©*Operative Dentistry, 0000,* **00-0,** 000-000

Wear Evaluation of Prosthetic Materials Opposing Themselves

C D'Arcangelo • L Vanini • GD Rondoni • M Vadini • F De Angelis

Clinical Relevance

Thanks to new composite resins and dental ceramics, an excellent esthetic may be clinically combined with outstanding functional features in terms of their wear behavior, which proved to be very similar to that of the well-known traditional gold alloys.

SUMMARY

The purpose of the present *in vitro* study was to compare the two-body wear resistance of a type 3 gold alloy (Aurocast8), two lithium disilicate glass ceramics (IPS e.max CAD and IPS e.max Press), a heat-pressed feldspathic porcelain (Cerabien ZR Press), an yttria-stabilized tetragonal zirconia polycrystal ceramic (Katana Zirconia ML), and three heat-cured composite resins (Ceram.X Universal, Enamel Plus Function, and Enamel Plus HRi) opposing antagonistic cusps made out of the same restorative materials. Ten 6-mm-thick samples and 10 cusp-shaped abraders were manufactured with each test material (n=10) according to standard laboratory procedures. All sample/antagonist pairs made out of the same material were subjected to a two-body wear test in a dual-axis chewing simulator for up to 120,000 loading cycles. The total vertical wear (mm) and the total volumetric loss (mm^3) for each sample/antagonist pair were calculated. Data were statistically analyzed using one-way analysis of variance tests. The total vertical wear for the gold alloy was not significantly different compared to Ceram.X Universal, Enamel Plus Function, IPS e.max CAD, and Cerabien ZR Press. Significantly increased wear values were observed for Enamel Plus HRi and IPS e.max Press. The lowest values for total vertical wear and volumetric loss were recorded on the monolithic zirconia.

INTRODUCTION

A huge number of dental restorative materials are available today for prosthetic purposes. The ideal restorative should resemble as close as possible the tooth hard tissues that are to be replaced. Among material properties, wear behavior seems of crucial importance, as over time either a reduced wear resistance or an exaggerated abrasiveness may severely jeopardize the esthetic and functional outcome of extensive occlusal rehabilitations, especially when treating patients with parafunctions.

Several studies have analyzed the *in vitro* wear resistance of restorative materials opposing either

---

*Camillo D'Arcangelo, DDS, Department of Medical, Oral, and Biotechnological Sciences, University of Chieti, Chieti, Italy

Lorenzo Vanini, DDS, private practitioner, Chiasso, Switzerland

Giuseppe Daniele Rondoni, DT, private practitioner, Savona, Italy

Mirco Vadini, PhD, DDS, Department of Medical, Oral, and Biotechnological Sciences, University of Chieti, Chieti, Italy

Francesco De Angelis, PhD, DDS, Department of Medical, Oral, and Biotechnological Sciences, University of Chieti, Chieti, Italy

*Corresponding author: Via dei Vestini, 31, Chieti 66100, Italy; e-mail: cdarcang@unich.it

DOI: 10.2341/16-212-L

human enamel antagonists or dedicated artificial abraders.[1-4] The abrasiveness of gold-based alloys, resin composites, feldspathic porcelains, glass ceramics, and polycrystalline zirconia-based materials toward tooth hard tissues has also been the subject of extensive investigation.[5-9]

In previous research, dental gold-based alloys showed wear characteristics very similar to human enamel.[1,2] Nevertheless, in spite of their excellent marginal accuracy[10,11] and uncontested mechanical/tribological properties,[12] an increasing demand for better esthetics persuaded clinicians to withdraw full-gold restorations in favor of alternative tooth-colored materials.

Dental ceramics exhibit superior optical properties, excellent color stability, and proven biocompatibility.[13-15] Their clinical reliability has also increased[16-20] following the latest advances in adhesive dentistry[21-25] and the recent introduction of strengthened and enhanced ceramic systems.[26] Ceramic materials are wear resistant,[3,4] but they may damage the opposing enamel.[27-30] The general belief that human enamel might be subject to accelerated wear when opposed by traditional porcelain-fused-to-metal crowns[5] was further confirmed *in vivo* in 2011 by Silva and others.[6] Contradictorily, in a similar *in vivo* study by Etman and others,[7] metal-ceramic crowns produced the least tooth wear in comparison to polycrystalline-alumina copings veneered with feldspathic porcelain and to hot-pressed high-leucite glass ceramics. A recent review indicated that some all-ceramic crowns are as wear friendly as metal-ceramic crowns.[8] The author of the same review failed to find a strong association between tooth wear against ceramics and any specific causal agent,[8] including the material hardness or its chemical composition, thus underlying the compelling need for additional studies on this specific research topic. The most recent *in vitro* studies reported for some new all-ceramic systems an abrasiveness very close to that of human enamel[9] as well as a wear resistance similar to that of traditional gold alloys.[2]

In a direct comparison between properties, such as flexural strength, hardness, or optical behavior, ceramic/glass-ceramic materials are generally superior to dental composites.[31] Nevertheless, thanks to continuous innovations in filler composition and particle size/morphology, current micro-/nanohybrid composites definitely show proper esthetic/mechanical features for successful use in all areas of the mouth.[32,33] Additionally, the increasing appeal of composite resins is warranted by their ease of use, the possibility of an easy and invisible intraoral repair of minor defects induced by function, and the opportunity to choose a direct or an indirect approach.[31] Those characteristics are extremely attractive, as minimally invasive solutions today seem to be preferred in every branch of dentistry.[34-36] Composites are traditionally considered more wear friendly than dental ceramics. In general, resin-based materials produce lower enamel antagonist wear than ceramic-based ones, both in the manually polymerized and in the CAD/CAM versions.[37] In a recent *in vitro* study, resin composite antagonists led to the lowest wear on the opposing enamel, being significantly reduced compared to the enamel wear recorded against lithium disilicate glass-ceramic abraders.[38]

Moreover, innovative and enhanced resin composites have been recently introduced, showing promising *in vitro* wear resistance values, statistically similar to those of human enamel and gold-based alloys.[1]

Notwithstanding the great efforts that have been made toward investigating the wear properties of prosthetic materials opposing human enamel or dedicated artificial abraders, little is currently known about the *in vitro* wear behavior of a specific dental restorative material opposing itself.

The likelihood of restorative materials opposing themselves in routine clinical practice appears rather strong. The full-mouth rehabilitation of completely edentulous patients using traditional or implant-supported prostheses likely leads to an artificial occlusion with a prosthetic material on the upper jaw opposing the same prosthetic material on the lower jaw.[39] A similar condition may also occur when partially edentulous patients are treated to replace or restore missing or damaged antagonistic teeth. Today, the esthetic and functional rehabilitation of severely eroded or abraded patients is preferably accomplished with additive ceramic/composite-based restorations, which are almost simultaneously bonded to all teeth, finally leaving each newly restored tooth in functional contact with a similarly restored antagonistic tooth.[40] A full-mouth prosthetic approach has been described to be the best treatment option in the less frequent cases of amelogenesis imperfecta.[41,42] Even when only a single tooth requires a full-coverage restoration, it is not uncommon to ascertain that the antagonist had already been restored by employing the same dental material.

