Graded Ultra-Translucent Zirconia (5Y-PSZ) for Strength and Functionalities

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Abstract

Ultra-translucent zirconias are drawing immense attention due to their fascinating esthetic appearance. However, the high translucency came at the expense of diminishing strength along with the reduced ability of transformation toughening due to the increased cubic zirconia content. We aim to address these issues by infiltrating glass on the surface of an ultra-translucent zirconia (5Y-PSZ). Glasses of different shades can be used and the resulting graded glass/zirconia layer is expected to improve the material's flexural strength without compromising its esthetics. We also aim to elucidate how clinically relevant surface treatments—namely, air abrasion, glazing, or polishing—affect the fracture resistance of these zirconias with a high cubic content. All surface treatments were performed on bar-shaped ($2 \times 3 \times 25 \text{ mm}^3$) and plate-shaped ($12 \times 12 \times 1 \text{ mm}^3$) specimens, which were then subjected to a 4-point bending test and translucency measurements, respectively. 5Y-PSZ proved to be significantly more translucent than 3Y-TZP but also much weaker. Our hypothesis was accepted, as the strength of the glass-infiltrated ultra-translucent 5Y-PSZ ($582 \pm 20 \text{ MPa}$) is over 70% higher than its uninfiltrated counterpart ($324 \pm 57 \text{ MPa}$). Its strength is also over 25% higher than the highly polished 5Y-PSZ ($467 \pm 38 \text{ MPa}$). In addition, the translucency of 5Y-PSZ (translucency parameter $[TP] = 34$, contrast ratio $[CR] = 0.31$) is not affected by glass infiltration ($TP = 34$, $CR = 0.32$) when the residual surface glass is removed by gentle polishing using 6- and then 3- μm diamond grits. Finally, both air abrasion and the presence of a glaze layer on the tensile surface decreased flexural strength significantly, being 274 ± 55 and $211 \pm 21 \text{ MPa}$, respectively. With a combined high strength and translucency, the newly developed glass-infiltrated 5Y-PSZ may be considered a suitable material for next-generation, damage-resistant, and esthetic dental restorations.

Keywords: surface glass infiltration, graded zirconia, esthetics, flexural strength, air abrasion (sandblasting), glazing

Introduction

Prosthetic dentistry is undergoing a paradigm shift from metal-ceramic restorations to all-ceramic prostheses, primarily for esthetics and biocompatibility (Zhang and Kelly 2017). However, ceramics are brittle and susceptible to fracture. Therefore, the development of strong yet esthetic ceramic materials has been a recent focus. Traditionally, dental zirconias are predominantly made of fine tetragonal zirconia crystals with small amounts of yttria stabilizer (i.e., 3Y-TZP). While exceptionally strong, 3Y-TZP ceramics have poor translucency. The current method to improve zirconia translucency is to introduce an optically isotropic cubic (c) phase into tetragonal (t) zirconia (Zhang and Lawn 2018). This has been achieved by using a higher yttria content to produce partially stabilized zirconias, 4 mol% (4Y-PSZ) or 5 mol% (5Y-PSZ). However, the c-phase diminishes the stress-induced transformation toughening of zirconia, resulting in decreased strength and toughness. Therefore, the most translucent 5Y-PSZ materials are somewhat restricted to single-unit crowns and short-span fixed dental prostheses (FDPs) in the anterior zone. To fully capitalize on the ultra-translucency advantage of 5Y-PSZ, it is necessary to increase the strength of these materials.

It is well documented that the conventional etching-silane treatment is not effective for zirconia (Blatz et al. 2018). Thus, appropriate surface modifications are necessary. Traditionally,

air abrasion is used to modify the intaglio surface of zirconia for mechanical retention (Kosmac et al. 1999). For 3Y-TZPs, air abrasion has a 2-fold effect: producing a protective surface compressive layer due to $t \rightarrow m$ (monoclinic) transformation and work hardening while introducing strength-limiting surface flaws (Zhang et al. 2006). Thus, air abrasion can either reduce (Guess et al. 2010; Ozcan et al. 2013) or increase (Kosmac et al. 2008; Scherrer et al. 2011) the flexural strength of 3Y-TZP, depending on the type and size of abrading particles, the air pressure applied, and the thermal history. However, the effect of air abrasion on the flexural strength of 5Y-PSZ has not been studied extensively.

