

# Wear evaluation of CAD-CAM dental ceramic materials by chewing simulation

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**PURPOSE.** To evaluate the wear of computer-aided design/computer-aided manufacturing (CAD-CAM) dental ceramic materials opposed by enamel as a function of increased chewing forces. **MATERIALS AND METHODS.** The enamel cusps of healthy human third molar teeth (n = 40) opposed by materials from CAD-CAM dental ceramic groups (n = 10), including Vita Enamic® (ENA), a polymer-infiltrated ceramic network (PICN); GC Cerasmart® (CERA), a resin nano-ceramic; Celtra® Duo (DUO), a zirconia-reinforced lithium silicate (ZLS) ceramic; and IPS e.max ZirCAD (ZIR), a polycrystalline zirconia, were exposed to chewing simulation (1,200,000 cycles; 120 N load; 1 Hz frequency; 0.7 mm lateral and 2 mm vertical motion). The wear of both enamel cusps and materials was quantified using a 3D laser scanner, and the wear mechanisms were evaluated by scanning electron microscopy (SEM). The results were analysed using Welch ANOVA and Kruskal Wallis test ( $\alpha = .05$ ). **RESULTS.** ZIR showed lower volume loss ( $0.02 \pm 0.01 \text{ mm}^3$ ) than ENA, CERA and DUO ( $P = .001$ ,  $P = .018$  and  $P = .005$ , respectively). The wear of cusp/DUO [ $0.59 \text{ mm}^3$  ( $0.50\text{-}1.63 \text{ mm}^3$ )] was higher than cusp/CERA [ $0.17 \text{ mm}^3$  ( $0.04\text{-}0.41 \text{ mm}^3$ )] ( $P = .007$ ). ZIR showed completely different wear mechanism in SEM. **CONCLUSION.** Composite structured materials such as PICN and ZLS ceramic exhibit more abrasive effect on opposing enamel due to their loss against wear, compared to uniform structured zirconia. The resin nano-ceramic causes the lowest enamel wear thanks to its flexible nano-ceramic microstructure. While zirconia appears to be an enamel-friendly material in wear volume loss, it can cause microstructural defects of enamel. [J Adv Prosthodont 2021;13:281-91]

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## KEYWORDS

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## INTRODUCTION

In prosthetic dentistry, ceramic materials have been widely used due to their intrinsic properties such as biocompatibility, chemical integrity, mechanical

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resistance, and optical characters.<sup>1</sup> In recent years, digital technologies have been expanding rapidly in the field of dentistry, improving the quality of materials by computerized manufacturing methods at high precision.<sup>2,3</sup> New possibilities have opened by the development of the ceramic base and computer-aided design/computer-aided manufacturing (CAD-CAM) materials.<sup>4,5</sup>

Resin-matrix CAD-CAM materials are recommended as aesthetic alternatives for various clinical indications and have recently been coded as "ceramics" by the American Dental Association (ADA) with their ceramic-like properties.<sup>6</sup> A resin-matrix ceramic material GC Cerasmart (CERA, GC Corporation, Tokyo, Japan), referred as flexible nano-ceramic, consists of relatively small and uniformly distributed particles of alumina-barium silicate embedded in a polymer matrix. It has approximately 71% by weight of silica and barium glass nanoparticles and 29% composite resin (GC Corporation; GC Cerasmart® technical product information data sheet. n.d.) Another resin-matrix material Vita Enamic (ENA, Vita Zahnfabrik, Bad Säckingen, Germany), a polymer-infiltrated ceramic network (PICN) material, has recently been introduced and referred to as a hybrid material. Typically, it is composed of a dual network, such as 86% by weight of feldspathic ceramic network and 14% by weight of polymer network (Vita Zahnfabrik; Vita Enamic® technical product information data sheet. n.d.). Compositional analysis of PICN reveals a dominant ceramic network with leucite as the main phase and zirconia as a minor phase associated with a polymer-based network.<sup>7</sup>

Celtra Duo (DUO, Dentsply Sirona, York, PA, USA) is a zirconia-reinforced lithium silicate (ZLS) ceramic consisting of 58% silica, lithium-metasilicate, -disilicate, and phosphate crystals, and 10% zirconia crystals in addition to other minor ingredients (Dentsply Sirona, Celtra® Duo technical product information data sheet. n.d.). The submicron-sized zirconia particles in the glassy matrix are incorporated to reinforce the structure of lithium silicate ceramic and improve mechanical properties.<sup>8,9</sup>

