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Making yttria-stabilized tetragonal zirconia translucent

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ABSTRACT

Objective. The aim of this study was to provide a design guideline for developing tetragonal yttria-stabilized zirconia with improved translucency.
Methods. The translucency, the in-line transmission in particular, of 3 mol.% yttria-stabilized tetragonal zirconia (3Y-TZP) has been examined using the Rayleigh scattering model. The theory predicts that the in-line transmission of 3Y-TZP can be related to its thickness with grain size and birefringence the governing parameters. To achieve a threshold value of translucency, the critical grain size of 3Y-TZP was predicted for various thicknesses (0.3–2.0 mm). The threshold value was defined by a measured average in-line transmission value of a suite of dental porcelains with a common thickness of 1 mm. Our theoretical predictions were calibrated with one of the very few experimental data available in the literature.
Results. For a dense, high-purity zirconia, its in-line transmission increased with decreasing grain size and thickness. To achieve a translucency similar to that of dental porcelains, a nanocyrstalline 3Y-TZP structure was necessitated, due primarily to its large birefringence and high refractive index. Such a grain size dependence became more pronounced as the 3Y-TZP thickness increased. For example, at a thickness of 1.3 mm, the mean grain size of a translucent 3Y-TZP should be 82 nm. At 1.5 mm and 2 mm thicknesses, the mean grain size needed to be 77 nm and 70 nm, respectively.
Significance. A promising future for zirconia restorations, with combined translucency and mechanical properties, can be realized by reducing its grain size.

1. Introduction

Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) has been used as a dental restorative material for over a decade [1]. While it is still the strongest and toughest ceramic ever used in dentistry, its esthetics—in particular, its translucency—remains as a major drawback. The opacity of zirconia becomes a problem especially when placing an anterior crown or shortspan fixed dental prosthesis in the presence of other anterior natural teeth. In this case, the reflectance and light scattering do not always appear natural. In order to create space for a porcelain veneer thick enough to cover the opaque zirconia core and to match the optical properties

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of the adjacent natural dentition, a substantial reduction of tooth structure is required. In addition, in an effort to prevent veneer chipping [2–5] and delamination [6–8], monolithic zirconia is often used in full arch restorations, posterior crowns and fixed dental prostheses [9–16]. In these cases, the opacity of zirconia can pose a problem.

After a decade of research and development, some progress has been made in improving the translucency of Y-TZP (e.g. increase the density of zirconia and eliminate the alumina sintering aid). However, close examinations have revealed that unless it is thin (<0.5 mm), the so-called commercial translucent Y-TZP restorative materials remain predominantly opaque. Beyond such phenomenon lies a critical question: how do we improve the translucency of Y-TZP? To answer this question, we must begin with the interactions of light and solids.

Light, X-rays, and heat are all part of electromagnetic waves; each is characterized by a specific range of wavelengths. X-rays have a wavelength typically in the range of 0.01–10 nm, while visible light lies between 400 nm (violet) and 700 nm (red). Under daylight conditions, the normal human eye is most sensitive to a wavelength of 555 nm, leading to a perception that green light, at this wavelength, is far "brighter" than the light at other wavelengths.

When light proceeds from air into a solid, part is reflected, part is absorbed, but part may be transmitted. Reflection occurs at the interfaces between the solid and air. Absorption happens when a photon of light transfers its energy and momentum to a valence band electron, excites the electron, across the band gap, into the conduction band. Naturally, these excitations with the accompanying absorption can take place only if the photon energy is greater than that of the band gap. The band gap of Y-TZP is around 5.2 eV and 6.0 eV according to the theoretical calculation and experimental determination, respectively [17]. Both values are much greater than the maximum energy 3.1 eV associated with the minimum wavelength 400 nm of visible light, suggesting that no significant adsorptions occur over the visible region of the spectrum. The question then arises: what makes an inherently transparent Y-TZP material opaque? In the following section, we examine the light transmission properties of Y-TZP.

Light that transmitted into the interior of Y-TZP may experience interior reflection and refraction; the phenomenon is termed as scattering. This internal light scattering may result from several sources, including pores, impurities, defects, and grain boundaries (Fig. 1).