To our knowledge, only one *in vitro* study has investigated the two- and three-body wear between

Table 1: *Summary of the Materials Used in the Experimental Groups. Technical Data Were Provided by the Respective Manufacturers.*

Material	Lot Number	Shade	Manufacturer	Technical Data
Katana Zirconia ML	DNTZC	ML DARK	Kuraray Noritake Dental Inc (Tokyo, Japan)	Multilayered yttria-stabilized tetragonal zirconia polycrystal ceramic
Aurocast8	15L 02 55	—	Nobil-Metal S.p.A. (Villafranca d'Asti, Italy)	Type 3 high-gold dental alloy. Composition (W/W): Au = 85.4%, Ag = 9.0%, Cu = 5.0%, Pd < 1.0%, Ir < 1.0%
Cerabien ZR Press	BJ5NY	L—A2	Kuraray Noritake Dental	Heat-pressed feldspathic porcelain. Composition (W/W): SiO_2 = 66%, Al_2O_3 = 16.5%, K_2O = 10%, Na_2O = 4.5%, CaO = <1%, MgO = <1%, Li_2O = <1%, B_2O_3 = <1%, traces of ceramic pigments
IPS e.max Press	S42514	LT—A1	Ivoclar Vivadent (Schaan, Liechtenstein)	Heat-pressed lithium disilicate ($Li_2Si_2O_5$) glass-ceramic. Composition (W/W): SiO_2 = 57%-80%, Li_2O = 11%-19%, K_2O = 0%-13%, P_2O_5 = 0%-11%, ZrO_2 = 0%-8%, ZnO = 0%-8%, other oxides and ceramic pigments = 0%-10%
IPS e.max CAD	V13882	LT—A1	Ivoclar Vivadent	Milled lithium disilicate ($Li_2Si_2O_5$) glass-ceramic. Composition (W/W): SiO_2 = 57%-80%, Li_2O = 11%-19%, K_2O = 0%-13%, P_2O_5 = 0%-11%, ZrO_2 = 0%-8%, ZnO = 0%-8%, other oxides and ceramic pigments = 0%-10%
Enamel Plus HRi	2014004972	UE2	Micerium S.p.A. (Genova, Italy)	Nanohybrid resin composite. Filler content: 80% W/W (12% zirconium-oxide fillers, 68% innovative proprietary glass-based filler). Mean particle size: 1000 nm
Enamel Plus Function	2014007020	EF2	Micerium	Microhybrid resin composite. Filler content: 75% W/W. Mean particle size: 700 nm (including 40 nm fumed silica)
Ceram.X Universal	1504004052	A2	Dentsply DeTrey (Konstanz, Germany)	Nanoceramic composite. Filler content: 73% W/W. Particle size: 100 nm-3 μm. Mean particle size: 600 nm

resin composites used both as samples and as antagonistic abraders.[43] Yet for the reasons outlined above, such information seems particularly important both when planning extensive full-mouth rehabilitations and when selecting the appropriate material to restore one or more teeth that oppose already restored antagonistic teeth.

On these bases, the purpose of the present *in vitro* study was to assess the two-body wear of a type 3 gold alloy, an yttria-stabilized zirconia polycrystalline ceramic, a heat-pressed feldspathic porcelain, a lithium disilicate glass ceramic (milled and heat pressed), and three different heat-cured resin composites opposing standardized antagonistic cusps made out of the same restorative materials. Each sample was subjected to 120,000 mastication simulation cycles. The null hypothesis tested was that no difference could be detected in the wear resistance among the materials under investigation.

METHODS AND MATERIALS

A complete list of the materials tested in the present study, together with some data about their composition, is given in Table 1.

Sample Fabrication

Ten IPS e.max Press and 10 Cerabien ZR Press cylindrical specimens were fabricated according to the conventional lost-wax technique by investing and eliminating acrylic resin disks (Plexiglas, Evonik Röhm GmbH, Darmstadt, Germany) 7 mm in diameter and 6 mm thick. The void was filled with the pressable ceramic, following the pressing parameters of each respective manufacturer.

For CAD/CAM materials (IPS e.max CAD and Katana Zirconia ML), ceramic blocks were secured to the arm of a saw (Micromet M, Remet s.a.s., Bologna, Italy) and subjected to consecutive cuts to obtain 6-mm-thick slices. Ten lithium disilicate specimens were produced and subsequently crystallized in a ceramic furnace (Programat EP 5000, Ivoclar Vivadent, Schaan, Liechtenstein) at 840°C to 850°C. Ten zirconia slices were sintered at 1500°C for two hours.

For each of the three resin composites under investigation (Ceram.X Universal, shade A2; Enamel Plus Function, shade EF2; and Enamel Plus HRi, shade UE2), 10 cylinders were manufactured using transparent polyethylene molds measuring 7 mm in diameter and 6 mm in height. The mold was positioned on a glass surface and then filled. The resin composite was applied in three 2-mm-thick layers. Each layer was individually polymerized for 40 seconds (L.E.Demetron I, Sybron/Kerr, Orange, CA, USA) with a 1200-mW/cm^2 output. After mold removal, composite cylinders underwent a further heat-curing cycle (Laborlux, Micerium S.p.A., Genova, Italy) at 80°C for 10 minutes.

Gold alloy (Aurocast8) cylindrical specimens (n=10) were made using the traditional lost-wax technique.

Antagonist Fabrication

An artificial stainless-steel cusp having a slight conical shape and a 2-mm-diameter round tip (Figure 1a,b) was used as a template to produce eight sets of 10 standard antagonists (n=10) employing each one of the eight restorative materials under investigation.

For IPS e.max CAD and Katana Zirconia ML (Figure 1c), the template steel cusp was scanned in order to guide the CAM of the antagonists.

For Ceram.X Universal, Enamel Plus Function (Figure 1g), and Enamel Plus HRi, a polyvinylsiloxane impression of the template steel cusp was taken. The so-achieved cusp-shaped silicon mold was used to produce standard resin-based composite

