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Optical behavior of dental zirconia and dentin analyzed by Kubelka–Munk theory

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ABSTRACT

Objectives. To use the Kubelka–Munk theory to evaluate the scattering (*S*), absorption (*K*) and transmittance (*T*) of non-colored and colored dental zirconia systems and human (HD) and bovine (BD) dentins.

Methods. Two zirconia systems were used: ZC- ZirCAD (Ivoclar Vivadent) and LV-LAVA (3M ESPE). Specimens from each ceramic system were divided into 3 groups ($n=5$): ZC1 and LV1 (non-colored); ZC2 and LV2 colored to shade A1, and ZC3 and LV3 colored to shade A3. Five human and bovine anterior teeth were flattened and polished through 1200 grit SiC paper to expose the superficial buccal dentin. All samples were prepared to a final thickness of 0.5 mm. Diffuse reflectance was measured against white and black backgrounds, using a spectroradiometer in a viewing booth with D65 illuminant and d/0° geometry. *S* and *K* coefficients and *T* were calculated using Kubelka–Munk's equations. Data was statistically analyzed using Kruskal–Wallis, Mann–Whitney tests, and VAF coefficient.

Results. Spectral distributions of *S*, *K* and *T* were wavelength dependent. The spectral behavior of *S* and *T* was similar to HD (VAF $\geq$ 96.80), even though they were statistically different ($p \leq 0.05$). The spectral behavior of *K* was also similar to HD, except for LV1 (VAF = 38.62), yet all ceramics were statistically different from HD ($p \leq 0.05$). HD and BD showed similar values of *S* and *T* ($p > 0.05$).

Significance. The dental professional should consider the optical behavior differences between the zirconia systems evaluated and the human dentin to achieve optimal esthetics in restorative dentistry.

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1. Introduction

The fabrication of a dental restoration with natural appearance requires not only the matching of color (value, hue and chroma), but also the blending of specific optical characteristics of the adjacent dental structures [1]. When light strikes a tooth surface, four phenomena can be described: (a) specular transmission of the light flux through dental structures, (b) specular light reflection at the tooth surface, (c) diffuse light reflection at the tooth surface, and (d) absorption and scattering of light within the dental tissues [2,3]. Thus, for optimal esthetic results, a favorable shade and appearance of the restoration is of extreme importance.

A large variety of all ceramic systems were recently introduced due to the increased esthetic requirements and demands of both patients and dental professionals [4]. The tetragonal polycrystalline zirconia doped with 3 mol% yttria (3Y-TZP) has generated considerable interest in the dental community due to its peculiar mechanical properties and optimal biocompatibility [5,6].

Initially, 3Y-TZP ceramic systems were considered as completely opaque materials, due to their high refractive index ($n = 2.1$–2.2), low absorption coefficient and high opacity in the visible and infrared regions of the spectrum. The opacity of the zirconium oxide is often attributed to some of its structural characteristics, such as the particle size, which is slightly greater than the wavelength of the incident light, the density (residual porosity < 0.05%) and the homogeneity [7]. Different grades of zirconia have different levels of translucency; the higher the grade, the more translucent the material. Pressing methods, different additives (stabilizing oxides) and sintering conditions may affect its translucency [7].

Zirconia-based dental restorations are obtained by porcelain veneering a zirconia core. Yet, it has been reported that using a shaded zirconia core results in better esthetics and greater natural appearance, similar to the chromatic dentin overlaid by translucent enamel [5]. Various zirconia core shades have been introduced with few reports on the effect of shaded zirconia on the translucency of the ceramic restorations. One of these studies showed similar translucency parameter (TP) values for 3Y-TZP systems compared to 0.5-mm thick human dentin [8].

It is well known that the translucency of a material depends on its scattering (μ_s) and absorption (μ_a) coefficients as well as on the thickness of the sample. The scattering and absorption coefficients of dentin are greater than for enamel. In contrast to enamel, the dentin coefficients of scattering and absorption do not change significantly with wavelength [9]. Yet, few reports are available on the scattering and absorption behavior of dental zirconia. One of these studies reported that zirconia (sintered LAVA™ Zirconia) showed a scattering angular behavior more similar to the human dentin than to dental materials and that a thicker (0.5 mm) sample yielded less directed scattering profile than a thinner (0.3 mm) sample [10].