IPS e.max ZirCAD (ZIR, Ivoclar Vivadent AG, Schaan, Liechtenstein) is a tetragonal polycrystalline zirconia, partially stabilized with 3% mol with yttria (3 Y-TZP)

(88 - 95.5 % ZrO<sub>2</sub>) (Ivoclar Vivadent AG, IPS e.max ZirCAD technical product information data sheet. n.d.). The first-generation 3Y-TZP zirconia was introduced to optimize its strength and toughness.<sup>10</sup> The composition and microstructure of dental materials determine their mechanical and physical properties.<sup>11</sup>

Physiological tooth wear occurring throughout lifetime is a normal process that indicates a need for improved chewing efficiency and reduced susceptibility of dentition to disease and malocclusion.<sup>12,13</sup> Conversely, excessive tooth wear may result in poor chewing ability, damaged tooth surface, destroyed structural stability and reduced life of ceramic materials, which are replaced to compensate for partial or total loss of dental structures.<sup>14-17</sup>

Microstructural material-related factors of the dental ceramics and bruxism as a patient-related factor might influence enamel wear.<sup>18-21</sup> In recent years, the prevalence of bruxism has increased in general adult population and is usually regarded as one of the causative factors of tooth wear, possibly because of tooth overload.<sup>22,23</sup> Chewing forces play an essential role in patients, especially those with sleep bruxism, which creates non-physiological force and velocity contraction during mastication.<sup>24,25</sup> While physiologic chewing forces are at 10 - 120 N, parafunctional forces are at 200 - 800 N, which is approximately 10 times greater and may reach up to 1000 N.<sup>19,26</sup> The selection of the loading force is a significant component of wear testing methods. 49 - 50 N can be regarded as the mean value of physiological chewing forces.<sup>27,28</sup> Higher loads, such as 75 N and 100 N loads, can lead to higher wear rates during *in vitro* wear simulation.<sup>29</sup>

With the growing popularity and clinical use of CAD-CAM ceramic restorations and the increasing prevalence of patients with bruxism, it is critical to understand the wear potential of both materials and enamel. Therefore, the present study aimed to evaluate the wear performance of new-generation CAD-CAM dental ceramic materials and opposing enamel cusps by chewing simulation as a function of increased chewing forces.

The null hypotheses of this study were the following: 1) there would be no difference among the materials in terms of their wear volume loss by chewing simulation under increased loads, and 2) the materi-

als would have no effect on opposing enamel cusps by chewing simulation under increased loads.

## MATERIALS AND METHODS

All teeth considered in this study were collected with the approval from the Yeditepe University Ethics Committee of Clinical Research (CREC Decision Number:1257). According to the power analysis and sample size software PASS 15 (NCSS, LLC, Kaysville, UT, USA), 40 tooth cusp samples achieved 95% power to detect differences with a significance level of 0.05. Healthy human permanent third molars were visually inspected to ensure the absence of caries, damages, or fillers/sealants. No significant signs of attrition were observed. Residual particles were removed from the teeth before storing them in distilled water at 4°C to avoid deterioration. Then, the teeth were disinfected with 1.0% chloramine T-trihydrate bacteriostatic/bactericidal solution (Merck KGaA, Darmstadt, Germany) at room temperature for 1 week. This disinfection and storage procedure were performed according to ISO/ TS 11405 (“ISO/TS 11405: 2015- Dentistry-Testing of adhesion to tooth structure”).<sup>30</sup> After disinfection, each tooth was divided into four parts from the crown to the root to have four independent cusps. Tooth cusp samples were identified according to their op-

posing material such as “cusp/material name”.

The materials used in this study and their compositions are listed in Table 1. Each CAD-CAM ceramic material (n = 10) was sectioned into approximately 6 × 6 × 6 mm<sup>3</sup> flat-surface specimens using a precision saw (Micromet 5114, Buehler, Lake Bluff, IL, USA), and then polished with silicon carbide abrasive papers (600-, 800-,1200- grit papers, 3M, St. Paul, MN, USA) in a polisher (Phoenix Beta Grinder, Buehler, IL, USA) under water irrigation. Zirconia reinforced lithium silicate (ZLS) ceramic blocks (Celtra Duo, Dentsply Sirona, York, PA, USA) were subjected to a subsequent firing process at 810°C for crystallization (Programat P310, Ivoclar Vivadent AG, Schaan, Liechtenstein). Zirconia samples from a disk (IPS e.max ZirCAD, Ivoclar Vivadent AG, Schaan, Liechtenstein) were cut 20% thicker than specified size and then subjected to sintering (inFire HTC speed, Dentsply Sirona, York, PA, USA) at 1500°C. Crystallization and sintering were performed according to the manufacturer’s recommendations. All samples were kept in ultrasonic cleaner with distilled and deionized water for 10 min.