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Traditionally, glazing is applied to the external surface of monolithic zirconia prostheses for better esthetics. More recently, glazing has been applied to the intaglio surface of zirconia prostheses for better resin bonding (Khan et al. 2017). In dental crowns and FDPs, the main areas subject to tensile stresses are the intaglio surface, cervical margin, and connectors. Therefore, the glazed surface (cameo or intaglio) can experience tensile stresses. Unfortunately, glazing has been found to diminish the flexural strength of 3Y-TZP (Yener et al. 2011; Lai et al. 2017). The question then arises: what effect does glazing have on the flexural strength of 5Y-PSZ?

Consequently, this study aims to elucidate the effects of glazing, air abrasion, and polishing on the flexural strength of the newly developed ultra-translucent 5Y-PSZ materials. In addition, we propose to improve the strength of 5Y-PSZ by surface infiltration with in-house feldspathic glasses. We hypothesize that glazing and air abrasion can have detrimental effects, whereas glass infiltration has propitious effects on the strength of 5Y-PSZ.

Theory

Translucency Parameter and Contrast Ratio

The translucency parameter (TP) of the material can be determined by the color difference between the specimen on black (B) and white (W) backgrounds (Kaizer et al. 2017):

$$TP = \sqrt{(L_B^* - L_W^*)^2 + (a_B^* - a_W^*)^2 + (b_B^* - b_W^*)^2}, \quad (1)$$

where L^* , a^* , and b^* refer respectively to the lightness, redness to greenness, and yellowness to blueness coordinates in the CIE color space (CIE 2004).

CR is the ratio of spectral reflectance of the light (Y) of the specimen on black (Y_B) and white (Y_W) backgrounds (Nogueira and Della Bona 2013):

$$CR = \frac{Y_B}{Y_W} \quad (2)$$

$$Y = \left(\frac{L^* + 16}{116} \right)^3 Y_n. \quad (3)$$

The specified white stimulus (Y_n) is normally chosen since it is a perfect reflecting diffuser, that is, $Y_n = 100$. CR values range from 0.0 (for a transparent material) to 1.0 (a totally opaque material).

Maximum Stress in Simply Supported Multilayer Beams

In a 4-point long beam flexural test (Fig. 1a), the axial force P produces a maximum bending moment M in the beam portion between upper load points (Chai et al. 2014):

Figure 1. The 4-point flexural test used for long beams of monolithic, bilayer, and trilayer configurations.

$$M = \frac{P(L-S)}{4}, \quad (4)$$

where L and S denote distances between lower and upper supporting pins.

The bending stress σ along the direction of the load axis can be derived from

$$\sigma = \frac{My}{I}, \quad (5)$$

where y is the distance from the neutral axis. I is the moment of inertia around the neutral axis.

Thus, the maximum tensile stress or flexural strength of a beam can be calculated by defining y and I as follows:

For monolithic beams (Fig. 1b):

$$y_m = \frac{t}{2}, \quad (6a),$$

$$I_m = \frac{wt^3}{12}, \quad (6b),$$

where w and t are beam width and thickness, respectively.

For bilayer beams (Fig. 1c) (Figueiredo et al. 2017):

$$y_{bi} = \frac{\frac{t_z^2}{2} + \frac{E_g}{E_z} \left(\frac{t_g^2}{2} + t_g t_z \right)}{t_z + \left(\frac{E_g}{E_z} \right) t_g}, \quad (7a)$$

$$I_{bi} = \frac{1}{12} \left(\frac{E_g}{E_z} \right) w t_g^3 + \left(\frac{E_g}{E_z} \right) w t_g \left(t_z + \frac{t_g^2}{2} - y_{bi} \right)^2 + \frac{1}{12} w t_z^3 + w t_z \left(\frac{t_z}{2} - y_{bi} \right)^2. \quad (7b)$$