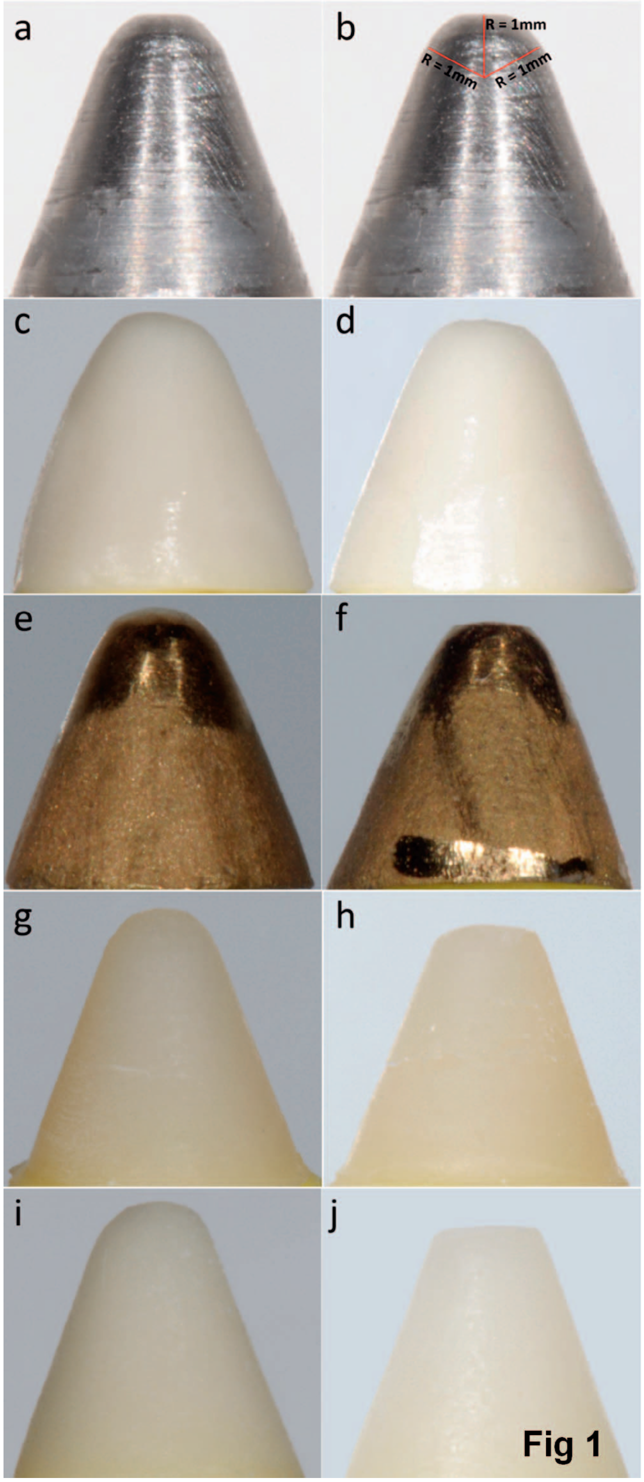

Figure 1. *A stainless-steel cusp (a) having a 1-mm-radius round tip (b) was used as a template to manufacture the standard antagonistic abraders required for chewing simulation testing. The figure shows some representative antagonistic cusps from the following experimental groups: Katana Zirconia ML (before [c] and after [d] testing); Aurocast8 gold alloy (before [e] and after [f] testing); heat-cured Enamel Plus Function (before [g] and after [h] testing); IPS e.max Press lithium disilicate glass-ceramic (before [i] and after [j] testing).*

Table 2: *Configuration of Parameters Set for Wear Method.*

Number of cycles	120,000
Force	49 N
Height	3 mm
Lateral movement	−0.7 mm
Descendent speed	60 mm/s
Lifting speed	60 mm/s
Feed speed	40 mm/s
Return speed	40 mm/s
Frequency	1.6 Hz

antagonists by applying and individually light curing three 2-mm-thick composite layers. After manufacturing, resin composite cusps were heat cured as already described for composite cylindrical specimens.

The same cusp-shaped silicon mold employed for composite antagonists was also used to produce wax replicas of the template steel cusp. The wax replicas were then invested in order to manufacture standard IPS e.max Press (Figure 1i), Cerabien ZR Press, and Aurocast8 (Figure 1e) antagonists following the lost-wax technique and the respective manufacturer instructions.

Polishing Procedures

Samples and cusps made out of heat-pressed lithium disilicate ceramic, heat-pressed feldspathic porcelain, and milled lithium disilicate ceramic (IPS e.max Press, Cerabien ZR Press, and IPS e.max CAD groups) were hand polished with silicon-carbide silicon polishers (Pink Medium Midgets, RA #15; Dedeco International Inc, Long Eddy, NY, USA) and paper-abrasive cones (L-Red Meister Cones, Kuraray Noritake Dental Inc, Tokyo, Japan), followed by a diamond polishing paste (Signum HP, Heraeus Kulzer GmbH, Hanau, Germany) delivered with a goat hair brush (RA Shiny S, Micerium).

Zirconia samples and cusps (Katana Zirconia ML group) were treated using the same silicon polishers and the same paper-abrasive cones employed on lithium disilicate, but their surface was subsequently polished to a final finish using a zirconia-specific diamond paste (Pearl Surface Z, Kuraray Noritake Dental).

Resin composite samples and cusps were gently finished with a rubber point (Shiny 14, Micerium) and electric hand piece. A polishing procedure was than performed using diamond pastes containing 3-μm (Shiny A, Micerium) and 1-μm (Shiny B, Micerium) diamond particles, delivered with a goat hair brush, followed by an aluminum oxide paste (Shiny C, Micerium), delivered with a felt wheel (Shiny F, Micerium).

Silicone rubber polishers (Blue Fine and Pink Extra-Fine Midgets, HP #15, Dedeco International) and an alloy-specific diamond paste (Dia Past, Nobil-Metal S.p.A., Villafranca d'Asti, Italy), delivered with a felt wheel, were used to polish gold alloy samples and antagonists.

Every step of the above described polishing procedures was performed with an electric hand piece at 15,000 rpm with hand pressure for one minute.

Wear Testing

After manufacturing, all specimens and cusps were stored for 24 hours at 37°C and then subjected to a two-body wear test in a dual-axis chewing simulator (CS-4.2, SD Mechatronik GmbH, Feldkirchen-Westerham, Germany) according to the methodology described by D'Arcangelo and others.[1] In brief, autopolymerizing acrylic resin was used to secure the cusps on the antagonist holders and to fix each specimen inside the sample chamber.

Each specimen was loaded against a standard cusp made out of the same restorative material at 1.6 Hz for a total of 120,000 chewing cycles. The masticatory cycle in this study consisted of three phases: contact with a vertical force of 5 kg, horizontal sliding of 0.7 mm, and separation of the specimen and its antagonistic cusp. The chewing simulation parameters used are summarized in Table 2.

Data Analysis

After wear testing, a three-dimensional surface analysis of all specimens was performed with a CAD/CAM contact scanner (Dental Scanner, Renishaw Inc, West Dundee, IL, USA): the sample vertical wear (mm) and its volumetric loss (mm^3) were then calculated.[1] Moreover, the difference between the pretest and posttest height of each antagonistic cusp was measured and assumed as the antagonist vertical wear (mm). The vertical wear of each cusp was also used to calculate the volume of the spherical cap corresponding to the antagonist volumetric loss (mm^3), according to the following formula:

$$\text{antagonist volumetric loss} = \pi \cdot h^2 \cdot (3R - h)/3,$$

where h is the spherical cap height, corresponding to the antagonist vertical wear (mm), and R is the

Table 3: *Mean values (and standard deviations [SD]) for the sample vertical wear (mm), antagonist vertical wear (mm), and total vertical wear (mm) achieved in the experimental groups (n=10). Total vertical wear mean values were compared using a one-way analysis of variance test. Same letters indicate no statistically significant differences.*

Material	Sample Vertical Wear (SD) *A*	Antagonist Vertical Wear (SD) *B*	Total Vertical Wear (SD) *A* + *B*
Katana Zirconia ML	0.018 (0.011)	0.092 (0.036)	0.109 (0.033) C
Aurocast8	0.073 (0.017)	0.142 (0.074)	0.215 (0.085) B
Enamel Plus Function (EF2), heat cured	0.065 (0.033)	0.207 (0.078)	0.272 (0.092) B
Ceram.X Universal (A2), heat cured	0.087 (0.018)	0.204 (0.079)	0.291 (0.083) B
Cerabien ZR Press	0.104 (0.022)	0.194 (0.041)	0.297 (0.061) B
IPS e.max CAD	0.166 (0.029)	0.147 (0.063)	0.313 (0.076) B
Enamel Plus HRi (UE2), heat cured	0.234 (0.029)	0.211 (0.091)	0.445 (0.087) A
IPS e.max Press	0.181 (0.037)	0.316 (0.042)	0.497 (0.059) A

spherical cap radius, equal to 1 mm for each antagonist because of the standardized manufacturing process.