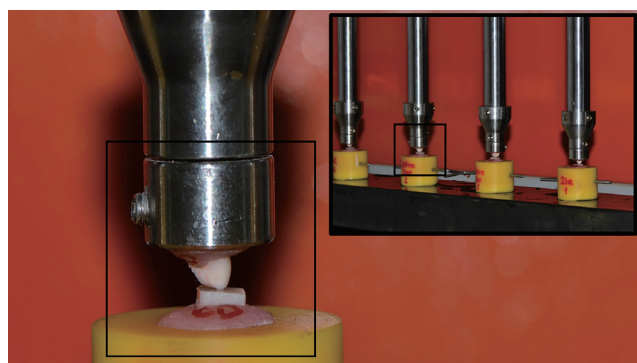
To mimic the physiological conditions of human mastication as closely as possible, an *in-vitro* wear test was conducted in a chewing simulator (Dent-ARGE/ ACS 8.1, Benart, Ankara, Turkey). To mimic the cusp-fossa relationship, enamel cusps were placed on

**Table 1.** Materials used in study

Material	Symbol	Classification*	Composition*	Lot and shade/size	Manufacturer
Vita Enamic	ENA	Polymer-infiltrated ceramic network (PICN)	86% feldspathic ceramic 14% polymer	73330 2M2-T/EM-14	Vita Zahnfabrik, Bad Säckingen, Germany
GC Cerasmart	CERA	Resin nano-ceramic	71% silica and barium nanoparticles 29% composite resin	1907241 A2 LT/14	GC Corporation, Tokyo, Japan
Celtra Duo	DUO	Zirconia-reinforced lithium silicate (ZLS) ceramic	58 % silica, lithium-meta-silicate, lithium-disilicate, phosphate crystals, and 10% zirconia crystals in addition to other minor ingredients	16004062 A2 LT/C14	Dentsply Sirona, York, PA, USA
IPS e.max ZirCAD	ZIR	Tetragonal polycrystalline zirconia partially stabilized with 3 mol-% yttria (3Y-TZP)	88 - 95.5 % ZrO <sub>2</sub>	Z000W8 A2 LT/98.5-18 mm	Ivoclar Vivadent AG, Schaan, Liechtenstein

\*According to technical product information data sheet.

a top support, while the material samples were fixed at the bottom with a self-curing acrylic resin (Imicryl, Konya, Turkey) (Fig. 1). Tests were performed with a load (maximum load capacity of the chewing simulator) 120 N, repetitions of 1 Hz, lateral motion of 0.7 mm, vertical motion of 2 mm, lateral speed of 20 mm/s and vertical speed of 40 mm/s, and 5 years of chewing by 1,200,000 chewing cycles,<sup>31,32</sup> with an additional thermal cycling between 5 and 55°C in every 2 min. One round of this *in-vitro* wear test lasted 9 days 23

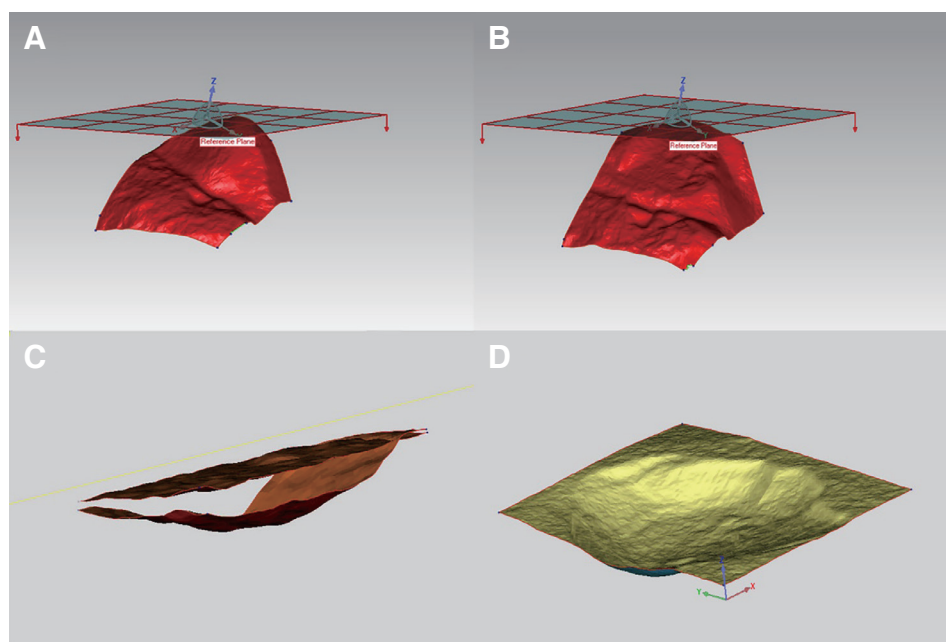


**Fig. 1.** Replacing of dental samples on a top support, and material samples at the bottom support of chewing simulator to mimic the cusp-fossa relationship.

hours 50 minutes.