Kubelka–Munk (K–M) reflectance theory is a mathematical model describing the reflectance resulting from two-flux radiation transfer in a homogenous and uniform medium placed over an opaque backing [11]. The main advantage of this theory is that the absorption and scattering coefficients (*K* and *S*, respectively) can be easily expressed as a function of the reflectance and transmittance of the sample. Yet, the K–M scattering (*S*) and absorption (*K*) coefficients are not directly related to μ_s and μ_a (physical scattering and physical absorption coefficients, respectively). Nevertheless, several authors [12–14] have reported on the relationship between Kubelka–Munk *S* and *K* coefficients and the μ_s and μ_a coefficients. Yet, previous studies used the reflectance measurements based on the K–M reflectance theory to calculate the optical properties of dental tissues and materials, such as: human enamel and dentin [3], porcelain materials [15,16], and direct restorative materials [2]. A study showed that corrected K–M reflectance theory may be used to accurately quantify the optical K–M absorption and scattering coefficients of dental resin-based composites [17].

The objective of this study was to use the Kubelka–Munk theory to evaluate the scattering, absorption and transmittance of non-colored and colored dental zirconia systems and human and bovine dentins, testing the null hypothesis that scattering, absorption and transmittance of dental zirconia systems are not significantly different from the human and bovine dentins.

Table 1 – Commercial properties of zirconia samples.

Features	IPS e.max® ZirCAD (Ivoclar Vivadent)[a]	LAVA™ Zirconia (3M ESPE)[a]
Components	ZrO_2, Y_2O_3, HfO_2, Al_2O_3	ZrO_2, Y_2O_3, HfO_2, Al_2O_3
Yttria content	3 mol%	3 mol%
Density	6.045–6.065 g/cm^3	6.08 g/cm^3
Sintering temperature	1500 °C	1500 °C
Grain size	0.52 ± 0.05 μm	0.5 μm
Batch #	16861	318814

[a] Manufacturer's data.

2. Material and methods

2.1. Sample preparation

2.1.1. Zirconia systems

Two commercially available 3Y-TZP ceramic systems with similar composition were evaluated (Table 1):

ZC: IPS e.max® ZirCAD (Ivoclar Vivadent, Schaan, Liechtenstein); and
LV: LAVA™ Zirconia (3M ESPE, St. Paul, MN, USA).

Specimens were cut from pre-sintered blocks using a low speed (100 rpm), water-cooled diamond saw (Accutom 50, Struers, Ballerup, Denmark) and subsequently polished with 500, 800 and 1200 grit SiC abrasive papers (Struers, Ballerup, Denmark) under constant water irrigation. Handling, preparation and sintering of each ceramic system was performed by the same operator in accordance with manufacturersínstructions. The final thickness (after sintering) of all ceramic specimens was 0.5 ± 0.01 mm. Specimens from each ceramic system (ZC and LV) were divided into 3 groups ($n = 5$), as follows:

ZC1: regular (no color) samples;
ZC2: samples from pre-shaded blocks MO1, corresponding to shades A1/A2;
ZC3: colored samples, using coloring liquid CL2 (Ivoclar Vivadent, Schaan, Liechtenstein) corresponding to shades A3/A3.5.

LV1: regular (no color) samples;
LV2: colored samples, using coloring liquid FS1 (3M ESPE, St. Paul, MN, USA), corresponding to shades A1/B1;
LV3: colored samples, using coloring liquid FS3 (3M ESPE, St. Paul, MN, USA), corresponding to shades A2/A3.

Coloring and sintering procedures were performed according to the manufacturers' indications.

2.1.2. *Preparation of human dentin (HD) and bovine dentin (BD)*

This study was approved by the local Ethics Committee. Anterior maxillary teeth ($n = 5$), free of caries and restorations, extracted because of periodontal disease, were obtained from voluntary patients that signed the informed consent to participate in the study. All teeth were cleaned from any debris and selected to visually match the A3 shade (VITA® Classical shade guide, VITA Zahnfabrik, Bad Säckingen, Germany). Additionally, 5 bovine incisors were also used in the study. All human and bovine teeth were carefully visual inspected. Teeth with any coronal crack or fracture were excluded from the study. Selected teeth were stored in 1% thymol solution under refrigeration (4 °C) until sample preparation and testing.

