Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.intl.elsevierhealth.com/journals/jden

Optical properties of CAD–CAM ceramic systems

Alvaro Della Bona *, *Audrea D. Nogueira*, *Oscar E. Pecho*

Post-graduate Program in Dentistry, Dental School, University of Passo Fundo, Campus I, BR 285, Km 171, PO Box 611, 99001-970 Passo Fundo, RS, Brazil

ARTICLE INFO

Article history:
Received 11 May 2014
Received in revised form
4 July 2014
Accepted 7 July 2014

Keywords:
Transmittance
Translucency
Opacity
Opalescence
Dental ceramics

ABSTRACT

Objectives: To evaluate the direct transmittance (T%), translucency, opacity and opalescence of CAD–CAM ceramic systems and the correlation between the translucency parameter (TP) and the contrast ratio (CR).

Methods: Specimens of shades A1, A2 and A3 ($n = 5$) were fabricated from CAD–CAM ceramic blocks (IPS e.max® CAD HT and LT, IPS Empress® CAD HT and LT, Paradigm™ C, and VITABLOCS® Mark II) and polished to 1.0 ± 0.01 mm in thickness. A spectrophotometer (Lambda 20) was used to measure T% on the wavelength range of 400–780 nm. Another spectrophotometer (VITA Easyshade® Advance) was used to measure the CIE $L^*a^*b^*$ coordinates and the reflectance value (Y) of samples on white and black backgrounds. TP, CR and the opalescence parameter (OP) were calculated. Data were statistically analysed using VAF (variance accounting for) coefficient with Cauchy–Schwarz inequality, one-way ANOVA, Tukey's test, Bonferroni correction and Pearson's correlation.

Results: T% of some ceramic systems is dependent on the wavelength. The spectral behaviour showed a slight and constant increase in T% up to approximately 550 nm, then some ceramics changed the behaviour as the wavelength gets longer. TP and CR values ranged, respectively, from 16.79 to 21.69 and from 0.52 to 0.64 ($r^2 = -0.97$). OP values ranged from 3.01 to 7.64.

Conclusions: The microstructure of CAD–CAM ceramic systems influenced the optical properties. TP and CR showed a strong correlation for all ceramic systems evaluated. Yet, all ceramics showed some degree of light transmittance.

Significance: In addition to shade, this study showed that other optical properties influence on the natural appearance of dental ceramics.

1. Introduction

Over the past 25 years, computer-aided design (CAD) and computer-aided manufacturing (CAM) have become an increasingly useful technology in dentistry.[1] With the evolution of this methodology and the increased of aesthetic requirements of patients and dental professionals, a large variety of aesthetic materials have been generated.[2]

The aesthetic appearance of a restoration should match the surrounding dental tissues. This requires that the optical properties of the restorative material need to be similar to that of the natural teeth.[2,3] A tooth, as most biological tissues, reflects, diffuses, absorbs and transmits light reaching its surface. Thus, for acceptable aesthetic results, favourable shade matching of the all-ceramic restorations should be achieved by controlling light absorption, reflection and transmission of dental ceramic materials.[2,4]

* Corresponding author. Tel.: +55 54 3316 8395; fax: +55 54 3316 8403.
E-mail address: dbona@upf.br (A. Della Bona).
http://dx.doi.org/10.1016/j.jdent.2014.07.005

Many methods of evaluating light reflectance, light transmittance and colour have been reported aiming to understand the phenomena that occur when light strikes an object.[5] The CIE (Commission Internationale de l'Eclairage) has been responsible for introducing the main colour systems, colour difference (ΔE) concepts and illumination patterns used in science.[5,6] Considering the CIELAB system, $\Delta E^{*}ab$ is the standard parameter for colour matching perception.[5,6] However, it only considers the CIELAB colour space (L^{*}: value coordinate; a^{*}: red–green coordinate; b^{*}: yellow–blue coordinate), neglecting other components and factors on colour perception, such as: translucency, opalescence, fluorescence, and surface texture.[7]

Translucency is one of the primary factors in controlling aesthetics and it is critical in the selection of materials. All ceramic systems have different composition, microstructure, crystalline content and phases (*e.g.*, lithium disilicate, fluorapatite and leucite), which may influence the optical properties of these systems. An increase in the crystalline content to achieve greater strength often results in greater opacity.[8,9] Translucency is a property of a material that occurs when a light beam, in passing through it, is partly scattered, reflected, and transmitted through the object. The greater the quantity of light that passes through the object, the higher the translucency of the material.[8,10] Therefore, the translucency can be described as a state between complete opacity and transparency.[9] When the colour of a restoration is combined with proper translucency, the restoration can closely match the surrounding tooth structure.