The cusps and dental ceramic materials were previously estimated from 3D profiles obtained using a 3D laser scanner (LAS-20, SD Mechatronic, Feldkirchen-Westerham, Germany). The start and end points were determined for the surface scans of the material and enamel cusp samples. It has been noted that the mid-point where wear will occur in the material samples and the peaks that will occur in the cusp samples are within the scanning area. The area around these points was scanned as a square area of 4 mm<sup>2</sup> by determining the X and Y coordinates. At the end of the scan, the Z coordinate of the 3D image is added by the system and calculated in mm<sup>3</sup> denoting the volume. The wear area must be within this square. After the wear, the wear area is kept within this area. After the wear test, scanning was repeated, and the 3D profiles were analysed using the Geomagic software program (Geomagic Control, 3D Systems Inc., Rock Hill, SC, USA) and the scans made before and after wear were superimposed to determine the wear volume loss (mm<sup>3</sup>) (Fig. 2) The volume loss was calculated automatically by calculating the difference between the initial volume and the final volume.

Scanning electron microscopy (SEM) images of the worn surfaces (cusps and materials) were obtained



**Fig. 2.** The 3D images of tooth cusp and material samples in Geomagic software (Geomagic Control; 3D Systems Inc.). (A) a tooth cusp sample before chewing simulation, (B) a tooth cusp sample after chewing simulation, (C) the overlap image of a material sample before and after chewing simulation, (D) a material sample after chewing simulation.

using a ZEISS scanning electron microscope (EVO 10, ZEISS, Ostfildern, Germany) with a voltage of 10 kV. The samples were previously coated with a thin film of Au/Pd deposited by sputtering.

Statistical analyses were performed using SPSS software version 25 (IBM® SPSS® Statistics 25.0, New York, NY, USA). Descriptive analyses were presented using means, standard deviations, medians, minimum values, and maximum values for continuous data. The Kolmogorov-Smirnov test was used to determine whether the variables were normally distributed. The homogeneity of the variances between groups was tested using Levene’s test. The wear volume loss of CAD-CAM dental ceramic materials was evaluated using Welch ANOVA test to compare means of more than two groups. Dunnett’s T3 test was performed to test the significance of pairwise differences. The wear volume loss of enamel cusps was evaluated using Kruskal-Wallis test to compare medians of more than two groups. The Mann-Whitney U test was performed to test the significance of multiple comparisons using Bonferroni correction applied to *P* values. Statistical significance was set at *P* < .05.

## RESULTS

The mean, standard deviations (SD), medians, minimum and maximum wear volume loss values of enamel cusps after chewing simulation are shown in Table 2. The Kruskal-Wallis test showed statistically significant differences in the wear volume loss of enamel cusp opposed by different CAD-CAM ceramic materials (*P* < .05). To arrange, cusp/CERA showed

the lowest volumetric loss. Cusp/ZIR and cusp/ENA followed, respectively. Cusp/DUO showed the highest volumetric loss. Even so, the statistically significant difference was found only between cusp/CERA and cusp/DUO (*P* = .007). Pairwise comparisons of enamel cusps by Mann-Whitney U test are shown in Table 3. Cusp/DUO showed a higher wear volume loss than cusp/CERA (Fig. 3A).

The mean, SD, lower bound, and upper bound wear volume loss values of CAD-CAM dental ceramic materials after chewing simulation are shown in Table 4. Welch ANOVA revealed significant differences among the dental ceramic materials (*P* < .05). Multiple comparisons of the materials by Dunnett T3 test are shown in Table 5. The ZIR group showed significantly lower volume loss than the ENA, CERA, and DUO groups (Fig. 3B) (*P* = .001, *P* = .018 and *P* = .005, respectively).

