Effect of ionizing radiation and chewing simulation on human enamel and zirconia

Beshr Hajhamid\textsuperscript{a}, Raheleh Mohammad Rahimi\textsuperscript{b}, David F. Bahr\textsuperscript{b}, Grace M. De Souza\textsuperscript{a}\textsuperscript{*}

\textsuperscript{a} Faculty of Dentistry, University of Toronto, Toronto, Canada
\textsuperscript{b} School of Materials Engineering, Purdue University, West Lafayette, USA

Abstract

\textbf{Purpose:} To evaluate the effect of ionizing irradiation on human enamel and zirconia after chewing simulation.

\textbf{Methods:} Twenty enamel and twenty translucent Yttria-stabilized zirconia (Y-PSZ) specimens were divided in 4 groups: Co (control) - no irradiation on enamel cusps/opposing zirconia slabs; E70 - irradiated (70 Gray) enamel cusps/opposing irradiated enamel slabs; Z70 - irradiated zirconia cusps/opposing irradiated zirconia slabs; EZ70 - irradiated enamel cusps/opposing irradiated zirconia slabs. Cusps were abraded against slabs in a chewing simulator (CS - one million cycles, 80 N, artificial saliva, 37°C). Wear and roughness of zirconia and enamel were analyzed using a stylus profilometer. The abraded enamel was analyzed by Electron probe micro-analyzer (EPMA) and zirconia was characterized by nanoindentation and X-ray diffraction. One-way analysis of variance (ANOVA) and Tukey test were used for analysis of wear, Repeated Measures and Bonferroni test for roughness, and hardness and modulus values were compared using Wilcoxon Mann Whitney rank sum test (overall 5% significance).

\textbf{Results:} Significantly higher volume loss was presented by cusps in the E70 group \( (p<0.001) \). Wear was similar between Co and EZ70 groups. There was no significant effect of irradiation on roughness of enamel or zirconia slabs \( (p=0.072) \). Irradiated Y-PSZ slabs had significantly higher hardness and modulus than non-irradiated ones and a 7% increase in m phase content was detected after irradiation.

\textbf{Conclusions:} The opposing surface characteristics played a more significant role on enamel wear than did ionizing radiation. However, irradiation affects Y-PSZ crystalline composition, hardness and modulus of elasticity.

\textbf{Keywords:} Phase transformation, Ionizing irradiation, Surface topography, Nanoindentation, Volumetric loss.

1. Introduction

Head and neck cancer is considered a worldwide health problem, with more than 550,000 people affected annually \cite{1}. Radiotherapy (RT) is frequently used for the treatment of malignancies in the head and neck region and significantly improves the patient survival rate \cite{2, 3}. However, RT can damage soft tissues and structures around the target area such as the salivary glands, bones, oral mucosa and dentition \cite{4, 5}. Previous studies reported that RT can compromise the function of the salivary glands resulting in decreased salivary flow and changes in saliva composition \cite{6}. Mucositis, osteoradionecrosis and radiation caries are also often reported \cite{6-8}. In spite of the high survivability of patients treated with RT, their quality of life may be significantly compromised due to the high incidence of radiation related caries (RRC), which affect approximately 25% of the patients exposed to RT, often resulting in tooth loss \cite{9, 10}. RRC is characterized by rapid progression and linked to xerostomia, due to the permanent effect of irradiation on the salivary glands \cite{11, 12}. In vitro studies have further shown that irradiation promotes changes on the dentin-enamel junction, crystalline structure of hydroxyapatite and, as a consequence, on the mechanical properties of enamel and dentin \cite{10, 13}. Some of the mechanical properties affected are compressive and tensile strength and hardness \cite{6, 8, 13, 14}.

The standard treatment for head and neck cancer is a final accumulated dose between 40-70 Gray (Gy), which is fractionated in doses of 2 Gy/day, 5 days/week \cite{6, 15}. When the interaction between irradiation doses and tooth damage is considered, results are conflicting. For example, one study found significant changes in enamel microhardness between 10 and 30 Gy but no effect with higher doses (40-60 Gy) \cite{10}. In a similar way, changes in dentin microhardness were reported as dose-related and occurred mainly in the middle dentin \cite{10}. Another study demonstrated that the threshold for permanent nanomechanical changes in enamel structure is around 30-50 Gy \cite{16}. Regardless of the dose range for changes in enamel and dentin properties, the maximum dose clinically applied is 70 Gy, which has been strongly associated with permanent damage of the salivary glands \cite{12, 17}.