The total vertical wear (mm) for each sample/antagonist pair was finally calculated as the sum of each sample vertical wear and the corresponding antagonist vertical wear. Similarly, the total volumetric loss (mm^3) was calculated as the sum of the sample volumetric loss and the corresponding antagonist volumetric loss.

Means (and standard deviations) for total vertical wear and total volumetric loss were calculated for the eight materials under investigation. Mean values were then compared using one-way analysis of variance (ANOVA) tests and Tukey honestly significant difference tests (α=0.05).

Scanning Electron Microscopy Analysis

After the quantitative wear evaluation, the abraded samples were sputter coated (except the gold alloy samples) and observed under a scanning electron microscope (SEM) (EVO 50 XVP LaB6, Carl Zeiss SMT Ltd, Cambridge, UK) at 50× magnification in order to analyze the wear facets produced throughout the chewing simulation. SEM conditions were set as follows: high vacuum ($2 \cdot 10^{-7}$ Torr), emission current 10 pA, accelerating voltage 10 kV, and working distance around 10 mm.

RESULTS

Tables 3 and 4 show the total vertical wear and total volumetric loss mean values recorded for each test material after 120,000 mastication simulation cycles against antagonistic cusps made out of the same restorative material. The contribution of mean antagonist wear and mean sample wear to the ultimate calculation of the total wear is also given. Data are presented as box plots in Figures 2 and 3, sorting groups from the least to the greatest wear on the category axis. The one-way ANOVA tests showed that the mean value differences observed for the total vertical wear (F=26.995; p<0.001) and for the

Table 4: *Mean values (and standard deviations [SD]) for the sample volumetric loss (mm^3), antagonist volumetric loss (mm^3), and total volumetric loss (mm^3) achieved in the experimental groups (n=10). Total volumetric loss mean values were compared using a one-way analysis of variance test. Same letters indicate no statistically significant differences.*

Material	Sample Volumetric Loss (SD) *C*	Antagonist Volumetric Loss (SD) *D*	Total Volumetric Loss (SD) *C* + *D*
Katana Zirconia ML	0.024 (0.019)	0.029 (0.024)	0.052 (0.029) E
Aurocast8	0.146 (0.058)	0.074 (0.067)	0.220 (0.119) D
Enamel Plus Function (EF2), heat cured	0.082 (0.059)	0.139 (0.094)	0.221 (0.135) D
Ceram.X Universal (A2), heat cured	0.175 (0.044)	0.137 (0.073)	0.311 (0.094) CD
Cerabien ZR Press	0.185 (0.066)	0.114 (0.046)	0.299 (0.111) CD
IPS e.max CAD	0.346 (0.126)	0.074 (0.060)	0.421 (0.155) BC
Enamel Plus HRi (UE2), heat cured	0.362 (0.058)	0.149 (0.116)	0.511 (0.100) B
IPS e.max Press	0.512 (0.085)	0.284 (0.066)	0.796 (0.127) A

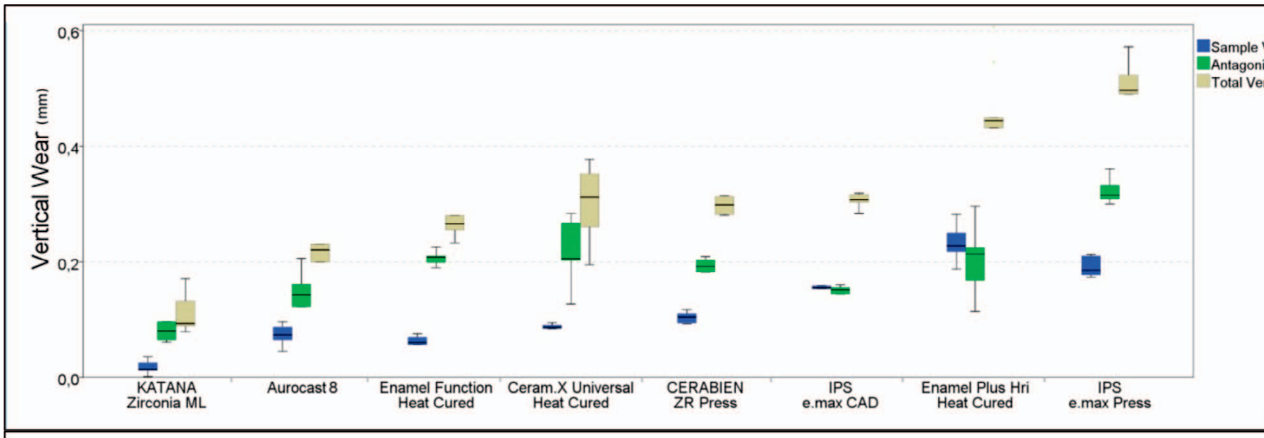

Fig 2

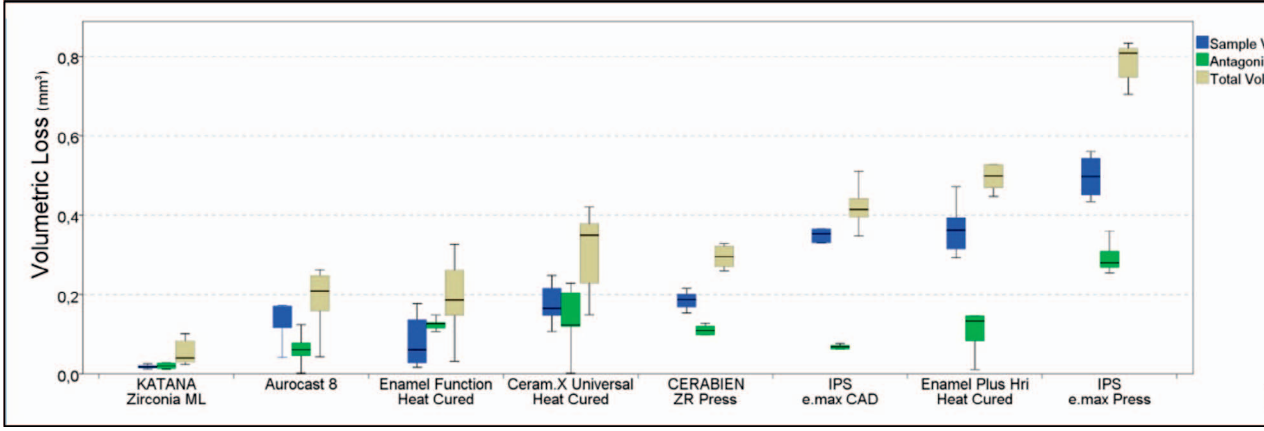

Fig 3

Figure 2. *Data for vertical wear (mm) have been plotted as box plots in order to visualize the distribution of the values observed in the experimental groups. The central line in the box represents the median, and the box represents the middle 50% of values (ie, it ranges from the 25th to the 75th percentile). The whiskers show the extent of the data. Groups on the category axis have been sorted from the least to the greatest observed mean vertical wear values.*

Figure 3. *Data for volumetric loss (mm^3) have been plotted as box plots in order to visualize the distribution of the values observed in the experimental groups. The central line in the box represents the median, and the box represents the middle 50% of values (ie, it ranges from the 25th to the 75th percentile). The whiskers show the extent of the data. Groups on the category axis have been sorted from the least to the greatest observed mean volumetric loss values.*

total volumetric loss (F=38.957; p<0.001) were statistically significant.