Human and bovine teeth were sectioned at the cementum-enamel junction using a diamond saw (Accutom 50, Struers, Ballerup, Denmark) under water cooling. The crowns were further cut following their long axis, dividing the buccal and lingual sides of the crowns. The roots and the lingual half of the crowns were discarded in a special container for biological waste following the *Biomedical Waste* Management Rules. The flattened lingual surface of the specimens was polished with 500-grit silicon carbide paper discs on a polisher (EXAKT Apparatebau D-2000, Norderstedt, Germany). In order to achieve regular thickness and parallel buccal-lingual surfaces, the buccal surface of all dental specimens was flattened to remove the enamel, exposing the superficial dentin. Specimens were additionally polished with silicon paper discs (800, 1000 and 1200 grit) to obtain 0.5-mm thick specimens, measured in the middle third of the crown slices. The specimens were further polished from 1 to 0.05-μm alumina slurry (Alumina Slurry, Electron Microscopy Sciences, Fort Washington, PA, USA). The smear layer was removed in a sonic bath of 0.27 M EDTA (pH 7.4) solution for 5 min and 0.34 M sodium hypochlorite (pH 12.3) solution for 3 min, followed by running water wash for 5 min [18].

The final thickness of the central area of all specimens was measured three times using a digital caliper (DIGC6, Thorlabs, Inc., NJ, USA) and averaging the value.

2.2. *Reflectance measurements*

The relative spectral radiance ($W/sr\,m^2$) of the zirconia, bovine and human dentin samples were measured against white ($L^* = 94.2$, $a^* = 1.3$ and $b^* = 1.7$) and black ($L^* = 3.1$, $a^* = 0.7$ and $b^* = 2.4$) backgrounds (50 mm × 50 mm ceramic tile, Ceram, Staffordshire, United Kingdom), using a spectroradiometer (SpectraScan® PR-704, Photo Research Inc., Chatsworth, CA, USA) with 4% measurement accuracy. A saturated sucrose solution (refractive index $n = 1.5$, approximately) was used as contact between the samples and the background [17].

Specimens were measured inside of a color-assessment cabinet (CAC 60, Verivide Limited, Leicester, United Kingdom) under constant illumination (light source simulating the spectral relative irradiance of D65 CIE standard illuminant). Illuminating/measuring configuration corresponded to CIE d/0° [19].

Short-term repeated measurements without replacement were performed where each specimen was measured three times. A triangular stand was built to support the specimens and avoid specular reflection from the glossy surface. Since the field of measurement of the spectroradiometer was 1°, the spectroradiometer was placed 25 cm from the specimen, allowing for the measurement of the whole specimen [8,20].

Finally, the relative spectral radiance measured for all specimens at each wavelength was converted into absolute reflectance, based on measurements of a white reflectance standard (OPST3-C, Optopolymer, Germany).

2.3. *Kubelka–Munk coefficients*

The Kubelka–Munk scattering (S) and absorption (K) coefficients were calculated algebraically from the spectral reflectance data of each sample using the Kubelka–Munk equations as described below.

Secondary optical constants (a and b) were calculated from the experimentally obtained spectral reflectance values using the black and white backgrounds, as follows:

$$a = \frac{1}{2}R + \left[\frac{R_0 - R + R_g}{R_0 R_g}\right] \tag{1}$$

$$b = (a^2 - 1)^{1/2} \tag{2}$$

where R is the reflectance of the specimen over the white background, R_0 the reflectance of the specimen over the black background and R_g is the reflectance of the white background.

The scattering coefficient (S) for a unit of thickness of a specific material is defined by the following equation:

$$S(\mathrm{mm}^{-1}) = \frac{1}{bX} arctgh[(1 - aR_0)/bR_0] \tag{3}$$

where X is the actual thickness of the specimen, and *arctgh* is an inverse hyperbolic cotangent. In practical formulas, S always occurs together with the thickness X of the specimen, that is, as the product SX, known as "scattering power" of the specimen.

The absorption coefficient (K) and the transmittance (T) are then calculated as follows:

$$K(\mathrm{mm}^{-1}) = S(a-1) \quad (4)$$

$$T(x) = \frac{b}{a\sinh(bSX) + b\cosh(bSX)} \quad (5)$$

Finally, the ratio K/S, proportional to the ratio of the scattering and absorption coefficients μ_a and μ_s, was also calculated.

2.4. Statistical analysis

To study the variations in scattering, absorption, and transmittance, two statistical tests were used: the Kruskal–Wallis, which is a non-parametric method for testing average equality of measures among groups, and the Mann–Whitney U test ($\alpha = 0.05$) (SPSS 16.0, Chicago, SPSS Inc.), which is a non-parametric test that enables the pairwise comparison of two distributions.