**Table 3.** Pairwise wear volume loss comparisons of enamel cusps

Cusp 1 - Cusp 2	Adj. P-value
Cusp/CERA - Cusp/ZIR	1.000
Cusp/CERA - Cusp/ENA	.062
Cusp/CERA - Cusp/DUO	.007*
Cusp/ZIR - Cusp/ENA	.670
Cusp/ZIR - Cusp/DUO	.094
Cusp/ENA - Cusp/DUO	1.000

Mann-Whitney U test results with Bonferroni adjustment \* *P* < .05 statistically significant.

(ENA; Vita Enamic, CERA; GC Cerasmart, DUO; Celtra DUO, ZIR; IPS e.max ZirCAD)

**Table 2.** Wear volume loss of enamel cusps

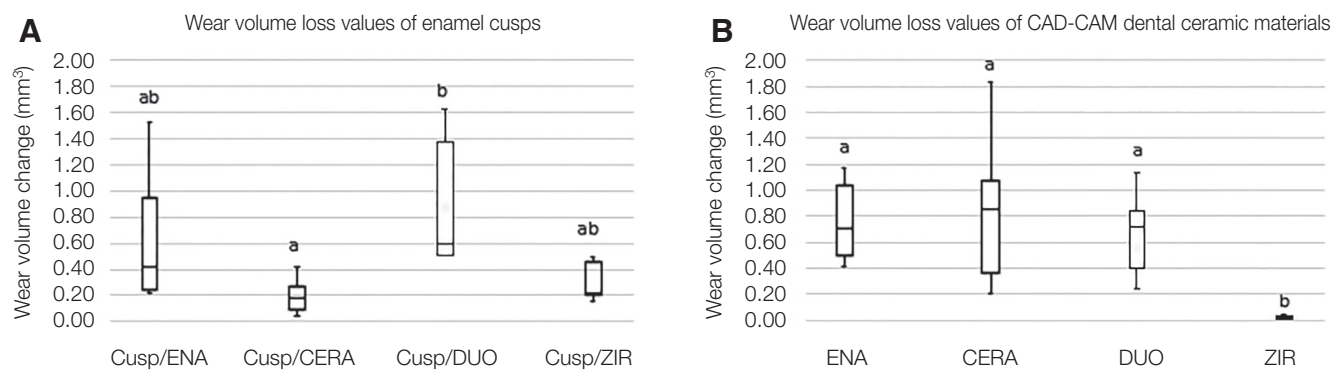
Volume loss (mm <sup>3</sup> )					
Cusp/Material	Mean (SD)	Median	Minimum value	Maximum value	P-value
Cusp/ENA	.60 (0.47)	.41 <sup>ab</sup>	.21	1.52	.004*
Cusp/CERA	.19 (0.12)	.17 <sup>a</sup>	.041	.41	
Cusp/DUO	.82 (0.53)	.59 <sup>b</sup>	.50	1.63	
Cusp/ZIR	.29 (0.13)	.22 <sup>ab</sup>	.15	.49	

Kruskal Wallis test, \* *P* < .05 statistically significant.

SD, standard deviation.

Same superscript letters indicate no statistically significant differences.

(ENA; Vita Enamic, CERA; GC Cerasmart, DUO; Celtra DUO, ZIR; IPS e.max ZirCAD)



**Fig. 3.** (A) Box chart of wear volume loss values of enamel cusps, (B) Box chart of wear volume loss values of CAD-CAM dental ceramic materials.

\*Same superscript letters indicate no statistically significant differences.  
(ENA; Vita Enamic, CERA; GC Cerasmart, DUO; Celtra DUO, ZIR; IPS e.max ZirCAD)

**Table 4.** Wear volume loss of CAD-CAM dental ceramics

Material group	Volume loss (mm <sup>3</sup> )	95% Confidence interval for mean		P-value
	Mean (SD)	Lower bound	Upper bound	
ENA	.74 (0.28) <sup>a</sup>	.50	.97	.000*
CERA	.82 (0.52) <sup>a</sup>	.38	1.27	
DUO	.69 (0.29) <sup>a</sup>	.96	.24	
ZIR	.02 (0.01) <sup>b</sup>	.03	.003	

Welch ANOVA test, \* *P* < .05 statistically significant.  
SD, standard deviation. Same superscript letters indicate no statistically significant differences.  
(ENA; Vita Enamic, CERA; GC Cerasmart, DUO; Celtra DUO, ZIR; IPS e.max ZirCAD)