For trilayer beams (Fig. 1d) (Della Bona et al. 2003):

$$y_{tri} = \frac{\frac{t_z^2}{2} + \frac{E_g}{E_z} \left(\frac{t_g^2}{2} + t_g t_z \right) + \frac{E_r}{E_z} \left(\frac{t_r^2}{2} + t_r t_g + t_g t_z \right)}{t_z + \left(\frac{E_g}{E_z} \right) t_g + \left(\frac{E_r}{E_z} \right) t_r}, \quad (8a)$$

$$I_{tri} = \frac{1}{12} \left(\frac{E_r}{E_z} \right) w t_r^3 + \left(\frac{E_r}{E_z} \right) w t_r \left(t_z + t_g + \frac{t_r}{2} - y_{tri} \right)^2 + \frac{1}{12} \left(\frac{E_g}{E_z} \right) w t_g^3 + \left(\frac{E_g}{E_z} \right) w t_g \left(t_z + \frac{t_g}{2} - y_{tri} \right)^2 + \frac{1}{12} w t_z^3 + w t_z \left(\frac{t_z}{2} - y_{tri} \right)^2, \quad (8b)$$

where E represents the Young's modulus of the material. The subscripts z , g , and r denote the thickness of the zirconia, graded or glaze, and residual glass layers, respectively.

Experimental

Specimen Preparation

Ultra-translucency zirconia pucks (98 mm, Luxisse+; Heany Industries), produced using Tosoh Zpex Smile 5Y-PSZ powders, were sectioned into plates and beams using a low-speed diamond saw under water irrigation. All specimens were ground with 320-grit (32–36 μm) SiC abrasive paper, producing a computer-aided design and computer-aided manufacturing (CAD/CAM)-like surface, and dried in a desiccator for a week at room temperature. Sintering was conducted in a box furnace, following the manufacturer's recommendations: heating from room temperature to 1,000°C at 8°C/min and then from 1,000°C to 1,450°C at 2°C/min, dwelling at 1,450°C for 2 h, followed by natural cooling back to room temperature. The final dimensions of the sintered specimens were 12 $\times$ 12 $\times$ 1 mm³ for plates and 25 (length) $\times$ 3 (width) $\times$ 2 (height) mm³ for beams.

To study the influence of clinically relevant surface treatments on the optical and mechanical properties of ultra-translucent 5Y-PSZ, sintered specimens were subjected to the following:

- Polishing with diamond discs to a 0.5- μm finish (5Y-PSZ-P)
- Air abrasion with 50- μm alumina particles at 2 bar pressure for 20 s (5Y-PSZ-AA)
- Glazing with the Zenostar staining and glazing system (5Y-PSZ-G)
- A group of sintered specimens with a CAD/CAM-like surface (i.e., soft-ground with 320-grit SiC abrasive paper) was used as control (5Y-PSZ-Ctrl)

To investigate the effect of glass infiltration on the mechanical and optical properties of 5Y-PSZ, specimens with a CAD/CAM-like surface that is identical to the 320-grit soft-ground 5Y-PSZ-Ctrl surface were selected for glass infiltration. Three glass-infiltrated (GI) material systems were prepared:

- Shade yellow (5Y-PSZ-YGI and 5Y-PSZ-YGI-g)
- Shade white (5Y-PSZ-WGI and 5Y-PSZ-WGI-g)
- Shade mixed: a mixture of equal-weight portions of white and yellow glasses (5Y-PSZ-MGI and 5Y-PSZ-MGI-g)

Note: groups ending with “-g” contained an external residual glass layer.

The final compositions by weight of the in-house developed infiltrating feldspathic glasses according to X-ray fluorescence analysis were as follows ($n = 3$):

White: 66.2% SiO₂, 11.2% Al₂O₃, 10.2% Na₂O, 7.9% K₂O, 3.0% CaO, and balance Ba, Ce, Zr, Sn, Y

Yellow: 65.5% SiO₂, 11.7% Al₂O₃, 10.0% K₂O, 7.3% Na₂O, 3.0% CaO, and balance Zr, Ti, Sn, Y, Ce

The coefficient of thermal expansion (CTE) of both yellow and white glasses—measured by a dilatometer (L75VD1600; Linseis)—was $\sim 10.4 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ within 25 to 450°C at a heating rate of 5°C/min ($n = 3$) (Zhang and Kim 2009). The T_g temperature for the glasses was measured by thermogravimetric analysis (SDT Q600; TA Instruments) within 25 to 1,500°C at a 10°C/min heating rate. The values were 887°C and 863°C for yellow and white glasses, respectively.