Also, to determine the level of similarity of two different distributions, the VAF (variance accounting for) coefficient with Cauchy–Schwarz inequality [8,20] was used as follows:

$$\mathrm{VAF} = \frac{\left(\sum_{k=400}^{700} a_k b_k\right)^2}{\left(\sum_{k=400}^{700} a_k^2\right)\left(\sum_{k=400}^{700} b_k^2\right)} \quad (6)$$

where a_k is the value of the absorption, scattering or transmittance at each wavelength for one measurement and b_k is the equivalent for another measurement. The closer this coefficient gets to unity (100%), the more similar the curves are.

3. Results

3.1. Scattering coefficient

The spectral distributions of the Kubelka–Munk scattering coefficient (S) for ZC (a) and LV (b) samples are shown in Fig. 1. Both zirconia ceramic systems were compared with human (HD) and bovine (BD) dentins. The spectral pattern of S distribution showed a maximum value at approximately 450 nm. For longer wavelengths, lower S values were recorded.

The spectral behavior of S for both human and bovine dentins did not change significantly for all wavelengths. Both dentins showed similar spectral behavior of the scattering coefficient (VAF = 99.92%) (Tables 2 and 3) and were not significantly different ($p > 0.05$).

Although the results showed similar spectral behavior of S for the zirconia groups and the dentins ($96.43 \le \mathrm{VAF} \le 99.70$), the S values of the zirconia groups were statistically different from the dentins ($p \le 0.05$) (Tables 2 and 3), with LV showing the highest S values. For ZC, S values increased when samples were colored ($p \le 0.05$), specially for medium and long wavelengths, while for LV samples, S values decreased when specimens were colored ($p \le 0.05$) (Fig. 1a and b).

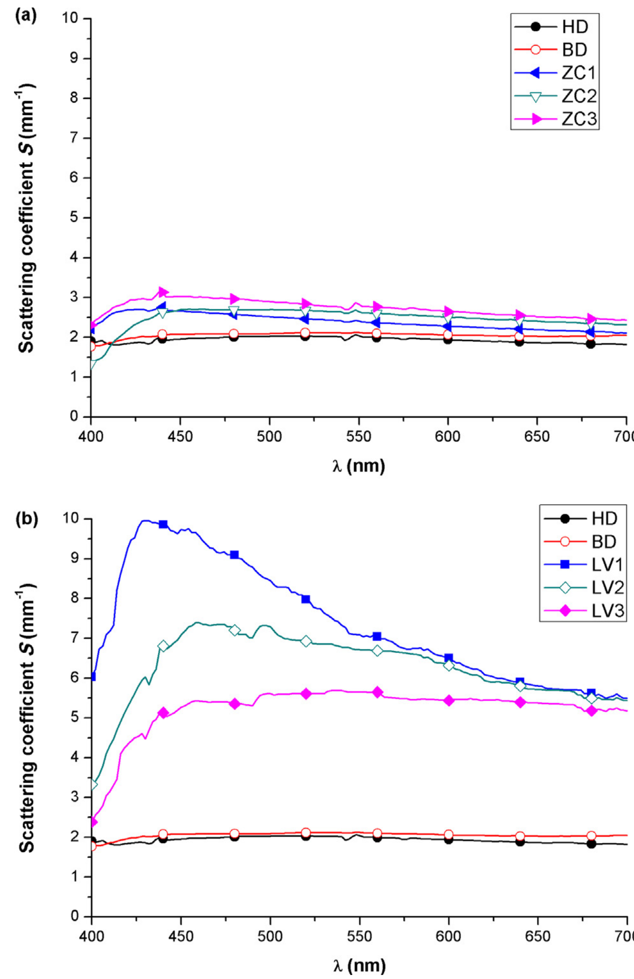

Fig. 1 – Spectral distribution of the Kubelka–Munk scattering coefficient (S) for (a) IPS e.max®ZirCAD (Ivoclar Vivadent) and (b) LAVA™ Zirconia (3M ESPE) systems compared with human and bovine dentin samples.

3.2. Absorption coefficient

The spectral distributions of the Kubelka–Munk absorption coefficient (K) for ZC and LV samples in comparison to both dentins are shown in Fig. 2a and b, respectively. The spectral behavior of K decreased with wavelength, presenting smaller values for long wavelengths. Non-colored samples (ZC1 and LV1) showed the lowest K values for all wavelengths.