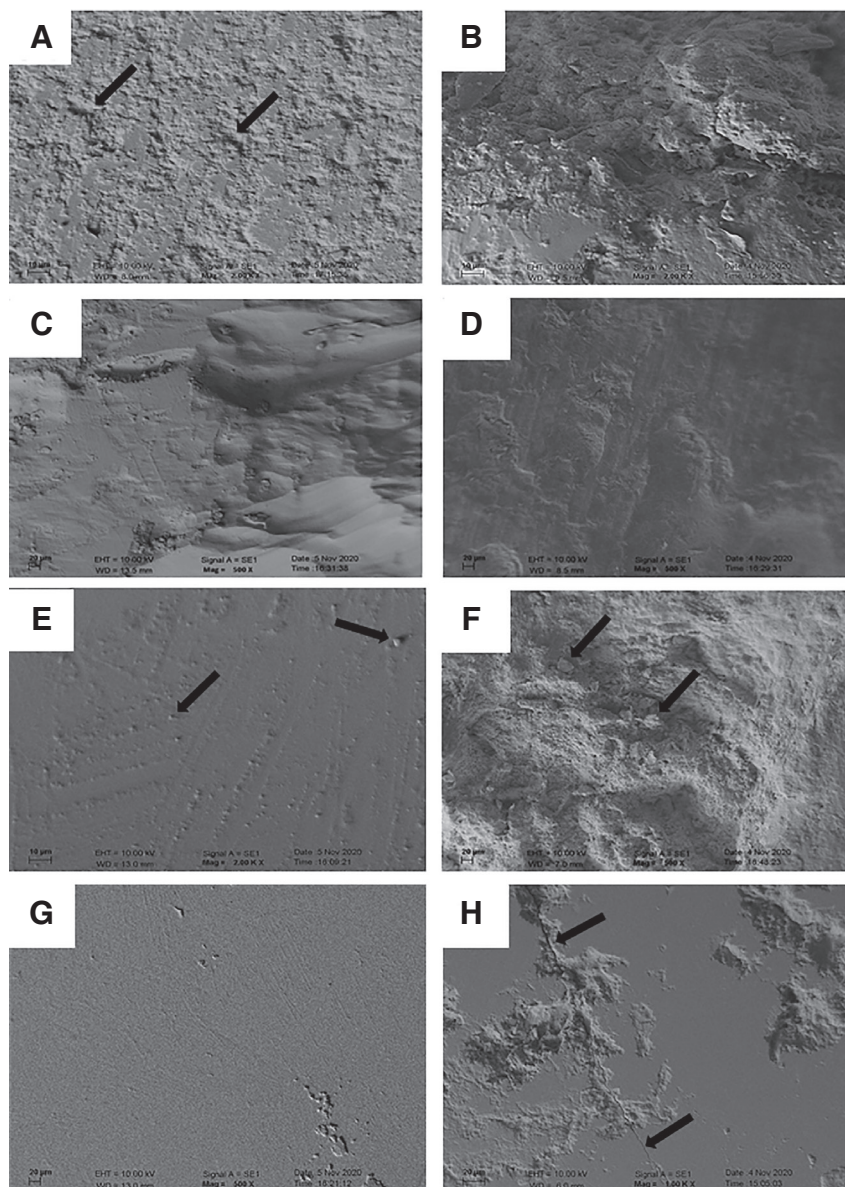
**Table 5.** Multiple comparisons of wear volume loss of CAD-CAM dental ceramics

Material group (1)	Different 3 groups (2)	Mean difference (1-2)	95% Confidence interval		P-value
			Lower bound	Upper bound	
ENA	CERA	-.08	-.75	.58	.998
	DUO	.05	-.40	.51	.999
	ZIR	.71	.37	1.06	.001*
CERA	ENA	.08	-.58	.75	.998
	DUO	.13	-.54	.82	.985
	ZIR	.80	.15	1.45	.018*
DUO	ENA	-.05	-.51	.40	.999
	CERA	-.13	-.82	.54	.985
	ZIR	.66	.25	1.07	.005*
ZIR	ENA	-.71	-1.06	-.37	.001*
	CERA	-.80	-1.45	-.15	.018*
	DUO	-.66	-1.0	-.25	.005*

Dunnett T3 test, \* *P* < .05 statistically significant.  
(ENA; Vita Enamic, CERA; GC Cerasmart, DUO; Celtra DUO, ZIR; IPS e.max ZirCAD)

Regarding the wear mechanisms, SEM images showed that ENA had microcracks throughout the surface of the specimen. Upon closer inspection of wear cracks, residual spaces remaining from breaking polymer pieces out of the resin-matrix were observed (arrows in Fig. 4A). In addition, when the cusp/ENA was observed, there is a roughened and irregular surface with broken out enamel pieces (Fig. 4B). Closer inspection of CERA revealed large wear paths in the area where the opposing enamel contacted and slid against the surface of the specimen by collapsing the ceramic nanoparticles at the tip of the wear track, which were pulled across the resin-matrix (Fig.

