showed that the least enamel wear depth was produced by resin composite and monolithic zirconia. In addition, a comparison between enamel R_a before and after testing showed that resin composite was the only material that caused similar R_a values and was supported by its SEM image (Fig 3). Since the wear mechanisms for dental restorative materials and tooth enamel differ depending on type of material, the rational explanation of these findings should be considered separately – wear of ceramic (as well as enamel) occurs due to a microfracture mechanism, while metal and composite wear is due to adhesion (Anusavice, 2013).

Concerning enamel wear by ceramics, an interesting outcome is that monolithic zirconia does not cause greater wear of human enamel compared with lithium-disilicate glass-ceramic. This observation about the small amount of antagonist wear by zirconia has some connections with the investigation by Preis et al (2011). They reported lower wear of steatite antagonist against zirconia compared to veneering porcelain. Their SEM images exhibited a comparable range of steatite- and enamel-wear areas, and also showed that enamel was polished when opposed to zirconia but ground when opposed to veneering porcelain. In our study, the possible explanation of enamel wear between zirconia and glass-ceramic is that zirconia is less susceptible to the microfracture mechanism than glass-ceramic due to the much higher fracture resistance of zirconia (Table 1). Fracture toughness of the material is a key to the prevention of cracking (Fischer et al., 1989). Besides, the microfracture mechanism is considered to be the dominant mechanism responsible for surface breakdown of ceramic and the subsequent damage that a roughened ceramic surface can cause to enamel surfaces (Anusavice, 2013). Consequently, under the same condition of wear process, the microcrack is probably more difficult to propagate through the crystalline structure of zirconia. Hence, the zirconia surface remains smoother because fewer microfractures occur during abrasive wear. The smoother surface of zirconia throughout the test, as shown by its SEM image (Fig 3), leads to the lower wear depth of opposing enamel (Fig 2). On the contrary, the roughened surface of glass-ceramic causes more depth of enamel wear due to the increased development of microfractures along the surface (Fig 3).

Surface roughness of the ceramic surface is taken into account. An in vitro study by Kadokawa, Suzuki and Tanaka (2006) showed that the wear rate of enamel when opposed to a smooth porcelain surface was significantly lower than when opposed to a rough porcelain surface (Kadokawa et al., 2006). In this study, rough ceramic surfaces or asperities originated during the period of the abrasive wear process (Fig 3). This might relate to the clinical situation when polished restorations are in daily function and then start to develop roughness on the contact surfaces. Moreover, differences in wear rates of mutual opposing teeth and/or restorations might alter an individual’s occlusal relationship (Yip et al., 2004). Thus it should be kept in mind that periodically checking on the occlusion and maintaining the smoothness of restoration surfaces might be necessary (Rosentritt et al., 2012).

Another possibility of higher enamel wear by glass-ceramic might arise from the formation of wear debris. Glass particles that come off during the wear process might behave as an abrasive medium and lead to a three-body wear mechanism (Ratledge et al., 1994). These abrasive particles might emphasize the consequences of enamel wear. Although this wear test was run under distilled water, which would help lubricate the contact surface, flush out debris and reduce heat generation from abrasion, some wear debris may still remain in the wear track and influence the contact stresses and wear (Fischer et al., 2000).

Modern resin composites are widely used as posterior resin composites due to the improvement of their physical and mechanical properties, particularly in filler composition, size and morphology (Shimane et al., 2010). There has been an attempt to develop a composite that is resistant to wear from the opposing dentition, and also does not cause excessive wear of human enamel. Unlike the case of ceramics, hardness is suggested to be a reliable predictor of enamel wear by resin composite, as the wear of enamel occurs through hard filler protruding from the abraded resin matrix, and the amount of enamel wear is directly correlated with the composite's hardness value (Suzuki et al., 1993; Shimane et al., 2010). The resin composite used in this study (Premise; Kerr) has the least hardness value compared with other test materials (Table 1). According to the general knowledge about wear between two contacting materials, softer material is abraded more easily than harder material (Shimane et al., 2010). Thus, the amount of enamel wear produced by composite would be less, and this supposition was supported by the results of this study. However, as the wear behavior of a composite is different from that of a brittle substrate (ceramic or enamel), hardness could not be used as a wear predictor for other test materials.

Although both resin composite and monolithic zirconia produced the least enamel wear depth, the SEM image of enamel specimen abraded by monolithic zirconia showed some wear and cracks, while enamel specimen abraded by resin composite showed no wear or even smoother surface compared to baseline (Fig 3). This SEM investigation conformed with the results of enamel roughness after wear testing obtained by profilometry (Table 4). The reason why resin composite was the only material that made similar R_a values might also be answered by its hardness value.

It was noted that enamel wear by enamel made a significant depth of wear, together with high standard deviation. Similar findings were obtained by Ratledge et al (1994) who suggested that three-body wear occurred because of chipped hydroxyapatite particles acting as an abrasive medium (Ratledge et al., 1994). Regarding the high variation of the results, one possible supposition is the lack of homogeneity in natural enamel (Preis et al., 2011; Krejci et al., 1999). Not only variations between teeth have an influence on this, but also variations within individual teeth: that is, the different position of enamel on the tooth results in different properties of the enamel (Anusavice, 2013). This test group consisted of human occlusal enamel in both upper and lower members. Thus, a high scattering of the result was anticipated.

Regarding the methods of wear testing, the amount and duration of load, as well as speed, are some of the factors that influence the amount of enamel wear (O'Brien, 2008); The greater the speed at which the abrasive moves along the surface of the substrate, the greater the rate of abrasion; also, the greater the pressure applied, the more rapid the abrasion. The lack of standardization is a problem found in wear-related literature (Magne et al., 1999; Eichhold and Brown, 1996). Dissimilarities in the testing method may lead to a different outcome in any individual study, so it is difficult to directly compare the present result with various prior investigations. Moreover, the pin-on-disc wear tester used in this study was not invented for simulation of human masticatory function; therefore it is difficult to directly imply the study's result to use in clinical practice. However, the constant contact of the specimens thorough the wear process might resemble characteristics of grinding or clenching habits.

Conclusions

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

The depths of enamel worn by monolithic zirconia and resin composite were significantly lower than those by glass-ceramic and enamel.

Surface roughness of enamel specimens worn by glass-ceramic, monolithic zirconia and enamel increased significantly after wear testing, but no significant difference was found among these materials. For the resin composite group, surface roughness of enamel specimen before and after wear tests was not significantly different.

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