Glass infiltration followed a previously described technique (Zhang and Kim 2009). Briefly, bars and plates were first presintered at 1,350°C for 1 h. A powdered glass slurry with 30 wt% solids was uniformly applied to the surface of the specimen using a standard enameling technique. Glass infiltration and densification were carried out simultaneously at 1,450°C for 2 h with a heating rate of 14°C/min.

All surface treatments (i.e., glass infiltration, glazing, air abrasion, and polishing) were performed on one side of the specimen only.

Compositional and Microstructural Analyses

The crystalline phase assembly of 5Y-PSZ and surface-treated 5Y-PSZs ($n = 3$) was characterized by X-ray diffraction (XRD; PANalytical X'Pert) with nickel-filtered Cu K α radiation,

operating at 45 kV and 40 mA. Scans were performed over the 2θ range of 25° to 80° at a scan rate of $0.2^\circ/\text{min}$ and a step size of 0.02° . Quantitative phase analysis was carried out using the Rietveld refinement method by Highscore Plus (PANalytical).

The microstructure was observed on polished and thermally etched samples by scanning electron microscopy (SEM) using secondary electrons (SEs) ($n = 3$). To prevent grain growth, thermal etching was carried out at a relatively low temperature ($1,250^\circ\text{C}$ for 20 min) and fast heating rate ($20^\circ\text{C}/\text{min}$). For grain-size analysis, at least 300 grains were measured using the linear intercept method (ASTM E112 2013). A correction factor of 1.56 for tetrakaidecahedral grains was used (Wurst and Nelson 1972). The microstructure of glass-infiltrated 5Y-PSZs was imaged on polished ($0.5\text{-}\mu\text{m}$ finish) cross-sections, using backscattered electrons (BSEs) ($n = 3$).

Optical Properties Determination

The translucency parameter (TP) and contrast ratio (CR) were evaluated on plate specimens ($n = 3$), measured by a calibrated dental colorimeter (SpectroShade Micro; MHT), and calculated using Equations 1 to 3. Specimens were positioned with their treated surface facing down during testing. Color coordinates $CIE L^*a^*b^*$ were measured over standard backgrounds (black $L^* = 1.8$, $a^* = 1.3$, $b^* = -1.5$ and white $L^* = 95.7$, $a^* = -1.3$, $b^* = 2.6$). To ensure optical continuity, a drop of glycerol ($n = 1.472$) was placed between the specimen and background (Nogueira and Della Bona 2013).

Physical and Mechanical Characterization

Density was measured by the Archimedes principle ($n = 3$) (Zhang et al. 2001). The theoretical density value used for Zpex Smile was $5.99\text{ g}/\text{cm}^3$ (calculated based on 30 wt% $t\text{-ZrO}_2$ at $6.10\text{ g}/\text{cm}^3$ and 70 wt% $c\text{-ZrO}_2$ at $5.95\text{ g}/\text{cm}^3$).

Flexural strength was determined using 4-point bending (20-mm outer span, 10-mm inner span) of bar specimens with beveled edges ($n = 10$). All specimens were loaded with the treated surface in tension. The load rate was $1\text{ mm}/\text{min}$ (ASTM C1161-13 2013). Flexural strength was calculated using Equations 4 to 8 for monolithic (5Y-PSZ-Ctrl, 5Y-PSZ-P, 5Y-PSZ-AA), bilayer (5Y-PSZ-G, 5Y-PSZ-YGI, 5Y-PSZ-MGI, 5Y-PSZ-WGI), and trilayer (5Y-PSZ-YGI-g) configurations. The thickness of the glaze, residual glass, or graded layers was measured by SEM examination of polished cross-sections ($n = 3$).

Statistical Analysis

The translucency and strength data of different materials were compared using the 1-way analysis of variance (ANOVA). Multiple comparisons were performed using the Tukey test. The significance level was set at 5%.