The influence of pore size and pore population on light scattering in zirconia has been examined by a number of authors [18–20]. It was found that pore sizes in the range of 200–400 nm (typical of the current dental zirconia) and pore populations as low as 0.05% can significantly relegate the translucency of Y-TZP. The dental community is well-aware the deleterious effect of porosity on zirconia translucency. Measures, such as high sintering temperatures (1510–1550 °C) coupled with prolonged dwell time (up to 6 h) (BruxZir, Glidewell, Newport Beach, CA), have been taken to ensure a respectable density.

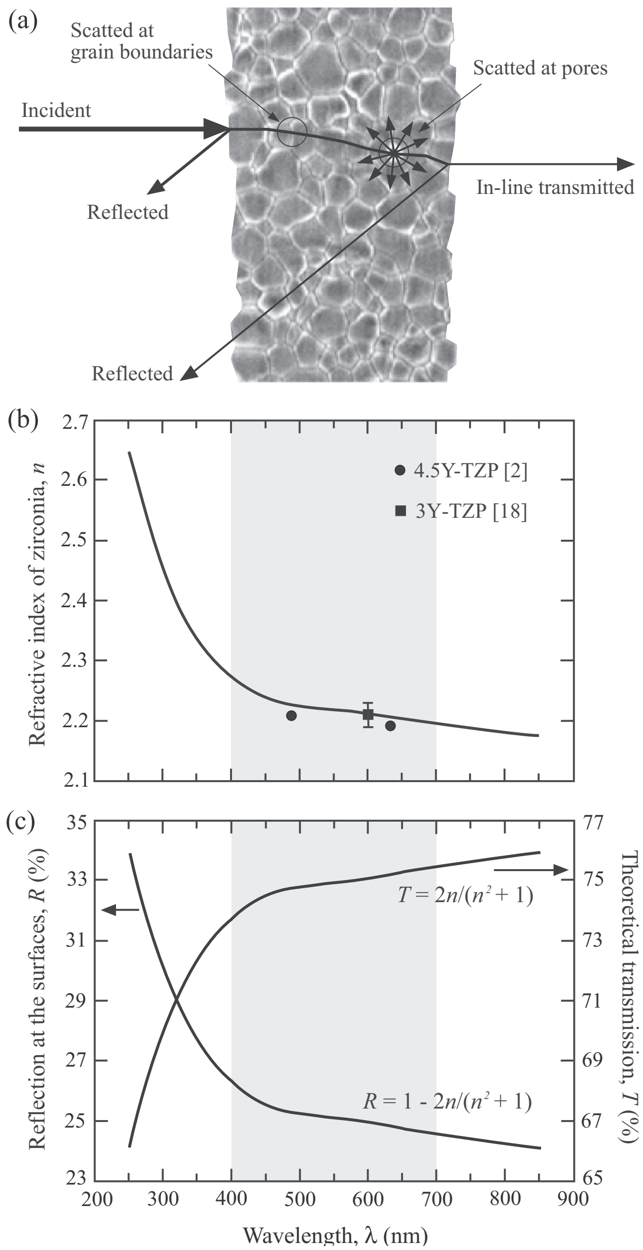

Fig. 1 – The interactions of light and zirconia. (a) Schematic of light transmission through tetragonal zirconia. Losses in intensity of the incident light are due to reflection at zirconia surfaces, and scattering by optical birefringence and at pores. Wavelength dependence of (b) the refractive index of tetragonal zirconia, and (c) theoretical transmission and reflection (at the surfaces).

Impurities that have different refractive index than zirconia (e.g. alumina sintering additives) can dampen the translucency of Y-TZP [21]. (The index of refraction for alumina and zirconia, at 600 nm wave length, is $n = 1.76$ and $n = 2.21$, respectively.) In this case, scattering of light occurs when a light beam travels across the two phase boundaries. To achieve a better translucency, some dental manufacturers have eliminated the light-scattering alumina sintering aids (e.g. Glidewell, Newport Beach, CA and 3M ESPE AG, Seefeld, Germany).