Although VAF values for K between HD and BD showed similar spectral behavior (96.75%) (Tables 2 and 3), they presented statistically significant differences ($p \le 0.05$). This is probably due to the high values of the absorption coefficient of the human dentin for wavelengths shorter than 450 nm.

VAF coefficients (Tables 2 and 3) showed differences in the spectral behavior between colored and non-colored samples of ZC (VAF < 83.70%) and LV (VAF < 32.56%). K values for colored and non-colored specimens (ZC and LV) showed statistically significant differences ($p \le 0.05$). LV1 showed the lowest values (Fig. 2b). When all groups were compared with HD, colored samples showed a similar spectral behavior of K (VAF > 93.99%)

Table 2 – VAF comparison of the scattering and absorption coefficients and transmittance between IPS e.max® ZirCAD (Ivoclar Vivadent) system and human and bovine dentin samples.

Comparison of scattering and absorption coefficient and transmittance—IPS e.max® ZirCAD (IvoclarVivadent)

		HD		BD		ZC1		ZC2		ZC3	
		VAF	*p*	VAF	*p*	VAF	*p*	VAF	*p*	VAF	*p*
S	HD	100	–	99.92		99.52	*	99.31	*	99.70	*
	BD			100	–	99.36	*	99.47	*	99.59	*
	ZC1					100	–	98.77	*	99.93	*
	ZC2							100	–	99.26	*
	ZC3									100	–
K	HD	100	–	96.75	*	89.68	*	93.99	*	97.34	*
	BD			100	–	96.97	*	84.38	*	91.93	*
	ZC1					100	–	75.60	*	83.70	*
	ZC2							100	–	96.20	
	ZC3									100	–
T	HD	100	–	99.29		98.53	*	99.91	*	99.80	*
	BD			100	–	99.81		99.64	*	99.59	*
	ZC1					100	–	99.08	*	99.16	*
	ZC2							100	–	99.87	*
	ZC3									100	–

Statistical test: Non-parametric Mann–Whitney *U* test and VAF (%) (*) $p \leq 0.05$: statistically significant differences.

(Tables 2 and 3). Statistically significant differences were found between all groups except for LV3 and HD ($p > 0.05$).

3.3. *K/S* ratio

Fig. 3 shows the *K/S* ratio for ZC (a) and LV (b) zirconias. The values obtained for this ratio are higher for shorter wavelengths, decrease as the wavelength increases up to approximately 550 nm, and apparently kept a constant behavior for medium and long wavelengths. According to this results, for all wavelengths (with the exception of HD at 400 nm), the Kubelka–Munk scattering coefficient presents higher values than the absorption coefficient, being this effect more pronounced for medium and large wavelengths. It is noteworthy that for LV1, the values of the *K/S* ratio are close to zero for all wavelengths, indicating a strong prevalence of absorption over scattering for this group.

3.4. *Transmittance*

Fig. 4 shows the values of transmittance (*T*) as a function of wavelength for both zirconia systems: ZC (a) and LV (b)

Table 3 – VAF comparison of the scattering and absorption coefficients and transmittance between LAVA™ Zirconia (3M ESPE) system and human and bovine dentin samples.

Comparison of scattering and absorption coefficient and transmittance—LAVA™ Zirconia (3M ESPE)

		HD		BD		LV1		LV2		LV3	
		VAF	*p*	VAF	*p*	VAF	*p*	VAF	*p*	VAF	*p*
S	HD	100	–	99.92		96.80	*	98.88	*	98.88	*
	BD			100	–	96.43	*	98.89	*	99.21	*
	LV1					100	–	97.22	*	94.69	*
	LV2							100	–	99.26	*
	LV3									100	–
K	HD	100	–	96.75	*	38.62	*	95.06	*	98.03	
	BD			100	–	53.94	*	88.36	*	94.01	*
	LV1					100	–	26.92	*	32.56	*
	LV2							100	–	96.59	*
	LV3									100	–
T	HD	100	–	99.29		97.91	*	98.91	*	99.70	*
	BD			100	–	98.29	*	99.37	*	99.05	*
	LV1					100	–	99.53	*	98.76	*
	LV2							100	–	99.29	
	LV3									100	–

Statistical test: Non-parametric Mann–Whitney *U* test and VAF (%) (*) $p \leq 0.05$: statistically significant differences.