Figure 2. Scanning electron microscopy images of polished and thermally etched zirconia ceramics. (a) 5Y-PSZ, (b) 3Y-TZP, and (c) their grain-size distributions. (d) Backscattered electron image of the cross-section of a yellow shade glass infiltrated 5Y-PSZ ceramics. (e) X-ray diffraction spectra of 5Y-PSZs with and without surface glass infiltration. (f) Diffraction peaks in 2θ range of 29° to 36° , illustrating the major peaks of t - and c -phase zirconia. Detailed Rietveld refinement revealed that the t - and c -phase contents of these 2 particular spectra were 29.7 wt% and 70.3 wt% ($R_{wp} = 7.21$, $\chi^2 = 5.89$) for glass-infiltrated 5Y-PSZ-YGI-g and 31.2 wt% and 68.8 wt% ($R_{wp} = 5.17$, $\chi^2 = 1.95$) for soft-ground and sintered 5Y-PSZ-Ctrl.

Results

An SEM image of a polished and thermally etched 5Y-PSZ material (Zpex Smile) is shown in Figure 2a. For comparison, the microstructure of a previously studied conventional 3Y-TZP (Zpex) is also included (Fig. 2b) (Tong et al. 2016). As seen from their corresponding grain-size distributions (Fig. 2c), the average grain size was $1.17 \pm 0.19\text{ }\mu\text{m}$ for 5Y-PSZ and $0.57 \pm 0.14\text{ }\mu\text{m}$ for 3Y-TZP. To reveal the surface modifications induced by glass infiltration, cross-sections of infiltrated 5Y-PSZ were examined using the SEM BSE imaging technique. It was found that the subsurface microstructure of 5Y-PSZ infiltrated with various glass compositions was very similar. They all consisted of an external residual glass layer ($\sim 20\text{ }\mu\text{m}$), a graded glass/zirconia layer ($\sim 50\text{ }\mu\text{m}$), and a dense zirconia interior. In addition, a $\sim 5\text{-}\mu\text{m}$ -thin layer of fine-grained particles was observed on the glass-infiltrated surface of all compositions. For illustration, a representative cross-sectional BSE image of 5Y-PSZ-YGI-g is shown in Figure 2d.

Table 1. Powder Composition and Sintered Density of an Ultra-Translucent Zirconia Relative to Its Conventional Counterpart ($n = 3$).

Materials	5Y-PSZ (Zpex Smile)	3Y-TZP (Zpex)
Composition	9.32 wt% Y_2O_3 , 0.05 wt% Al_2O_3	5.20 wt% Y_2O_3 , 0.05 wt% Al_2O_3
Density, g/cm^3	6.00 ± 0.01	6.09 ± 0.01
Theoretical density, g/cm^3	6.00	6.10
Relative density, %	>99.9	>99.8
Green density, g/cm^3	3.14 ± 0.01	3.15 ± 0.01

Table 2. Optical and Mechanical Properties of 5Y-PSZ (Zpex Smile) and 3Y-TZP (Zpex).

Materials	TP	CR	σ (MPa)
5Y-PSZ-Ctrl	32.81 (1.42) ^A	0.34 (0.02) ^F	324 (57) ^D
5Y-PSZ-P	34.17 (0.39) ^A	0.31 (0.005) ^G	467 (38) ^C
5Y-PSZ-AA	29.96 (0.73) ^B	0.38 (0.01) ^E	211 (21) ^E
5Y-PSZ-G	33.84 (1.39) ^A	0.34 (0.02) ^F	274 (55) ^{DE}
5Y-PSZ-YGI	33.57 (0.18) ^A	0.32 (0.002) ^G	582 (20) ^B
5Y-PSZ-YGI-g	22.12 (1.06) ^C	0.55 (0.02) ^B	527 (40) ^{BC}
5Y-PSZ-MGI	29.17 (0.11) ^B	0.37 (0.002) ^E	574 (36) ^B
5Y-PSZ-MGI-g	23.07 (0.07) ^C	0.52 (0.003) ^C	
5Y-PSZ-WGI	30.15 (0.15) ^B	0.38 (0.001) ^E	551 (65) ^{BC}
5Y-PSZ-WGI-g	19.63 (0.35) ^D	0.57 (0.01) ^A	
3Y-TZP	16.35 (0.99) ^E	0.48 (0.004) ^D	990 (39) ^A

TP and CR were measured on plates with a common thickness of 1 mm ($n = 3$). Flexural strength was determined on beams of 25 (length) $\times$ 3 (width) $\times$ 2 (height) mm in dimension using 4-point bend testing ($n = 10$). Different means (standard deviations) are identified by superscript letters.