The least total vertical wear and total volumetric loss mean values were recorded on zirconia samples opposing zirconia cusps, with a statistically significant difference compared to the total wear of the gold alloy facing gold alloy cusps (p=0.044 for vertical wear; p=0.033 for volumetric loss). Compared to the gold alloy, slightly increased but not significantly different total mean wear values were registered on heat-cured Enamel Plus Function (p=0.671 for vertical wear; p=1.000 for volumetric loss), heat-cured Ceram.X (p=0.311 for vertical wear; p=0.627 for volumetric loss), and Cerabien ZR Press (p=0.217 for vertical wear; p=0.770 for volumetric loss). The use of e.max CAD led to significantly increased total volumetric loss mean values compared to the gold alloy (p=0.005), while no statistically significant differences were recorded between the same two materials in terms of total vertical wear (p=0.074). The use of heat-cured Enamel Plus HRi and e.max Press was associated with the highest total vertical wear mean values and significantly increased compared to the vertical wear observed in all the other experimental groups but with no statistically significant difference between one another (p=0.775).

Representative SEM images of the wear facets observed on some abraded samples are shown in Figure 4. No wear or shallow depressions were observed on Zirconia (Figure 4a). A slight increase in wear facet dimension was observed on gold alloy (Figure 4b) and on Enamel Plus Function (Figure 4c). The worn surfaces on the heat-cured resin composite appeared smooth, and their borders were clear. Worn ceramic specimens (Figure 4d) showed instead a fairly coarse surface.

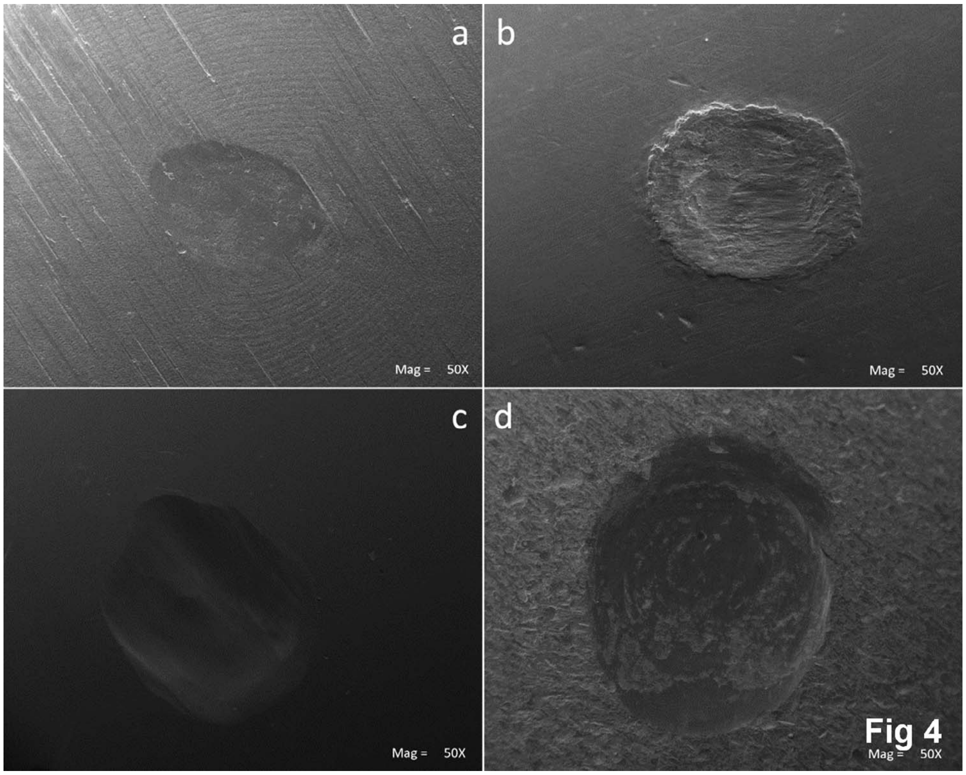

Figure 4. *Scanning electron microphotographs (original magnification 50×) showing the wear facets of some representative samples from the Katana Zirconia ML group (a), Aurocast8 gold alloy group (b), Enamel Plus Function heat-cured group (c), and IPS e.max Press lithium disilicate glass-ceramic group (d).*

DISCUSSION

The null hypothesis tested in the present study had to be rejected. Significant differences were observed in the wear behavior among the restorative materials under investigation. In an experimental model where every material was tested against an antagonistic cusp made out of the same material, the highest total vertical wear and volumetric loss values were recorded on the heat-pressed lithium disilicate (e.max Press) and on a particular heat-cured nanohybrid composite (Enamel Plus HRi, shade UE2), specifically commercialized by the manufacturer as an esthetic material for anterior restorations.

Sample/antagonist pairs made out of Katana Zirconia ML showed the least total vertical wear and volumetric loss mean values, confirming the high wear resistance exhibited by zirconia-based polycrystalline ceramics in previous investigations.[44]

Two innovative resin-based composites were also tested in the present study. After 120,000 chewing simulation cycles against antagonists made out of the same material, the heat-cured Enamel Plus Function and the heat-cured Ceram.X Universal showed an extremely promising wear behavior, very similar to that of the gold-based alloy, in terms of both vertical wear and volumetric loss. Enamel Plus Function was recently introduced by the manufacturer as a clinical alternative to Enamel Plus HRi for posterior teeth, with the goal of increasing mechanical properties and improving long-term outcomes when used on load-bearing occlusal surfaces.[1] It has been formulated by putting the greatest effort toward optimizing the bond between filler particles and the resin matrix,[1] which might explain the positive wear resistance observed. Ceram.X Universal, on the other hand, is based on a proprietary filler technology called SphereTEC and contains granulated spherical submicron glass fillers. According to the manufacturer, this new filler technology, in combination with an optimized resin matrix, improves the esthetics and polishability and provides high fracture toughness. Even the enhanced wear properties recorded in the present study for this new resin-based composite might be somehow correlated with its unique chemical composition.

The total vertical wear mean values for the milled lithium disilicate ceramic (e.max CAD) and for the heat-pressed feldspathic porcelain (Cerabien ZR

Press) were also not statistically different from the gold alloy. Nevertheless, the wear behavior of ceramics should not be considered similar to that of metal or composite resin. To some extent, metal and composite resins wear through a mechanism involving plastic deformation and adhesion, while ceramics wear through microfractures.[38,45]

The wear properties of the gold alloy are likely due to its inherently increased ductility, provided by metal bonds in its structure, compared to the brittle property of ceramics.[46] The SEM pictures of worn gold alloy samples suggest the occurrence of a plastic deformation over the wear process (Figure 4b). On the other hand, the SEM photographs of worn ceramic specimens (Figure 4d) demonstrated a coarse surface and flaws probably generated by exfoliated hard debris. Even if crack formations of ceramic could not be seen in the SEM observation, fatigue wear might have occurred due to repetitive loading on the brittle ceramic surface. The heat-cured Enamel Plus Function (Figure 4c) displayed a relatively uniform wear surface: the lack of evident irregularities and images of filler dislodgement/protrusion might be correlated to the optimum bond between filler particles and resin matrix.

For decades, the use of metal or gold on the occlusal surfaces has been considered a valid solution in all cases where the prosthetic occlusion was in contact with natural enamel, resin composite, porcelain, or a combination of such materials,[47] causing minimal wear to the antagonist[48] and little interference with the patient occlusal balance.[3] In recent *in vitro* studies, a type 3 gold alloy exhibited the same wear rates of human enamel.[1,2] As a consequence, dental materials that closely resemble the gold alloy in their wear behavior should probably be considered the most physiological substitutes for lost tooth hard tissues.