4C). Cusp/CERA also showed flattened indentation areas running along the length of the wear track with parallel fine scratches (Fig. 4D). On the other hand, DUO exhibited delamination of the surface as zirconia nanoparticles appeared half and half clinging to the surface of the material (arrows in Fig. 4E). In addition, as a probable result of the abrasive effect of the ejected zirconia crystals, zirconia particles were embedded in the flaking worn surface of the opposing enamel cusp. Cusp/DUO showed these as nanometric irregular particles accumulated at the worn surface (arrows in Fig. 4F). Observation of the wear tracks on the ZIR showed a completely different wear pattern



**Fig. 4.** Scanning electron microscope images. (A) Vita Enamic surface (original magnification  $\times 2000$ ), (B) Cusp/Vita Enamic surface (original magnification  $\times 2000$ ), (C) GC Cerasmart surface (original magnification  $\times 500$ ), (D) Cusp/GC Cerasmart surface (original magnification  $\times 500$ ), (E) Celtra Duo surface (original magnification  $\times 2000$ ), (F) Cusp/Celtra Duo surface (original magnification  $\times 500$ ), (G) IPS e.max ZirCAD surface (original magnification  $\times 500$ ), (H) Cusp/IPS e.max CAD (original magnification  $\times 1000$ ).

\* Arrows serve to illustrate the wear mechanisms of cusp/material and/or CAD-CAM material groups. See the discussion section for detailed information.

with smooth scratches running along the length of the contact site and across the sliding path of the opposing enamel without any fractures or microcracks (Fig. 4G). Cusp/ZIR showed flattened surface characteristic on the contact area; however, it had thinner crack lines and revealed clusters of small chipping areas of enamel pieces (arrows in Fig. 4H).

## DISCUSSION

The wear of CAD-CAM dental ceramic materials and opposing enamel cusps was evaluated. The first null hypothesis that there was no difference between wear volume loss of CAD-CAM dental ceramic materials by chewing simulation under increased loads was rejected, except ZIR. The second null hypothesis that there was no effect of different CAD-CAM dental ceramic materials on the wear of opposing enamel cusps by chewing simulation under increased loads was also rejected, except CERA and DUO.

Loading force is an essential part of an *in-vitro* wear test study. In human mouth, physiologic chewing forces are in the range of 10 - 120 N.<sup>19,26</sup> A load of 49 - 50 N is generally considered to be the mean value of physiological occlusal forces and has been used in various chewing simulation studies.<sup>3,27,33,34</sup> According to a study, higher loads, such as 75 N and 100 N loads, lead to higher wear rates during *in vitro* wear simulation.<sup>29</sup> However, the increase in wear may not be linearly related to the increase in load. The maximum load capacity of the chewing simulator using in this study is 120 N, the upper limit of physiological forces. 120 N was used to simulate the increased chewing forces of patients and aimed to achieve an evaluation of wear performance in 5-year with chewing cycles of 1,200,000.<sup>31,32</sup> It may lead to surface degradation of materials and opposing enamel cusps that can affect wear mechanisms.

The results obtained in the present study showed that ZIR, a tetragonal polycrystalline zirconia, had the lowest volumetric loss among the material groups. Vardhaman *et al.*<sup>10</sup> stated that, under mild wear conditions, in which pull out of grains was the principal mechanism of wear, no microcracks and fractures were identified in zirconia. They evaluated wear stages from mild to severe by 10,000 to 500,000 cycles un-

der 30 N load and characterized the severe wear conditions with uniform crack distribution accompanied by subsurface microcracks throughout the wear area. The wear mechanisms depend on the test conditions such as load, time, and antagonist.<sup>35-38</sup> Considering that 120 N load and 1,200,000 cycles were used in this study, it is possible to observe deep subsurface fractures with simulation of more severe wear. However, since enamel was used instead of spherical zirconia samples as an antagonist in this study, deep microcracks expected to be observed in zirconia were not encountered. The results of a study clearly reveal the favourable wear behaviour of polished zirconia opposed by natural human enamel. The YTZ ceramic exhibited extremely high wear resistance against enamel, and no zirconia wear could be detected after wear simulation.<sup>39</sup> Many studies have also reported that zirconia causes less wear of opposing enamel compared to enamel and other dental ceramics.<sup>27,40-43</sup> Lohbauer and Reich could not detect statistically significant differences between the enamel antagonist and zirconia restorations in terms of mean wear volume loss and maximum vertical loss.<sup>44</sup> Besides, Esquivel-Upshaw *et al.*<sup>45</sup> have claimed that the wear of enamel opposed by zirconia was less than that of metal-ceramics, and enamel at 6 months, but more at 12 months with no statistically significant results. Although a 5-year chewing simulation was performed in this study, the wear volume loss of cusp/ZIR was not also statistically significant. While zirconia appears to cause little volume loss of enamel, it can cause structural defects such as microcrack formation that can lead to problems with long-term use. Wear quantification by measuring the volume loss does not fully reflect wear characteristics, but also requires qualification of the surface properties of a material and enamel by visual microscopic evaluations such as scanning electron microscopy (SEM) to assess wear mechanisms and to determine how future loss may progress.<sup>46</sup>