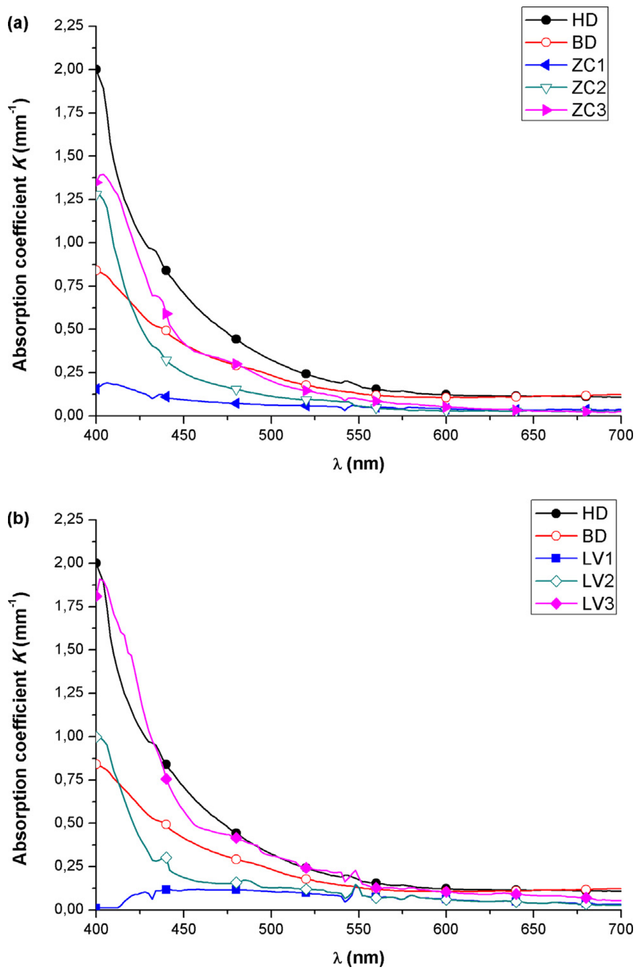

Fig. 2 – Spectral distribution of the Kubelka–Munk absorption coefficient (K) for (a) IPS e.max®ZirCAD (Ivoclar Vivadent) and (b) LAVA™ Zirconia (3M ESPE) systems compared with human and bovine dentin samples.

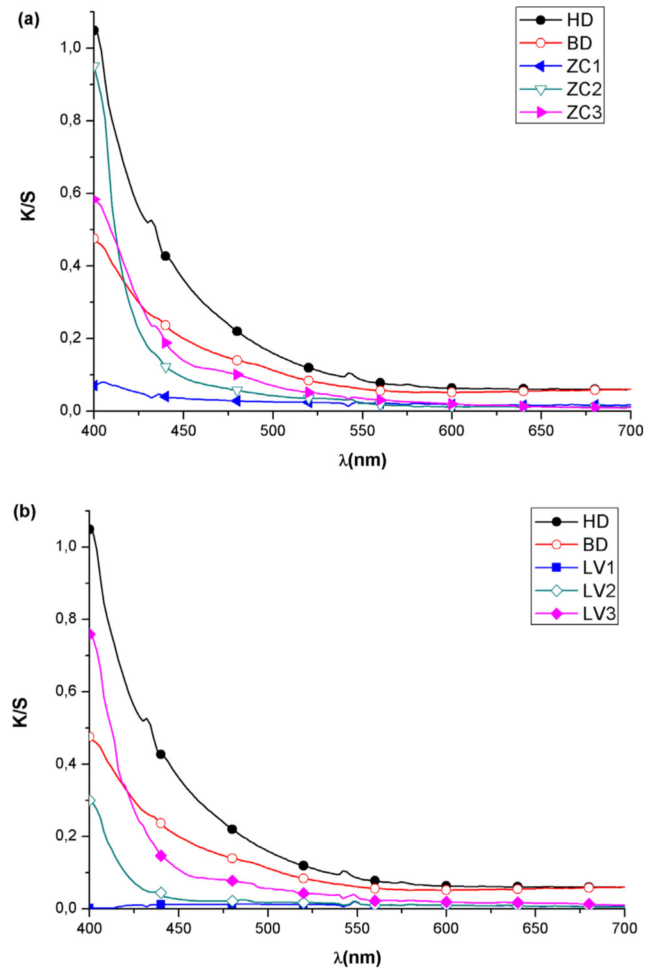

Fig. 3 – Spectral distribution of K/S ratio for (a) IPS e.max®ZirCAD (Ivoclar Vivadent) and (b) LAVA™ Zirconia (3M ESPE) systems compared with human and bovine dentin samples.

compared with HD and BD. The spectral behavior of T increased with wavelength, presenting higher values for long wavelengths.