Excessive wear or exaggerated abrasiveness, on the other hand, should be avoided, as it may lead to unacceptable restoration and/or antagonist damage, with possible alterations of the functional path of masticatory movements. When anterior teeth are involved, both esthetics and anterior guidance function are impaired, finally leading to increased stresses on the masticatory system and possible temporomandibular joint dysfunctions.[49-51]

Many studies have attempted to relate the wear resistance and/or the abrasiveness of dental materials to specific material properties, such as surface topography, fracture toughness, or hardness.[52-54]

According to Fischer and others,[55] for most materials, metal in particular, the wear resistance can indeed be considered directly proportional to the hardness. However, for the abrasion caused by most ceramics, hardness and wear are probably not strictly associated with each other.[56-58] The wear caused by ceramics appears more related to surface roughness and fracture toughness[55,59,60] and should be conveniently considered as a multifactorial condition.[61]

Unlike the case of ceramics, composites produce wear on their antagonist through hard filler protruding from the abraded resin matrix, and the hardness is thought to be a reliable predictor of their abrasiveness.[53,54]

According to the general knowledge about wear between two contacting materials, a softer material is abraded more easily than an opposing harder one.[54] However, in the present study, each tested material was also used to manufacture the respective antagonistic abrader in order to mimic *in vitro* the common clinical situation of two opposing restorations made out of the same dental material. Thus, in this study, every sample was tested against an antagonistic abrader showing exactly the same mechanical properties. Furthermore, the total wear (sample wear plus antagonist wear) was calculated and assumed as the parameter under investigation. In a similar experimental scenario, hardness is maybe less correlated with total wear because, even assuming that a harder material would easily abrade its antagonist, probably it is also less likely to be worn out compared to a softer one and vice versa. Interestingly, even though the manufacturer reports the same Vickers hardness value for both the heat-pressed and the milled versions of lithium disilicate (5800 MPa), in this study a statistically significant difference was detected in the wear properties of e.max Press and e.max CAD. This finding confirmed that the wear behavior of a brittle substrate (like ceramic) is perhaps different from that of a composite, and, consequently, the use of hardness as a wear predictor for all the materials tested did not seem an appropriate solution.

In the present study, both pressed and milled ceramic materials were subjected to a standardized surface polishing procedure before testing. Although in a few studies no statistically significant differences were recorded between the wear properties of polished and glazed lithium disilicate ceramics, a trend toward higher antagonist wear was noted for the glazed ones.[62,63] Moreover, several studies have reported that glazed zirconia may lead to increased opposing enamel wear compared to polished zirconia.[62,64-71]

As a consequence, assuming that wear-friendly dental materials should always be preferred, it appeared more clinically relevant to deepen the wear properties of a polished ceramic instead of focusing on a glazed one. Furthermore, the wear resistance and the abrasiveness of a glazed ceramic could be influenced by the specific ceramic glaze applied rather than representing an intrinsic property of the material itself.

As a general rule, well-conducted randomized controlled clinical trials should be considered the best method to evaluate the quality of dental materials. However, they are costly, time consuming, and hard to standardize. Therefore, *in vitro* research still remains an indispensable step for initial screening of material properties, and dynamic tests appear to be extremely valuable in predicting the clinical performance of biomaterials subjected to the cyclic solicitations generated by physiological movements.[28,72,73]

CONCLUSIONS

Within the limitations of an *in vitro* model designed to test the two-body wear resistance of a dental restorative material opposing an antagonist made out of the same material, the following conclusions could be drawn:

1) Among the esthetic and adhesive materials investigated, two heat-cured resin composites (Enamel Plus Function and Ceram.X Universal), a heat-pressed feldspathic porcelain (Cerabien ZR Press), and a milled lithium disilicate glass ceramic (IPS e.max CAD) showed a vertical wear statistically similar to the traditional type 3 gold alloy.
2) Total vertical wear and total volumetric loss observed on the monolithic zirconia (Katana Zirconia ML) were significantly reduced compared to the gold alloy and to all the other tested materials.
3) Total vertical wear and total volumetric loss recorded on the heat-pressed lithium disilicate glass ceramic (IPS e.max Press) were significantly increased compared to what was observed for the milled lithium disilicate glass ceramic (IPS e.max CAD).

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 7 March 2017)

REFERENCES

1. D'Arcangelo C, Vanini L, Rondoni GD, Pirani M, Vadini M, Gattone M, & De Angelis F (2014) Wear properties of a novel resin composite compared to human enamel and other restorative materials *Operative Dentistry* **39(6)** 612-618.
2. D'Arcangelo C, Vanini L, Rondoni GD, & De Angelis F. Wear properties of dental ceramics and porcelains compared with human enamel *Journal of Prosthetic Dentistry* **115(3)** 350-355, http://dx.doi.org/10.1016/j.prosdent.2015.09.010
3. Elmaria A, Goldstein G, Vijayaraghavan T, Legeros RZ, & Hittelman EL (2006) An evaluation of wear when enamel is opposed by various ceramic materials and gold *Journal of Prosthetic Dentistry* **96(5)** 345-353.
4. Hacker CH, Wagner WC, & Razzoog ME (1996) An in vitro investigation of the wear of enamel on porcelain and gold in saliva *Journal of Prosthetic Dentistry* **75(1)** 14-17.
5. Wiley MG (1989) Effects of porcelain on occluding surfaces of restored teeth *Journal of Prosthetic Dentistry* **61(2)** 133-137.
6. Silva NR, Thompson VP, Valverde GB, Coelho PG, Powers JM, Farah JW, & Esquivel-Upshaw J (2011) Comparative reliability analyses of zirconium oxide and lithium disilicate restorations in vitro and in vivo *Journal of the American Dental Association* **142(Supplement 2)** 4S-9S.
7. Etman MK, Woolford M, & Dunne S (2008) Quantitative measurement of tooth and ceramic wear: In vivo study *International Journal of Prosthodontics* **21(3)** 245-252.
8. Hmaidouch R, & Weigl P (2013) Tooth wear against ceramic crowns in posterior region: A systematic literature review *International Journal of Oral Science* **5(4)** 183-190, http://dx.doi.org/10.1038/ijos.2013.73
9. Zandparsa R, El Huni RM, Hirayama H, & Johnson MI (2016) Effect of different dental ceramic systems on the wear of human enamel: An in vitro study *Journal of Prosthetic Dentistry* **115(2)** 230-237, http://dx.doi.org/10.1016/j.prosdent.2015.09.005
10. Park JM, Hong YS, Park EJ, Heo SJ, & Oh N (2016) Clinical evaluations of cast gold alloy, machinable zirconia, and semiprecious alloy crowns: A multicenter study *Journal of Prosthetic Dentistry* **115(6)** 684-691, http://dx.doi.org/10.1016/j.prosdent.2015.10.018
11. Johnson R, Verrett R, Haney S, Mansueto M, & Challa S (2017) Marginal gap of milled versus cast gold restorations *Journal of Prosthodontics* **26(1)** 56-63, http://dx.doi.org/10.1111/jopr.12432
12. Tucker RV (2008) Why gold castings are excellent restorations *Operative Dentistry* **33(2)** 113-115.
13. Rosenblum MA, & Schulman A (1997) A review of all-ceramic restorations *Journal of the American Dental Association* **128(3)** 297-307.