Yttria-partially stabilized zirconia (Y-PSZ) is recommended for the restoration of severely damaged teeth and for the prosthetic rehabilitation of patients due to characteristics such as tooth-like appearance \cite{18} and superior mechanical performance when compared to other ceramics \cite{19}. Zirconia has three temperature-dependent
crystalline phases: monoclinic, tetragonal, and cubic [20]. Yttria is added to the composition of zirconia to stabilize the tetragonal phase at room temperature. However, surface roughness associated with long-term exposure of Y-PSZ to the oral environment is a concerning factor. This roughness may be a consequence of two factors: the metastability of the tetragonal phase, and the effect of often needed occlusal adjustments after insertion of an indirect restoration [19, 21]. Transformation of the tetragonal phase back to monoclinic (t-t transformation) causes a local granular expansion of 3–4 vol% [22, 23], and surface grain pull-out of transformed monoclinic grains also maximizes roughness [24]. Occlusal adjustments are also critical because of the uneven surface created by diamond burs [25]. Studies evaluating the effect of intra-oral polishing after zirconia restoration adjustment are not conclusive up to now [19, 22, 25]. The most critical consequence of surface roughness is the wear of the opposing substrate, and previous studies mentioned that polished zirconia causes less wear to the opposing enamel than enamel itself [26, 27], and then glazed or glazed/polished zirconia [19, 22, 28]. When the wear of gold, composite resin, zirconia and enamel opposing themselves was evaluated, the least wear volume recorded was for zirconia samples opposing zirconia cusps [29].

Studies have focused on the effect of irradiation on mechanical properties of enamel, dentin and direct restorative materials [6, 7, 16, 30], but the interaction between irradiated enamel and Y-PSZ restorations has not been investigated so far. This is critical since the outstanding mechanical properties of Y-PSZ, combined with possible surface phase transformation, may cause permanent damage to the natural enamel affected by RT. Therefore, the aim of this study was to investigate the effect of RT on the surface characteristics of human enamel and Y-PSZ. The null hypotheses for this study were:

1. The opposing substrate has no effect on wear of enamel or Y-PSZ;
2. Irradiation has no effect on the surface characteristics of Y-PSZ;
3. Irradiation has no effect on the surface characteristics of enamel.

2. Materials and methods

2.1. Samples preparation

After approval from the University Research Oversight and Compliance Office (protocol preference #34680), 11 bicuspid teeth extracted for reasons not related to this study were collected and stored in 10% neutral buffered formalin solution [31]. The teeth had their roots removed 1 mm below the cementum-enamel junction (CEJ) in 10% neutral buffered formalin solution [31]. The teeth had their roots removed 1 mm below the cementum-enamel junction (CEJ) with a diamond blade (15 LC, Buehler, Lake Bluff, IL, USA) in a saw (Isomet 1000, Buehler) under water cooling.

The lingual and buccal cusps of 8 bicuspid teeth were separated parallel to the tooth long axis under the central occlusal groove using a diamond blade and 16 cusps were obtained. For the preparation of flat enamel specimens, 3 bicuspid teeth were sectioned 3 mm away from the proximal surfaces and parallel to the tooth long axis to generate 5 enamel slices [32]. The external surfaces of enamel slabs were wet polished with 400-, 600- grit silicon carbide papers and 6 µm followed by 3 µm diamond paste (4 min. each) using a rotary grinder/polisher (Metaserv 250 Grinder/Polisher, Buehler) at a speed of 300 rpm.

Twenty zirconia specimens were prepared by cutting a pre-sintered block of 3 mol % Yttria-stabilized zirconium dioxide (IPS Emax Zircon, Ivoclar Vivadent AG, Schaan, Germany) with diamond-embedded blade in a saw to obtain 8.5x8 mm slices with 2.5 mm thickness. After sintering the samples according to manufacturer’s instructions, one surface of each sample was polished as previously described for the enamel slabs. The final dimension of the specimens was 6.5x 6 x 2 mm due to 20 to 25% sintering densification and polishing.

For the preparation of zirconia cusps, five of the previously polished zirconia specimens were prepared using a diamond reverse cone hollow bur under high speed to obtain a cusp-like shape. All zirconia samples were cleaned ultrasonically in acetone for 5 minutes and air-dried [33]. Zirconia specimens were annealed in a laboratory chamber furnace (CWF1300, Carbolite, Hope Valley, UK) to relieve compressive stress generated by the sample preparation process [34].

