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Load-bearing capacity of lithium disilicate and ultra-translucent zirconias

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ABSTRACT

Objective: The aim of this study was to evaluate the load-bearing capacity of monolithic lithium disilicate (LiDi - IPS e.max CAD) and novel ultra-translucent zirconia restorative systems of various compositions: 5Y-PSZ (5 mol% yttria-partially-stabilized zirconia) and 4Y-PSZ (4 mol% yttria-partially-stabilized zirconia); relative to a 3Y-TZP (3 mol% yttria-stabilized zirconia) control.

Materials and methods: Experiments were carried out with 10 disc specimens (Ø12 × 1 mm) per ceramic material. The zirconia intaglio surface (as machined) was sandblasted (50 µm Al_2O_3 at 2 bar), while LiDi was etched with 5% HF for 20 s. The ceramic discs were then adhesively bonded onto a dentin-like substrate (G10, a high-pressure fiberglass material) using Multilink Automix cement and Monobond Plus primer, producing a ceramic/cement/dentin-like substrate trilayer structure. The bonded specimens were stored in water for 3 days at 37 °C prior to a Hertzian indentation flexural radial fracture test. The plate-on-foundation theory was used to validate the load-bearing capacity of the trilayer systems based on the flexural tensile stress at the ceramic intaglio (cementation) surface—a cause for bulk fracture of ceramic onlays.

Results: The experiment data showed that, when bonded to and supported by a dentin-like substrate, the load-bearing capacity of LiDi (872 N) is superior to the 5Y-PSZ (715 N) and can even reach that of 4Y-PSZ (864 N), while 3Y-TZP still holds the highest load-bearing capacity (1195 N). Theoretical analyses agree with experimental observations. The translucency of 5Y-PSZ approaches that of LiDi, which are superior to both 4Y-PSZ and 3Y-TZP.

Conclusions: When adhesively bonded to and supported by dentin, lithium disilicate exhibits similar load-bearing properties to 4Y-PSZ but much better than 5Y-PSZ.

1. Introduction

Monolithic dental restorations fabricated with CAD/CAM technology are gaining popularity among patients and practitioners due to their ease of fabrication and cost-effective characteristics (Li et al., 2014; Zhang and Kelly, 2017). The monolithic crowns in the posterior area of the mouth are mainly fabricated with two types of ceramics: lithia-based glass-ceramics or zirconia (yttria-stabilized polycrystals). Particular characteristics of these two classes of materials guide their clinical indications, as well as the clinicians preferences (Belli et al., 2017; Tong et al., 2016; Wendler et al., 2017; Zhang, 2014; Zhang and Lawn, 2018; Zhang et al., 2013a). The most widely used lithia-based glass-ceramic is lithium disilicate (LiDi), which is available in a variety of shades and opacities. Also, its glassy matrix allows for excellent bondability, using the traditional etch/silane technique. Nonetheless, these materials have only moderate strength (400–600 MPa) and toughness (2–2.5 MPa $m^{1/2}$). On the other hand, traditional dental zirconia (3Y-TZP, 3 mol% yttria stabilized zirconia polycrystals) is the strongest (800–1200 MPa) and toughest (3.5–4.5 MPa $m^{1/2}$) dental ceramic, but it is fairly opaque. The translucency of dental zirconia has been improved by increasing the yttria content. The novel ultra-translucent zirconias (4Y-PSZ and 5Y-PSZ, respectively, 4 mol% and 5 mol% yttria partially stabilized zirconia) have increased volume fractions of the optically isotropic cubic-phase (> 50%), which have effectively increased the materials' translucency. However, the increase in cubic-content also results in reduced strength and toughness (Mao et al., 2018; Zhang et al., 2016a; Zhang and Lawn, 2018), likely to a level similar to that of LiDi.

Although the fracture resistance of ultra-translucent zirconia is significantly lower than that of traditional dental zirconia, their elastic modulus is the same (200–210 GPa), which is significantly higher than that of LiDi (95–105 GPa); both being stiffer than dental hard tissues (enamel ~70 GPa and dentin ~18 GPa) (Kinney et al., 2003; Poolthong et al., 1998; Zhang and Lawn, 2018). It's well known that the elastic

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modulus mismatch between ceramic and supporting structure influences the load-bearing capacity of the ceramic (Timoshenko and Woinowsky-Krieger, 1959). The same is valid for dental ceramic restorations when supported by dental structures (Zhang et al., 2009). A previous finite element analysis (Ma et al., 2013) showed that although the flexural strength of zirconia (3Y-TZP) is 2.5 times higher than that of the LiDi glass-ceramic, the difference in load-bearing property is significantly reduced when these materials are bonded to enamel supported by dentin. Therefore, we hypothesize that LiDi should have similar or even superior load-bearing capacity to that of novel ultra-translucent zirconias, owing to their similar flexural strength but smaller elastic mismatch between LiDi and dental hard tissues relative to zirconias. This study experimentally evaluated the load-bearing capacity of LiDi and zirconia bonded onto a dentin-like substrate, which was validated by the plate-on-foundation theory.

2. Materials and methods

2.1. Materials and sample preparation

Disc-shaped specimens (Ø12 mm × 1 mm thickness, final dimensions) were prepared from three dental zirconias (the Luxisse series; Heany Industries, USA) and lithium disilicate (IPS e.max CAD; Ivoclar Vivadent, Lichtenstein). The surface of each disc was grinded dry after cutting, using a 320-grit (~35 μm) silicon carbide paper, to simulate the surface produced by CAD/CAM milling. Descriptions of the materials and sintering temperatures are given in Table 1. The microstructure of these materials was observed on highly polished (0.5 μm) and thermally etched (zirconia) or acid etched (LiDi) samples by field emission scanning electron microscopy (Zeiss Merlin FE-SEM). To prevent grain growth, thermal etching was carried out at a relatively low temperature (1250 °C for 20 min) and fast heating rate (20 °C/min). For grain size analysis, at least 300 grains were measured using the linear intercept method (ASTM Standard, E112, 2013). A correction factor of 1.56 for tetrakaidecahedral grains was used (Wurst and Nelson, 1972).