14. Kelly JR, & Benetti P (2011) Ceramic materials in dentistry: Historical evolution and current practice *Australian Dental Journal* **56(Supplement 1)** 84-96, http://dx.doi.org/10.1111/j.1834-7819.2010.01299.x

15. McLean JW (2001) Evolution of dental ceramics in the twentieth century *Journal of Prosthetic Dentistry* **85(1)** 61-66.

16. Sailer I, Pjetursson BE, Zwahlen M, & Hämmerle CH (2007) A systematic review of the survival and complication rates of all-ceramic and metal-ceramic reconstructions after an observation period of at least 3 years. Part II: Fixed dental prostheses *Clinical Oral Implants Research* **18(Supplement 3)** 86-96.

17. Pjetursson BE, Sailer I, Zwahlen M, & Hämmerle CH (2007) A systematic review of the survival and complication rates of all-ceramic and metal-ceramic reconstructions after an observation period of at least 3 years. Part I: Single crowns *Clinical Oral Implants Research* **18(Supplement 3)** 73-85.

18. Malament KA, & Socransky SS (1999) Survival of Dicor glass-ceramic dental restorations over 14 years: Part I. Survival of Dicor complete coverage restorations and effect of internal surface acid etching, tooth position, gender, and age *Journal of Prosthetic Dentistry* **81(1)** 23-32.

19. Malament KA, Socransky SS, Thompson V, & Rekow D (2003) Survival of glass-ceramic materials and involved clinical risk: Variables affecting long-term survival *Practical Procedures and Aesthetic Dentistry* **2003(Supplement)** 5-11.

20. Malament KA (1988) Considerations in posterior glass-ceramic restorations *International Journal of Periodontics and Restorative Dentistry* **8(4)** 32-49.

21. D'Arcangelo C, Vanini L, Prosperi GD, Di Bussolo G, De Angelis F, D'Amario M, & Caputi S (2009) The influence of adhesive thickness on the microtensile bond strength of three adhesive systems *Journal of Adhesive Dentistry* **11(2)** 109-115.

22. Burke FJ, Fleming GJ, Nathanson D, & Marquis PM (2002) Are adhesive technologies needed to support ceramics? An assessment of the current evidence *Journal of Adhesive Dentistry* **4(1)** 7-22.

23. D'Arcangelo C, De Angelis F, Vadini M, D'Amario M, & Caputi S (2010) Fracture resistance and deflection of pulpless anterior teeth restored with composite or porcelain veneers *Journal of Endodontics* **36(1)** 153-156, http://dx.doi.org/10.1016/j.joen.2009.09.036

24. D'Arcangelo C, D'Amario M, De Angelis F, Zazzeroni S, Vadini M, & Caputi S (2007) Effect of application technique of luting agent on the retention of three types of fiber-reinforced post systems *Journal of Endodontics* **33(11)** 1378-1382.

25. D'Arcangelo C, D'Amario M, Vadini M, Zazzeroni S, De Angelis F, & Caputi S (2008) An evaluation of luting agent application technique effect on fibre post retention *Journal of Dentistry* **36(4)** 235-240, http://dx.doi.org/10.1016/j.jdent.2008.01.004

26. Santos MJ, Costa MD, Rubo JH, Pegoraro LF, & Santos GC Jr (2015) Current all-ceramic systems in dentistry: A review *Compendium of Continuing Education in Dentistry* **36(1)** 31-37.

27. ISO-Standards (2001) *ISO 14569-2 Dental Materials Guidance on Testing of Wear. Part 2: Wear by Two-and/or Three-Body Contact. Technical Specification* International Organization for Standardization, Geneva.

28. Heintze SD (2006) How to qualify and validate wear simulation devices and methods *Dental Materials* **22(8)** 712-734.

29. Heintze SD, Barkmeier WW, Latta MA, & Rousson V (2011) Round robin test: Wear of nine dental restorative materials in six different wear simulators—Supplement to the round robin test of 2005 *Dental Materials* **27(2)** e1-e9, http://dx.doi.org/10.1016/j.dental.2010.09.003

30. Heintze SD, Zellweger G, Grunert I, Muñoz-Viveros CA, & Hagenbuch K (2012) Laboratory methods for evaluating the wear of denture teeth and their correlation with clinical results *Dental Materials* **28(3)** 261-272, http://dx.doi.org/10.1016/j.dental.2011.10.012

31. Ruse ND, & Sadoun MJ (2014) Resin-composite blocks for dental CAD/CAM applications *Journal of Dental Research* **93(12)** 1232-1234, http://dx.doi.org/10.1177/0022034514553976

32. Ferracane JL (2011) Resin composite—State of the art *Dental Materials* **27(1)** 29-38, http://dx.doi.org/10.1016/j.dental.2010.10.020

33. Ilie N, & Hickel R (2009) Investigations on mechanical behaviour of dental composites *Clinical Oral Investigations* **13(4)** 427-438, http://dx.doi.org/10.1007/s00784-009-0258-4

34. Ryder MI, & Armitage GC (2016) Minimally invasive periodontal therapy for general practitioners *Periodontology 2000* **71(1)** 7-9, http://dx.doi.org/10.1111/prd.12132

35. D'Amario M, Baldi M, Petricca R, De Angelis F, El Abed R, & D'Arcangelo C (2013) Evaluation of a new nickel-titanium system to create the glide path in root canal preparation of curved canals *Journal of Endodontics* **39(12)** 1581-1584, http://dx.doi.org/10.1016/j.joen.2013.06.037

36. Opal S, Garg S, Dhindsa A, & Taluja T (2014) Minimally invasive clinical approach in indirect pulp therapy and healing of deep carious lesions *Journal of Clinical Pediatric Dentistry* **38(3)** 185-192.

37. Stawarczyk B, Özcan M, Trottmann A, Schmutz F, Roos M, & Hämmerle C (2013) Two-body wear rate of CAD/CAM resin blocks and their enamel antagonists *Journal of Prosthetic Dentistry* **109(5)** 325-332, http://dx.doi.org/10.1016/S0022-3913(13)60309-1

38. Sripetchdanond J, & Leevailoj C (2014) Wear of human enamel opposing monolithic zirconia, glass ceramic, and composite resin: An in vitro study *Journal of Prosthetic Dentistry* **112(5)** 1141-1150, http://dx.doi.org/10.1016/j.prosdent.2014.05.006

39. Bencharit S, Schardt-Sacco D, Border MB, & Barbaro CP (2010) Full mouth rehabilitation with implant-supported prostheses for severe periodontitis: A case report *Open Dentistry Journal* **13(4)** 165-171, http://dx.doi.org/10.2174/1874210601004010165