2.2. Irradiation procedures:

Enamel and zirconia specimens were distributed (n=5) as follows:

- Co: control, no irradiation on either enamel cusps or antagonist zirconia slabs;
- E70: 70 Gy irradiation applied on enamel cusps and antagonist enamel slabs;
- Z70: 70 Gy irradiation applied on zirconia cusps and antagonist zirconia slabs;
- EZ70: 70 Gy irradiation applied on enamel cusps and antagonist zirconia slabs.

Irradiation was delivered using parallel opposed beams (6 MV field size of 30x30 cm2, Elekta Infinity Linac, Palo Alto, CA, USA) at the Department of Radiation Oncology, Princess Margaret Cancer Center, Toronto, ON, Canada. Irradiated samples were fully submerged in a distilled water phantom and received half of the irradiation dose (35 Gy) from 0° angle and half of the dose from 180°. All enamel and zirconia specimens were stored in distilled water at 37°C until further tests were applied.

2.3. Cheving simulation

All zirconia and enamel specimens were embedded in polymethylmethacrylate (PMMA) and inserted into a metallic holder. The slabs were fixed to the base and the cusps were stabilized to the upper arm of a chewing simulator (Mechatronik CS 4.4, SD Mechatronik GMBH, Feldkirchen-Westerham, Germany). Four cusps and four slabs were cycled per time under the following conditions: artificial saliva [35] at 37°C, 80 N load applied for one million cycles with a 2 mm horizontal path using a speed of 60 mm/min.

2.4. Wear and roughness analysis

Enamel and zirconia specimens were scanned with a contact profilometer (Dektak XT profilometer, Bruker, Minneapolis, MN, USA) before and after chewing simulation for quantification of wear of the cusps and roughness of the antagonist slabs. A reference point was marked on each cusp incline before the measurement (permanent marker) as a starting point. Three guiding lines were drawn on the surface of the acrylic holder to use as reference points to ensure the same area of measurement before and after chewing simulation. A surface profilometer with a resolution of 0.666 µm scanned an area of 2.5 mm x 1 mm, with 40 traces and a distance of 25 µm between traces to measure the volume of each cusp. The same profilometer was used to analyze the roughness of slabs by scanning a 2 x 2 mm² area located at the center of each sample. Ten scans were obtained for each sample with 200 µm distance between scans.

2.5. Nanoindentation

Hardness and reduced modulus of one irradiated and one control zirconia sample were evaluated using nanoindentation (Hysitron Tribolindenter 950, Bruker). For that purpose, samples were cleaned in acetone (ultrasonic bath for 10 min) and a Berkovich indenter tip with a nominal radius of 300 nm, calibrated using a fused quartz standard, was used to perform 9 indents on the surface of each sample. A quasi-static load function including 6 partial loading-unloading segments was applied for each indentation. A grid of 3 x 3 indents with a 20 µm spacing between individual indents was defined to ensure no interaction between indentations. The hardness and reduced
modulus values were determined using the Oliver-Pharr method [36].

2.6. X-ray diffraction

One irradiated and one control zirconia were analyzed using X-ray diffraction (XRD). Patterns were obtained with a Philips XRD system (ICDD Powder Diffraction File data base and Rietveldt Refinement software, Markham, ON, Canada), between 251 and 651 (2θ) with Kα radiation. Scans were performed at 40 kV, 40 mA, step size of 0.0021/step and a scan time of 2.5 s/step: m and t content were obtained for each pattern based on Relative Intensity Ratio (RIR) [37].

2.7. Scanning Electron Microscopy/ Electron probe micro-analyzer (SEM/EPMA)

Abraded enamel cusps topography and composition were evaluated after chewing simulation (CS) using an Electron probe micro-analyzer (EPMA, JXA 8230, Joel, Peabody, MA, USA). Samples were sputter-coated with carbon prior to the test. An overview SEM image of the abraded enamel surface was obtained. The EPMA map of the elements Calcium (Ca), Oxygen (O), Phosphorus (P) and Zirconia (Zr) was examined in order to detect the possible Zr deposits on the abraded enamel surface. An accelerated voltage of 15 kV was used to minimize beam penetration while maintaining good analytical sensitivity. A 1 µm probe with current of 50 nm and pixel step of 5 µm was used for mapping. A tilted stage was used to dissociate Zr from P peaks, in order to have a qualitative indicator of the presence of Zr across the mapped area. The scale for all maps displayed blue/black indicating the lowest concentrations and red indicating the highest concentrations.