XRD spectra of soft-ground and sintered (5Y-PSZ-Ctrl) and glass-infiltrated (5Y-PSZ-YGI-g) 5Y-PSZs are shown in Figure 2e, f. Rietveld refinement revealed that both surfaces contained ~ 30 wt% t - ZrO_2 and ~ 70 wt% c - ZrO_2 . In addition, XRD analysis showed neither air abrasion nor glazing significantly altered t - and c -contents in 5Y-PSZ. In all cases, no m -phase was observed.

The density of the as-sintered materials is shown in Table 1. Both materials attained >99.8% of their respective theoretical densities.

Table 2 shows the TP, CR, and σ values of various 5Y-PSZ groups along with their 3Y-TZP reference. 5Y-PSZ was more translucent but also much weaker relative to 3Y-TZP. Various surface modifications had profound impacts on both strength and translucency. In general, polishing increased while air abrasion and glazing decreased the strength of 5Y-PSZ. However, glass infiltration (e.g., 582 ± 20 MPa, 5Y-PSZ-YGI) yielded a 25% increase in strength relative to polished 5Y-PSZ (467 ± 38 MPa), which was over 70% stronger than its uninfiltrated counterpart (324 ± 57 MPa, 5Y-PSZ-Ctrl). It is worth mentioning that the flexural strength of polished 5Y-PSZ is very similar to that (485 ± 78 MPa) of the same material subjected to 4-point bending in an independent study (Zhang et al. 2016).

To facilitate a direct comparison, digital images of various 5Y-PSZ plates (1 mm thick) against both white and black backgrounds are shown in Figure 3a. A 3Y-TZP specimen (Zpex) of the same thickness is included for reference. Figure 3b is a reflected-light digital image, illustrating different shades of 5Y-PSZ infiltrated with various feldspathic glass compositions: white, mixed, and yellow (from left to right).

Discussion

This work has examined the optical and mechanical properties of a new class of ultra-translucent zirconia-based materials relative to conventional zirconia. The base materials were an ultra-translucent 5Y-PSZ (Zpex Smile) and a conventional 3Y-TZP (Zpex). Both materials were fabricated from high-purity spray-dry granulated zirconia powders. The average granule size was ~ 45 μm , which consisted of primary crystallites ~ 40 nm in size. Both powder compositions contained trace amounts of Al_2O_3 (0.05 wt%), SiO_2 (≤ 0.02 wt%), and Fe_2O_3 (≤ 0.01 wt%). However, Zpex Smile was stabilized with 9.32 wt% (or 5 mol%) Y_2O_3 , whereas Zpex was doped with 5.2 wt% (3 mol%) Y_2O_3 . Both materials were sintered at $1,450^\circ C$ for 2 h and attained a similar relative density (Table 1). However, due to the higher amount of stabilizer content, Zpex Smile consisted of ~ 70 wt% c - ZrO_2 , while Zpex contained ~ 8 wt% c - ZrO_2 . The higher-amount c -content dramatically increased the translucency but also significantly lowered the strength of zirconia (Table 2). Compared to t - ZrO_2 , c - ZrO_2 has a coarser grain size and is optically isotropic, both of which can effectively reduce light scattering, thus improving translucency. However, the coarse grain size, coupled with lack of $t \rightarrow m$ transformation toughening in c - ZrO_2 , drastically diminishes the flexural strength of 5Y-PSZ.

We have demonstrated that surface glass infiltration of 5Y-PSZ can effectively increase its strength, while retaining a high level of translucency. The strength of grade 5Y-PSZ is over 70% higher than their uninfiltrated counterpart and 25%

higher than highly polished 5Y-PSZ. This is because, at elevated temperatures, the molten glass infiltrates the boundaries of the surface zirconia grains via capillary pressure, producing a glass-rich surface layer with diminished modulus. Such a graded layer can effectively reduce the surface stress and transfer the maximum stress into the interior, thus increasing the strength of zirconia (Zhang and Ma 2009). In addition, the molten glass penetrates surface flaws and pores, effectively reducing the population of surface defects and increasing zirconia strength. The nature of glass infiltration is very similar in 5Y-PSZ and 3Y-TZP, according to microstructural examinations and the amount of strengthening achieved by glass infiltration (Zhang 2012).