The spectral behavior of T for HD and BD was very similar (VAF = 99.29%) and were not significantly different ($p > 0.05$) (Tables 2 and 3).

Although all zirconia groups showed similar spectral behavior of T to the human dentin ($97.91 \leq \text{VAF} \leq 99.91$), the values were statistically different ($p \leq 0.05$) (Tables 2 and 3). Both zirconia systems showed lower T values than the dentins. Nevertheless, LV showed the lowest values (Fig. 4). For ZC, statistically significant differences were found ($p \leq 0.05$) between T values for all groups (Table 2), while for LV, no statistically significant differences were found ($p \leq 0.05$) between T values for colored samples (LV2 and LV3) (Table 3).

4. Discussion

A successful dental esthetic restoration involves a visible match between the restorative material and the natural teeth. The main optical properties involved in such visible match are basically determined by the absorption and scattering characteristics of the light emerging on the surface and inside the substrate. Therefore, the present study used the Kubelka–Munk theory to evaluate the optical properties (scattering, absorption and transmittance) from two commercially available 3Y-TZP ceramic systems and the human and bovine dentins, at 400–700 nm wavelength range.

The use of a coupling medium between the sample and the background avoids the interference of the air refractive index, which could result in different values of optical properties [21].

The spectral behavior of S and T was very similar between the dentins (HD and BD) and all the ceramic groups, with VAF values above 96%. Yet, these values were statistically different ($p \leq 0.05$), except for the comparison ZC1-BD that showed a VAF of 99.8% with no statistical difference (Tables 1 and 2). Similar spectral behavior of K was observed. However, the VAF comparison between LV1 (non-colored LV) and the dentins (HD and BD) showed values below 55%, and once again the values were statistically different ($p \leq 0.05$), except for the comparison LV3-HD that showed a VAF of 98% with no statistical

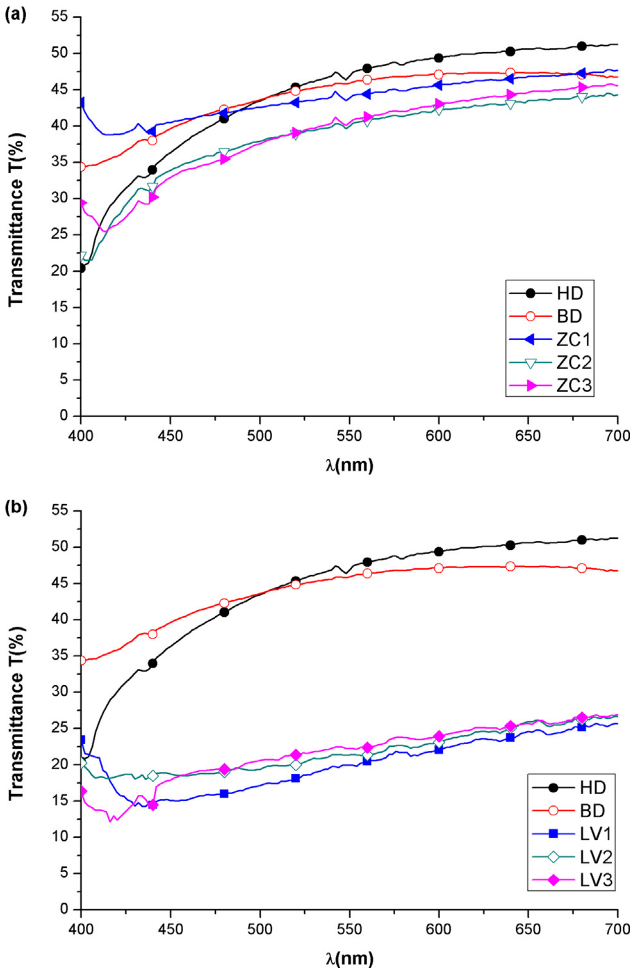

Fig. 4 – Spectral distribution of transmittance (T%) for (a) IPS e.max®ZirCAD (Ivoclar Vivadent) and (b) LAVA™ Zirconia (3M ESPE) systems compared with human and bovine dentin samples.

difference (Tables 1 and 2). The results from the present work mostly reject the study hypothesis.