Regarding the enamel cusps, the significantly lower wear of cusp/CERA compared to that of cusp/DUO might be the reason for specially designed nano-ceramic matrix of CERA that brings high strength and force absorbing manner. Leinfelder<sup>47</sup> assumed that hybrid ceramics exhibit a wear close to natural teeth and show similar deformation capacity. Ac-



According to Mendonca *et al.*,<sup>48</sup> both nano-ceramic and polymer-infiltrated ceramic network (PICN) groups showed lower elastic modulus and hardness values compared to lithium disilicate and zirconia-reinforced lithium silicate (ZLS) ceramics as the lower hardness of hybrid materials also prevents the wear of opposing enamel. While the CERA and ENA materials are included in the same resin-matrix hybrid ceramic category, ENA has a PICN structure. Their structural differences cause varying wear patterns and different effects of the two resin-matrix hybrid ceramic groups on enamel. In ENA, the matrix consisting of a polymer might have resulted in a wear faster than that in a matrix consisting of a ceramic, making it more abrasive on antagonist compared with traditional ceramics.<sup>49</sup> Under SEM, the abrasiveness of ENA on cusp/ENA was apparent (Fig. 4B).

DUO, a ZLS ceramic, exhibited delamination from the material surface due to wear. Exposure of zirconia crystals, which exhibit an abrasive effect, might be a probable result of the higher wear volume loss of cusp/DUO.

The materials used in this study (except zirconia) contain grains bound by a relatively weak glassy or polymeric matrix. Deformation of these bonding phases might have associated with interfacial microcracks that facilitate crystal detachment and dislodgment.<sup>38</sup>

The methodology is based on mimicking the cusp-fossa relationship between flat-surface dental ceramic materials and enamel cusps. It was necessary to use flat-surface material samples to provide a balanced stress distribution in the material, and to exclude possible rotation of the material or the opposing enamel cusp in supports of the chewing simulator. A limitation of this study was that the enamel-to-enamel combination was not used. Though, it was not possible to use flat enamel samples from occlusal enamel as it is not possible to remain in enamel without reaching underlying dentin. A flat-surface enamel sample could be obtained from the distal or mesial part of the tooth. However, distal or mesial enamel could not be used because it was different from occlusal enamel with its microstructure.<sup>50</sup> It was aimed to observe the wear on occlusal enamel, as the contact of the teeth is on the occlusal enamel in the human mouth.

## CONCLUSION

Uniform, polycrystalline structured zirconia (ZIR) showed the lowest material loss due to wear among the other three composite structured material groups (ENA, CERA and DUO) under increased loads. The opposing enamel cusp of zirconia (cusp/ZIR) did not show a statistically significant wear, which could indicate zirconia as an enamel-friendly material, especially under increased loads. However, zirconia causes microstructural defects of enamel with obvious crack lines and clusters of small chipping areas. This can lead to problems in the long-term use. A thoroughly wear qualification is needed. Zirconia involves a different wear mechanism than other composite structured dental ceramics such as ZLS ceramic (DUO) and resin-matrix hybrid ceramic (ENA) which can exhibit an abrasive character on enamel due to their microstructural loss against wear. The resin nano-ceramic (CERA), on the other hand, was the material that showed the lowest enamel wear despite high material loss thanks to its flexible nanoceramic microstructure. The force absorbing manner of nano-ceramics within the bonding phase can provide CERA an enamel-friendly behaviour. ZLS ceramic (DUO) causes more wear of opposing enamel than nano-ceramic (CERA), probably due to the abrasive character of ejected zirconia crystals upon wear.

Overall, it can be concluded that it is especially important to choose the right material for patients with increased chewing forces materials prior to antagonize them with natural tooth. Thus, it is necessary to evaluate the wear characteristics of restorative materials and opposing enamel according to their wear potential.

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