Compared to the highly polished specimens, all clinically relevant surface treatments (including the CAD/CAM-like surface) diminished the flexural strength of 5Y-PSZ. Strength reduction was most notable for the air-abraded and glazed groups. Air abrasion reducing the strength of 5Y-PSZ has also been reported in a previous study (McLaren et al. 2017). This is attributable to the diminished $t \rightarrow m$ transformation owing to a high c -content. Glazing, on the other hand, also decreased strength. Although a thin glaze layer ($\sim 50 \mu\text{m}$) is seemingly similar to the residual glass layer in graded zirconias, the relatively low-glaze firing temperature often results in a porous glaze layer that wets the zirconia surface poorly (Benetti et al. 2010; Lai et al. 2017). Our findings are consistent with previous reports, where glazing was found to significantly decrease the flexural strength of zirconia (Yener et al. 2011; Lai et al. 2017).

It is important to note that high-polishing with submicron diamond particles is routinely used in laboratories to prepare the tensile surface of dental ceramics for flexural strength measurements. However, such polishing procedure is different from polishing in a clinical setting. The latter is likely to include a significant amount of microscopic defects, resulting in relatively low strength.

When computing the flexural strength of graded zirconias, we assumed an average elastic modulus value for the thin-graded layer for simplicity. Given the thinness of the graded layer ($\sim 50 \mu\text{m}$) relative to the beam thickness (on the order of $2,000 \mu\text{m}$), this assumption is quite reasonable. For demonstration, we calculated the flexural strength of the glass-infiltrated 5Y-PSZ bilayer beams (Fig. 1c) using the monolithic model (Fig. 1b), without accounting for the presence of a thin-graded layer. The difference is negligible with the strength of glass-infiltrated bilayer zirconias only being $\sim 1\%$ higher than their monolithic counterparts, suggesting that the assumption of an

Figure 3. Digital photographs of various zirconia materials, illustrating their translucency properties and shade selections. (a) Translucency properties (from left to right): glass-infiltrated 5Y-PSZ shade white, shade mixed, shade yellow, 5Y-PSZ polished, glazed, air-abraded, control (soft-machined), and 3Y-TZP. (b) Shade selections (from left to right): glass-infiltrated 5Y-PSZ shade white, mixed, yellow.

average modulus for the graded layer and its corresponding strength value is reasonable.

Finally, the glass infiltration method has been successfully used in anatomically correct crowns (Zhang et al. 2012), inlay retained FDP, and 4-unit FDPs (Ren et al. 2011) on both cameo and intaglio surfaces. There is no problem with infiltrating the intaglio surface. In fact, it increases the resistance to flexural fracture of the cementation surface and cervical margin while providing a much-improved resin bond strength (Chai et al. 2015) relative to its uninfiltrated counterpart.

Conclusion

Surface glass infiltration produces a glass-rich surface, which lowers the surface elastic modulus. Such an elastically graded structure not only improves the flexural strength and facilitates a durable resin cement bond but also provides shade options and retains the translucency of 5Y-PSZ. On the other hand, air abrasion and glazing significantly reduce the strength of 5Y-PSZ, owing to the reduced $t \rightarrow m$ transformation content in c -containing zirconias.

Author Contributions

Y. Zhang, contributed to conception, design, data acquisition, analysis, and interpretation, drafted and critically revised the manuscript; L. Mao, contributed to data acquisition and analysis, drafted the manuscript; M.R. Kaizer, contributed to data acquisition and analysis, drafted and critically revised the manuscript; M. Zhao, contributed to data analysis, drafted the manuscript; B. Guo, contributed to data interpretation, critically revised the manuscript; Y. Song, contributed to conception and data

interpretation, critically revised the manuscript. All authors gave final approval and agree to be accountable for all aspects of the work.

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