2.8. Data analysis

One-way analysis of variance (ANOVA) and Tukey post–hoc (SPSS INC) test were used to evaluate the effect of irradiation on cusp wear. Mixed repeated measures test associated with Bonferroni correction were performed to evaluate the effect of irradiation on roughness of slabs before and after CS. Wilcoxon Mann Whitney was used to analyze the effect of irradiation on hardness and modulus of Y-PSZ. An overall significance of 5% was determined.

3. Result

3.1. Wear and roughness

ANOVA indicated that there was a significant effect of irradiation (p<0.001) on cusp volume loss after CS (Table 1). Tukey test results showed that irradiated enamel cusps antagonist enamel slabs exhibited higher wear than the cusps (irradiated or not) abraded against Y-PSZ slabs.

After checking the variance of covariance (p=0.164), repetitive measures test showed no significant effect of irradiation and CS on surface roughness (p=0.072). Overall, control (non-irradiated) enamel abraded against zirconia slabs presented lower roughness and irradiated zirconia abraded against zirconia slabs presented higher roughness, but no significant differences were detected (Table 2).

3.2. Nanoindentation

Fig. 1. shows typical load-depth curves of both samples. The hardness and modulus were assessed at each unloading position. The loads were chosen to ensure no fracture would occur within the experimental conditions and no evidence of fracture was found after indentation, suggesting the measured materials properties are reflective of the bulk material. Y-PSZ samples presented an increase in surface hardness and modulus after irradiation. The modulus of the irradiated sample was approximately 19% higher than the control sample while the hardness increased by approximately 25% after irradiation. Table 3 shows the mean and standard deviation of the nanoindentation data from both samples, irradiated and non-irradiated, over the entire range of loads.

3.3. X-ray diffraction

XRD spectra for control and irradiated (Fig. 2) specimens indicate an increase in m phase content as a consequence of irradiation (control 13%, irradiated 20%), when the pattern was analyzed based on relative intensity ratio (RIR)

3.4. SEM/EPMA

Analysis of abraded enamel cusps after irradiation and CS revealed surface structure and composition compatible with hydroxyapatite elements, with similar pattern of O, P and Ca in enamel cusps. When enamel abraded against enamel was compared to enamel abraded against zirconia, the latter showed deposition of zirconium elements on its surface EZ 70. And CO groups. The map of non-irradiated enamel cusp opposing non-irradiated zirconia slabs illustrated higher content

![Table 1. Mean and standard deviation (SD) for enamel cusp volumetric loss after CS (different lowercase letters indicate significant differences at p<0.001 by one-way ANOVA).](image)

| Group  | Percentage of volumetric loss (±SD) |
|--------|-----------------------------------|
| Control     | 27.38 (10.0) |
| E70      | 50.69 (12.7) |
| Z70     | 14.85 (2.1) |
| EZ70     | 27.1 (10.1) |

![Table 2. Mean and standard deviation for zirconia Ra (µm) before and after CS.](image)

| Group  | Before CS (±SD) | After CS (±SD) |
|--------|----------------|---------------|
| Control     | 2.66 (1.1) | 3.12 (1.1) |
| E70      | 5.7 (2.8)  | 5.24 (3.1)  |
| Z70     | 6.52 (4.6) | 7.63 (4.4) |
| EZ70     | 4.63 (3.1) | 5.06 (3.2) |

![Table 3. Mean and standard deviation (SD) for surface hardness (GPa) and reduced modulus (GPa) (different superscript letters indicate significant difference at <0.05 by Wilcoxon Mann Whitney rank sum test).](image)

| Group  | Modulus (±SD) | Hardness (±SD) |
|--------|---------------|---------------|
| Non-irradiated | 116.57 (21.9) | 8.67 (1.3) |
| Irradiated   | 138.33 (15.8) | 11.03 (1.0) |
of Zr than irradiated enamel cusp opposing irradiated zirconia slabs (Fig. 3 and 4).

4. Discussion

Radiotherapy in a total dose of 70 Gy is frequently used for the treatment of head and neck cancer lesions [6, 38]. The standard irradiation treatment consists of daily fractionated doses of 2 Gy. The use of fractionated doses is based on a principle called "5Rs": repair, redistribution, reoxygenation, regeneration and radiosensitivity [39]. Since the present study did not evaluate any biological material, irradiation was applied in a single dose, similarly to a previous study [40].

