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Strength, toughness and aging stability of highly-translucent Y-TZP ceramics for dental restorations

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ABSTRACT

Objective. The aim was to evaluate the optical properties, mechanical properties and aging stability of yttria-stabilized zirconia with different compositions, highlighting the influence of the alumina addition, Y_2O_3 content and La_2O_3 doping on the translucency.

Methods. Five different Y-TZP zirconia powders (3 commercially available and 2 experimentally modified) were sintered under the same conditions and characterized by X-ray diffraction with Rietveld analysis and scanning electron microscopy (SEM). Translucency (n = 6/group) was measured with a color meter, allowing to calculate the translucency parameter (TP) and the contrast ratio (CR). Mechanical properties were appraised with four-point bending strength (n = 10), single edge V-notched beam (SEVNB) fracture toughness (n = 8) and Vickers hardness (n = 10). The aging stability was evaluated by measuring the tetragonal to monoclinic transformation (n = 3) after accelerated hydrothermal aging in steam at 134 °C, and the transformation curves were fitted by the Mehl–Avrami–Johnson (MAJ) equation. Data were analyzed by one-way ANOVA, followed by Tukey's HSD test ($\alpha = 0.05$).

Results. Lowering the alumina content below 0.25 wt.% avoided the formation of alumina particles and therefore increased the translucency of 3Y-TZP ceramics, but the hydrothermal aging stability was reduced. A higher yttria content (5 mol%) introduced about 50% cubic zirconia phase and gave rise to the most translucent and aging-resistant Y-TZP ceramics, but the fracture toughness and strength were considerably sacrificed. 0.2 mol% La_2O_3 doping of 3Y-TZP tailored the grain boundary chemistry and significantly improved the aging resistance and translucency. Although the translucency improvement by La_2O_3 doping was less effective than for introducing a substantial amount of cubic zirconia, this strategy was able to maintain the mechanical properties of typical 3Y-TZP ceramics.

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Significance. Three different approaches were compared to improve the translucency of 3Y-TZP ceramics.

1. Introduction

Although porcelain-fused-to-metal (PFM) systems have represented the "gold standard" for many years to produce fixed dental prostheses (FDP) in restorative dentistry, the gray and opaque metal framework does not allow them to mimic the translucent dental tissues [1–3]. All-ceramic restorations are becoming increasingly popular due to their aesthetic appearance, chemical inertness and biocompatibility [1,3,4]. However, most dental ceramics are brittle, limiting their use to small anterior restorations [3–5]. The excellent mechanical properties of zirconia ceramics, as the result of an inherent transformation toughening mechanism [6], has made them particularly attractive for fabricating diverse dental restorations [1,7–11]. In particular, 3 mol% yttria-stabilized tetragonal zirconia polycrystalline (3Y-TZP) ceramics can be fully densified with fine-grained microstructure to combine a high wear resistance, fracture toughness (5–9 $MPa\,m^{1/2}$) and extraordinary bending strength (>1000 MPa) [7,12,13]. Furthermore, 3Y-TZP is white, allows some light transmission and can be rather easily colored by adding trace amounts of rare-earth elements [14,15]. Therefore, nowadays, 3Y-TZP has been widely accepted as a promising material for fabricating dental crowns [4] and more importantly for larger all-ceramic FPDs in both anterior and stress-bearing posterior area [7,10,16,17].

The limited translucency however is a major drawback of 3Y-TZP restorations. 3Y-TZP was initially considered as an opaque material [18] and zirconia-based dental restorations are obtained by porcelain veneering a zirconia core. Recently, different grades of 3Y-TZP showed some degree of light transmittance [19–22], but the translucency of zirconia-based ceramics is still lower than that of glass-ceramics, for which excellent aesthetic results are documented [19–21]. The translucency of the framework, however, directly influences the appearance of dental restorations [4,23]. In order to avoid the veneer chipping problem, monolithic zirconia using highly-translucent 3Y-TZP is the latest trend as a promising alternative to porcelain-fused-to-zirconia restorations [24–27]. A higher translucency of ceramic frameworks can also improve the curing efficiency of light-cured cements [28].

Another potential risk of Y-TZP is low-temperature degradation, in which the tetragonal zirconia (t-ZrO_2) phase spontaneously transforms to the monoclinic (*m*-ZrO_2) phase in the presence of water or water vapor (hydrothermal aging) without applied stress [29]. The consequences of hydrothermal aging are surface roughening, enhanced wear rates, loss of mechanical properties and even catastrophic failure [29,30].

Therefore, it is of utmost importance to improve the translucency of new dental restorative 3Y-TZP ceramics while ensuring and extending their aging stability without compromising the attractive mechanical properties. In principle, Y-TZP have the potential to gain optical translucency or even transparency, and the loss of optical transparency is mainly due to the light scattering by porosity, secondary phases, and grains with different crystallographic orientation (birefringence at the grain boundary) [31,32]. It is known that a slight variation in the zirconia composition and minute differences in the microstructure can cause a considerable difference in properties. Different dental manufacturers eliminated/reduced the alumina addition or increased the yttria content to improve the translucency of dental restorative 3Y-TZP ceramics [14,22,25,32–34]. Recently, we reported that the co-doping of 0.2 mol% La_2O_3 and 0.1–0.25 wt.% Al_2O_3 in 3Y-TZP resulted in a high translucency by manipulating the chemistry of the grain boundaries [35]. In this work, different commercially available and experimental starting powder compositions were compared, aiming to seek the most desirable combination of translucency, hydrothermal stability and mechanical properties of the sintered 3Y-TZP.

2. Materials and methods

2.1. *Materials*

Five zirconia compositions were investigated. Three commercially available zirconia powders (TZ-3YE, Zpex® and Zpex® Smile (Tosoh, Japan)) and two lab-made zirconia powders were used. TZ-3YE contained 3 mol% (5.2 wt.%) Y_2O_3 and 0.25 wt.% Al_2O_3, which was a widely used composition for dental restorations, and the resulting ceramic was referred to as 3Y-0.25Al throughout the text. Zpex® and Zpex® Smile were claimed to have a higher translucency by reducing alumina content and increased yttria content respectively. Zpex® contained 3 mol% (5.2 wt.%) Y_2O_3 and 0.05 wt.% Al_2O_3, referred to as 3Y-0.05Al. Zpex® Smile contained 5 mol% (9.35 wt.%) Y_2O_3 and 0.05 wt.% Al_2O_3, encoded as 5Y-0.05Al. The compositions of the two lab-made zirconia powders were 3 mol% (5.2 wt.%) Y_2O_3, 0.25 or 0.1 wt.% Al_2O_3 and 0.2 mol% La_2O_3, further referred to as 3Y-0.25Al-0.2La and 3Y-0.1Al-0.2La. These two powders were prepared by mixing tetragonal zirconia powder (grade TZ-3Y, Tosoh, Japan) with La_2O_3 (Chempur, purity of 99.99%) and Al_2O_3 (TM-DAR, purity of 99.99%) on a multidirectional mixer (Turbula type T2C, Basel, Switzerland) for 24 h in ethanol using 5 mm Y-TZP milling balls, and on a bead mill (Dispermat SL, Germany) for 3 h at 5000 rpm using 1 mm ZrO_2 beads (grade TZ-3Y, Tosoh, Japan), followed by drying and sieving through a 250 μm screen. In order to avoid any influence of the Y_2O_3 distribution, the lab-made powders were based on co-precipitated alumina-free 3Y-TZP powder which was also used as a reference material for the translucency measurement. More information on the preparation of these powders was provided elsewhere [35].