40. Grütter L, & Vailati F (2013) Full-mouth adhesive rehabilitation in case of severe dental erosion, a minimally invasive approach following the 3-step technique *European Journal of Esthetic Dentistry* **8(3)** 358-375.
41. Pinky, Naik S, & Nd S (2010) Amelogenesis imperfecta: Full mouth rehabilitation in deciduous dentition *International Journal of Clinical Pediatric Dentistry* **4(2)** 171-175, http://dx.doi.org/10.5005/jp-journals-10005-1105
42. Sabandal MM, & Schäfer E (2016) Amelogenesis imperfecta: Review of diagnostic findings and treatment concepts *Odontology* **104(3)** 245-256, http://dx.doi.org/10.1007/s10266-016-0266-1
43. Osiewicz MA, Werner A, Pytko-Polonczyk J, Roeters FJ, & Kleverlaan CJ (2015) Contact- and contact-free wear between various resin composites *Dental Materials* **31(2)** 134-140, http://dx.doi.org/10.1016/j.dental.2014.11.007
44. Nakashima J, Taira Y, & Sawase T (2016) In vitro wear of four ceramic materials and human enamel on enamel antagonist *European Journal of Oral Sciences* **124(3)** 295-300, http://dx.doi.org/10.1111/eos.12272
45. Oh WS, Delong R, & Anusavice KJ (2002) Factors affecting enamel and ceramic wear: A literature review *Journal of Prosthetic Dentistry* **87(4)** 451-459.
46. Ramp MH, Suzuki S, Cox CF, Lacefield WR, & Koth DL (1997) Evaluation of wear: Enamel opposing three ceramic materials and a gold alloy *Journal of Prosthetic Dentistry* **77(5)** 523-530.
47. Elkins WE (1973) Gold occlusal surfaces and organic occlusion in denture construction *Journal of Prosthetic Dentistry* **30(1)** 94-98.
48. Barco MT Jr, & Synnott SA (1989) Precision metal occlusal surfaces for removable partial dentures *International Journal of Prosthodontics* **2(4)** 365-367.
49. Schuyler CH (1951) Full denture service as influenced by tooth forms and materials *Journal of Prosthetic Dentistry* **1(1-2)** 33-37.
50. Bauer W, van den Hoven F, & Diedrich P (1997) Wear in the upper and lower incisors in relation to incisal and condylar guidance *Journal of Orofacial Orthopedics* **58(6)** 306-319.
51. Wedel A, Borrman H, & Carlsson GE (1998) Tooth wear and temporomandibular joint morphology in a skull material from the 17th century *Swedish Dental Journal* **22(3)** 85-95.
52. Anusavice KJ (2013) *Phillips' Science of Dental Materials* Elsevier, St Louis MO 48-68.
53. Suzuki S, & Leinfelder KF (1993) Wear of enamel cusps opposed by posterior composite resin *Quintessence International* **24(12)** 885-890.
54. Shimane T, Endo K, Zheng JH, Yanagi T, & Ohno H (2010) Wear of opposing teeth by posterior composite resins—Evaluation of newly developed wear test methods *Dental Materials Journal* **29(6)** 713-720.
55. Fischer TE, Anderson MP, & Jahanmir S (1989) Influence of fracture toughness on the wear resistance of yttria-doped zirconium oxide *Journal of the American Ceramic Society* **72(2)** 252-257, http://dx.doi.org/10.1111/j.1151-2916.1989.tb06110.x
56. DeLong R, Douglas WH, Sakaguchi RL, & Pintado MR (1986) The wear of dental porcelain in an artificial mouth *Dental Materials* **2(5)** 214-219.
57. Seghi RR, Rosenstiel SF, & Bauer P (1991) Abrasion of human enamel by different dental ceramics in vitro *Journal of Dental Research* **70(3)** 221-225.
58. Magne P, Oh WS, Pintado MR, & DeLong R (1999) Wear of enamel and veneering ceramics after laboratory and chairside finishing procedures *Journal of Prosthetic Dentistry* **82(6)** 669-679.
59. Metzler KT, Woody RD, Miller AW III, & Miller BH (1999) In vitro investigation of the wear of human enamel by dental porcelain *Journal of Prosthetic Dentistry* **81(3)** 356-364.
60. Fischer TE, Zhu Z, Kim H, & Shin DS (2000) Genesis and role of wear debris in sliding wear of ceramics *Wear* **245(1-2)** 53-60.
61. Faria AC, de Oliveira AA, Alves Gomes E, Silveira Rodrigues RC, & Faria Ribeiro R (2014) Wear resistance of a pressable low-fusing ceramic opposed by dental alloys *Journal of the Mechanical Behavior of Biomedical Materials* **32(April)** 46-51, http://dx.doi.org/10.1016/j.jmbbm.2013.12.018
62. Preis V, Weiser F, Handel G, & Rosentritt M (2013) Wear performance of monolithic dental ceramics with different surface treatments *Quintessence International* **44(5)** 393-405, http://dx.doi.org/10.3290/j.qi.a29151
63. Lawson NC, Janyavula S, Syklawer S, McLaren EA, & Burgess JO (2014) Wear of enamel opposing zirconia and lithium disilicate after adjustment, polishing and glazing *Journal of Dentistry* **42(12)** 1586-1591, http://dx.doi.org/10.1016/j.jdent.2014.09.008
64. Burgess JO, Janyavula S, Lawson NC, Lucas TJ, & Cakir D (2014) Enamel wear opposing polished and aged zirconia *Operative Dentistry* **39(2)** 189-194, http://dx.doi.org/10.2341/12-345-L
65. Janyavula S, Lawson N, Cakir D, Beck P, Ramp LC, & Burgess JO (2013) The wear of polished and glazed zirconia against enamel *Journal of Prosthetic Dentistry* **109(1)** 22-29, http://dx.doi.org/10.1016/S0022-3913(13)60005-0
66. Mitov G, Heintze SD, Walz S, Woll K, Muecklich F, & Pospiech P (2012) Wear behavior of dental Y-TZP ceramic against natural enamel after different finishing procedures *Dental Materials* **28(8)** 909-918, http://dx.doi.org/10.1016/j.dental.2012.04.010
67. Park JH, Park S, Lee K, Yun KD, & Lim HP (2014) Antagonist wear of three CAD/CAM anatomic contour zirconia ceramics *Journal of Prosthetic Dentistry* **111(1)** 20-29, http://dx.doi.org/10.1016/j.prosdent.2013.06.002
68. Preis V, Behr M, Kolbeck C, Hahnel S, Handel G, & Rosentritt M (2011) Wear performance of substructure ceramics and veneering porcelains *Dental Materials* **27(8)** 796-804, http://dx.doi.org/10.1016/j.dental.2011.04.001
69. Stawarczyk B, Özcan M, Schmutz F, Trottmann A, Roos M, & Hämmerle CH (2013) Two-body wear of monolithic, veneered and glazed zirconia and their corresponding enamel antagonists *Acta Odontologica Scandinavica* **71(1)** 102-112, http://dx.doi.org/10.3109/00016357.2011.654248

70. Jung YS, Lee JW, Choi YJ, Ahn JS, Shin SW, & Huh JB (2010) A study on the in-vitro wear of the natural tooth structure by opposing zirconia or dental porcelain *Journal of Advanced Prosthodontics* **2(3)** 111-115, http://dx.doi.org/10.4047/jap.2010.2.3.111

71. Heintze SD, Cavalleri A, Forjanic M, Zellweger G, & Rousson V (2008) Wear of ceramic and antagonist—A systematic evaluation of influencing factors in vitro *Dental Materials* **24(4)** 433-449.

72. Morresi AL, D'Amario M, Capogreco M, Gatto R, Marzo G, D'Arcangelo C, & Monaco A (2014) Thermal cycling for restorative materials: Does a standardized protocol exist in laboratory testing? A literature review *Journal of the Mechanical Behavior of Biomedical Materials* **29(January)** 295-308, http://dx.doi.org/10.1016/j.jmbbm.2013.09.013

73. Mazzitelli C, Monticelli F, Toledano M, Ferrari M, & Osorio R (2012) Effect of thermal cycling on the bond strength of self-adhesive cements to fiber posts *Clinical Oral Investigations* **16(3)** 909-915, http://dx.doi.org/10.1007/s00784-011-0576-1