The selection of a restorative material for the restoration of teeth prior to and after irradiation is based on personal clinical experience [41], but non-metallic restorations are recommended for patients who will receive radiotherapy to minimize the occurrence of mucositis. Mucositis adjacent to metal restorations due to dose scattering and localized dose enhancement has been observed [42]. A negative effect of ionizing irradiation on microhardness of both enamel and dentin has also been reported [14, 16]. Although zirconia is a material very frequently used for the oral rehabilitation of patients, dose scattering, surface mechanical properties or surface topography of restoration after irradiation have not been investigated.

The results of this study showed that the first null hypothesis, which stated that the opposing substrate has no effect on wear of enamel or Y-PSZ, should be rejected. Irradiated enamel cusp opposing irradiated enamel slabs presented significantly more wear than either irradiated or non-irradiated enamel cusps opposing zirconia slabs. Regardless of irradiation, the literature has shown significantly higher wear of enamel opposing enamel than when one of the substrates is made of zirconia [43, 44]. A previous study evaluating the sliding wear behavior of ceramics showed that zirconia has the lowest rate of wear compared to enamel, lithium disilicate, feldspathic ceramic and ceramic-polymer composites [45]. The findings of another in vitro study suggested that zirconia caused less wear to primary tooth enamel than different ceramic materials or enamel itself [46].

The second null hypothesis, which stated that irradiation has no effect on the surface characteristics of Y-PSZ, was partially rejected. Although there was no significant effect of irradiation on roughness of zirconia, the hardness and modulus of Y-PSZ significantly increased after irradiation. The XRD results also showed more m phase content in irradiated zirconia compared to non-irradiated zirconia. To minimize roughness prior to testing, all slabs in this study were polished up to 1 µm to generate a smooth baseline surface [47]. Zirconia polished slabs were also exposed to an annealing cycle prior to irradiation and
Zirconia causes granular volumetric expansion [16]. We hypothesize that this granular expansion increased compressive stress in the grain boundaries, offering more resistance to the penetration of the nanoindenter, affecting the surface mechanical properties measured in the nanoscale. Previous studies evaluated the effect of different ion’s irradiation on the hardness of zirconia [50, 51]. Although there was no difference in Y-PSZ hardness after Xe irradiation [52], surface hardness increased after irradiation with Pb ions [51].

The effect of irradiation on zirconia-based materials has been investigated in other studies and has been associated with generation and saturation of oxygen vacancies. Oxygen vacancies can be produced by different irradiation temperatures [53]. Lian et al. reported that ion beam-irradiation induced grain growth for both tetragonal (t) and cubic (c) phases in Y-PSZ materials [50] and the compressive stress associated with grain growth can potentially maximize t-m transformation [49]. Although the irradiation used in this study is different from the one used in previous studies [49, 50, 53], a similar effect was observed in terms of crystalline structure of Y-PSZ.

The results of the present study failed to reject the third null hypothesis, which stated that irradiation had no effect on the surface characteristics of enamel. Ionizing irradiation had no effect on the wear pattern of enamel after chewing simulation. Irradiated enamel cusps antagonist irradiated zirconia slabs presented similar wear pattern to non-irradiated enamel cusps antagonist non-irradiated zirconia slabs. To further analyze the effect of irradiation on enamel structure, samples were analyzed with EPMA. The surface of non-irradiated enamel cusp abraded against zirconia showed higher deposition of Zr in comparison to irradiated enamel cusp abraded against irradiated zirconia, which may be a consequence of the higher hardness of zirconia after irradiation being, therefore more resistance to wear abrasion.

The results of this study showed that RT has an effect on Y-PSZ crystalline structure and nanoscale mechanical properties. However, the wear pattern of enamel cusps was not affected by irradiation when opposing either enamel or zirconia. Further investigations on the interaction between irradiation, mastication and other challenges present in the oral environment. Additionally, only one zirconia brand was used and, thereafter, results cannot be extrapolated to other zirconia-based materials with dissimilar characteristics, such as grain size, translucency and composition. Lastly, the investigation of the association of shear forces caused by mastication and fractionated doses is also of interest.

5. Conclusion

Within the limitations of the current study, it was possible to conclude that:
1. 70 Gy irradiation has no effect on wear of enamel abraded against zirconia;
2. 70 Gy irradiation causes changes to zirconia’s microstructure and mechanical properties;
3. Zirconia is less deleterious to the wear of enamel than enamel itself.

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Conflict of interest

The authors declare that there is no conflict of interest for this project.
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