It is known that the structure of the dentin varies with depth, meaning, deeper dentin (near to the pulp) has greater density of tubules with larger diameters than superficial dentin [18], which may increase the scattering. The orientation of the tubules also varies with depth, and may affect the optical properties of the structure. As tooth preparation for zirconia-based restorations often results in the exposure of superficial dentin, this substrate was targeted in the present study.

Both, human and bovine dentine showed similar optical behavior, within the visible spectrum (VAF > 96%). Moreover, no statistically significant differences were found for the scattering coefficient (*S*) and transmittance (*T*) between them, which is probably due to the sample homogeneity and similar microstructures, as previously reported [18]. Considering the difficulty to obtain human anterior teeth in perfect conditions and the results of this study, it should be adequate to use bovine dentin as a substitute for human dentin to evaluate these optical properties.

The spectral behavior of the absorption coefficient (*K*) is similar for human and bovine enamel, with higher values at short wavelengths, which can be explained by the presence of the organic component, presumably aromatic aminoacids [22]. Since dentin presents more organic component than enamel, it was expected to find higher *K* values at short wavelengths. Differences in absorption between both types of dentins were also expected due to the natural differences in composition and structure among them. The organic content is higher in superficial human dentin than in superficial bovine dentin [23], which could justify the higher absorption values for HD found in the present study.

The *K*/*S* ratio showed a predominance of scattering (*S*), especially for medium and long wavelengths, for the materials (HD, BD, ZC and LV) evaluated. This effect is greater for the non-colored ceramics (ZC1 and LV1) than for the other materials, since they present absorption coefficient (*K*) values near to zero for all wavelengths in the visible spectrum, but the *S* values are considerably higher than the values for the colored ceramics. The pigments (oxides) present in the colored specimens are likely to be responsible for the absorption. Nevertheless, further research is necessary to improve knowledge on absorption between colored and non-colored zirconia.

Previous work [24] reported that scattering is the primary reason for the low translucency (opacity) of zirconias. This was confirmed for the 3Y-TZP ceramic systems evaluated in the present study with LV showing higher *S* and lower transmittance values than ZC (Figs. 1 and 4). These findings are in agreement with a previous report [8] that used the translucency parameter (TP) to show greater opacity for LV than for ZC.

It has been reported that light scattering is largely a function of the porosity of a material, so density plays a large role in the transparency of zirconia [25]. This should not play an important role for the ceramics evaluated in the present study since they have a density >99% [26] and, according to the manufacturers, an average grain size of approximately 0.5 μm. In addition, only pores larger than 50 nm cause significant scattering and thus reduction of transmission, while the maximum scattering efficiency is observed when the pore size is comparable with the wavelength of the incident radiation [25]. It is unlikely that the ceramic specimens from the present study present such large pores since pore diameter is often significantly smaller than the average grain size. Yet, residual porosity plays an important role in the scattering, mostly due to the large difference in refractive index between the ceramic and the air in the pores [27]. In fact, residual porosity represents the principal source of light scattering in ceramic materials, producing poor transparency even at a low level, such as 0.01% [27]. Anselmi-Tamburini et al. reported that a significant reduction of the in-line transmittance at low wavelength is only expected for a relative porosity of about 0.1%, which is higher than for the ceramic specimens of the present study. Thus, porosity alone cannot account for the observed lower transparency at low wavelengths [25].

For dentin, in contrast to enamel, the scattering and absorption coefficients do not change significantly for medium (543 nm) and large (632 nm) wavelengths [9]. Similar behavior was observed for scattering and absorption coefficients of HD and BD (Figs. 1 and 2). However, the *K* values at shorter wavelengths (<475 nm) are considerably different from the values at medium and long wavelengths.

Grain size is critical for zirconia ceramics. It has been reported that grain size above 1 μm lead to a lower stability and directly influences the mechanical and optical behavior of zirconia ceramics [28]. Zirconia was reported to be totally opaque (contrast ratio = 1) at 0.5 mm thick [29,30] that may justify its masking reputation. Zirconia systems with higher transmittance should be used to restore dental structures with no masking needs. Yet, zirconia-based restorations usually have a porcelain veneer that should have optical behavior similar to enamel for adequate esthetic appearance.

5. Conclusions

The optical behavior of the zirconia systems evaluated is different from the human dentin. Such difference should be taken into consideration to achieve a highly esthetic restoration with a natural appearance. In addition, bovine dentin (BD) can be used instead of human dentin (HD) to study the optical behavior of the dentin tissue.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.dental.2014.11.012.

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