2.2. Fracture resistance experiments

The free-standing biaxial strength of each material ($n = 10$) was determined by the piston-on-three-balls test, using a loading rate of 1 mm/min, following the ISO 6872 (ISO/FDIS, 6872, 2015).

To simulate the fracture resistance of ceramic prostheses supported by tooth dentin, ceramic specimens of each material ($n = 10$) were bonded to a dentin-like substrate (G10, Acculam, USA). G10 is a glass fiber reinforced epoxy resin, with elastic modulus $E = 18.6$ GPa similar to human dentin (Kinney et al., 2003). G10 rods were flattened and finished with 45 μm diamond grinding, then soaked in water for 21 days for complete hydration.

For adhesive bonding, the G10 surface was acid etched (5% HF for 2 min), while the zirconia intaglio surface was sandblasted (50 μm Al_2O_3 at 2 bar), and LiDi was acid etched (5% HF for 20 s), following recommended protocols for their clinical use. After that, all samples were cleaned in an ultrasonic water bath for 2 min and dried. Adhesive bonding was carried out using Multilink Automix cement and Monobond Plus primer (Ivoclar Vivadent, Amherst, NY). A static load of 1 kg was used for 120 s to standardize cement thickness. The samples were then light cured for 4 intervals of 30 s at directions 90º apart. The ceramic/cement/G10 trilayer specimens were stored in water for 3 days at 37 °C to allow the continuous polymerization and complete hydration of the cement layer prior to the Hertzian load-to-fracture test. The fracture resistance test was performed by loading the ceramic/cement/G10 trilayer specimens at the top ceramic surface with a rigid tungsten carbide (WC) indenter ($r = 3.18$ mm) under the loading rate of 1 mm/min. It is true that the elastic modulus of WC is 3 times that of the stiffest opposing ceramic prostheses. The theory of contact mechanics and our previous study (Ma et al., 2013) have shown that although the elastic modulus of the indenter has profound influence on the initiation of the near-contact cone cracks, it has little effect on the onset of the far-field flexural radial cracks. To suppress the formation of cone cracks and to achieve a uniform force distribution, a thin piece of nitrile foil was placed between the ceramic surface and the loading ball. The schematic of the test configuration along with the specimen geometric parameters is shown in Fig. 1. Critical load for the onset of radial fracture was registered. All ceramic discs were then carefully peeled off of their G10 substrate for optical microscopy examination. By using a combination of reflected and transmitted light illumination, it was possible to confirm that the fracture does indeed originate from the cementation radial cracks and not from the near-contact cone cracks.

2.3. Plate-on-foundation theory

The plate-on-foundation theory was used to predict the theoretical load-bearing capacity of the trilayer systems (ceramic/cement/dentin-like substrate) according to their elastic gradients (Fig. 1).

Critical load (P_R) for the onset of radial fracture from the ceramic intaglio surface was calculated by the plate (ceramic restoration) on foundation (cement/dentin assembly) theory. The mathematical model is composed of three equations (Kim et al., 2003; Timoshenko and Woinowsky-Krieger, 1959):

$$P_R = \frac{B\sigma d^2}{\log\left(\frac{CE}{E^*}\right)} \tag{1}$$

where E is the flexural modulus of the ceramic Table 1, zirconia (= 210 GPa) and lithium disilicate (= 95 GPa) (Ma et al., 2013); σ is the flexural strength of the ceramic, which was investigated in this study (Table 1); d is the thickness of the ceramic. C (≈ 1) and B ($= 1.35$) are the dimensionless constants (Miranda et al., 2003); E^* is the effective modulus of the cement/dentin (G10) layer which is based on contact mechanics (Gao et al., 1992; Hu and Lawn, 1998; Kim et al., 2003):

Table 1
Properties of materials used in this study.

Material	Manufacturer	Sintering condition	Composition (%)	Modulus, E^a (GPa)	Strength, σ (MPa)	Thickness, d/h (mm)
Zirconia						
Zpex (3Y-TZP)	Heany Dental	1530 °C for 2 h	t-ZrO_2: 71, c-ZrO_2: 29	210	904 (57) A	1.0 ± 0.2
Zpex 4 (4Y-PSZ)	Heany Dental	1450 °C for 2 h	t-ZrO_2: 43, c-ZrO_2: 57	210	749 (29) B	1.0 ± 0.2
Zpex Smile (5Y-PSZ)	Heany Dental	1450 °C for 2 h	t-ZrO_2: 31, c-ZrO_2: 69	210	593 (90) C	1.0 ± 0.2
Glass-ceramic						
IPS e.max CAD	Ivoclar Vivadent	820 °C for 2 min + 840 °C for 7 min	Crystals: 70, Glass: 30	95	488 (28) C	1.0 ± 0.2
Cement						
Multilink Automix	Ivoclar Vivadent	Light cured	Glass, DMA, HEMA	7.9	114[a]	0.04 ± 0.01
Composite						
G10	Acculam	Lab fabricated	Glass fiber, Epoxy	18.6	379[a]	15

Different letters indicate statistical difference among materials, within each property.

[a] Data from manufacturers.