Previous studies have reported on methods to evaluate translucency and opacity of aesthetic restorative materials, such as: direct transmittance of light,[11] the translucency parameter (TP)[4,12–16] and the contrast ratio (CR).[16–19] Recently, few studies compared some of these parameters and described possible correlations between them.[7,16,20] Despite of these studies, there is no standard or consensus on the method of choice to quantify translucency of aesthetic restorative materials.[7]

Opalescence is produced by scattering of shorter wavelengths of the visible light on particles the size of visible light wavelength or smaller, giving an object a bluish appearance in the reflected colour and an orange/brown appearance in the transmitted colour.[21,22] To produce highly aesthetic restorations that truly mimic the natural appearance of the tooth, materials with opalescent properties should be used.

As the optical properties of dental restorative materials are critical for acceptable aesthetic restorations, the objective of this study was to evaluate important optical properties of CAD–CAM ceramic systems, such as: direct transmittance, translucency, opacity and opalescence, testing the hypotheses that (1) the material microstructure significantly influences these optical properties and (2) there is a strong correlation between TP and CR.

2. Material and methods

The ceramic systems evaluated in the present study are shown in Table 1. Ceramic specimens (10 mm × 20 mm × 1 mm) from shades A1, A2 and A3 were fabricated using a CAD–CAM system (Sirona CEREC® inLab MC XL, Sirona Dental Services GmbH, Bensheim, Germany). All specimens ($n = 5$) were polished to 1 μm diamond paste and the thickness was verified with a digital calliper (Digimatic calliper, Mitutoyo Corp., Tokyo, Japan). Accepted thickness values were 1 ± 0.01 mm. IPS Empress® CAD and IPS e.max® CAD required additional heat treatment at 790 °C and 850 °C for 20 min, respectively.

2.1. *Direct transmittance (T%)*

For measuring the direct transmittance of light, in percentage (*T*%), an ultraviolet–visible (UV/vis) spectrophotometer (Lamba 20—Perkin Elmer, Orwalk, CT, USA) was used. The calibration parameters of the spectrophotometer in scan mode included: slit of 0.5 nm, scan speed of 240 nm/min, 10 nm smooth.

Table 1 – Description of the CAD–CAM ceramic systems used in the study.

Groups*	Shade	Brand	Ceramic type**	Manufacturer
emLT A1	A1	IPS e.max® CAD	Lithium disilicate-based glass–ceramic	Ivoclar Vivadent, Schaan, Liechtenstein
emLT A2	A2			
emLT A3	A3			
emHT A1	A1			
emHT A2	A2			
emHT A3	A3			
EmpLT A1	A1	IPS Empress® CAD	Leucite-reinforced glass–ceramic	Ivoclar Vivadent, Schaan, Liechtenstein
EmpLT A2	A2			
EmpLT A3	A3			
EmpHT A1	A1			
EmpHT A2	A2			
EmpHT A3	A3			
PaC A1	A1	Paradigm™C	Leucite-reinforced glass–ceramic	3M ESPE, St. Paul, MN, USA
PaC A2	A2			
PaC A3	A3			
MII A1	A1	VITABLOCS® Mark II for CEREC®	Feldspathic ceramic	VITA Zahnfabrik, Bad Sackingen, Germany
MII A2	A2			
MII A3	A3			

* LT (low translucency); HT (high translucency).
** From Ref. [8].

Measurements were made on the wavelength range of 400–780 nm with data interval of 5 nm. The mean $T\%$ values at 525 nm wavelength were used for comparison between materials and methods.[11] In addition, the values at 400 nm and at 780 nm were also considered for some analyses.

2.2. Translucency parameter (TP)

A dental spectrophotometer (VITA Easyshade® Advance, Vita Zahnfabrik, Germany) in Tooth Single mode was used to record the CIELAB coordinates (L^*, a^* and b^*) of the ceramic samples. Translucency parameter (TP) values were determined by calculating the colour difference between readings against black ($L^* = 1.12$, $a^* = -0.12$ and $b^* = -0.48$) and white ($L^* = 97.89$, $a^* = -0.11$ and $b^* = -0.18$) backgrounds for the same specimen, according to the following equation:[12]

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

where the subscripts B and W refer to colour coordinates over black and white backgrounds, respectively. The greater the TP value, the higher the translucency of the ceramic specimen.

2.3. Contrast ratio (CR)

L^* values were also used to calculate the spectral reflectance, Y (luminance from Tristimulus Colour Space/XYZ), as follows:[7,23]

$$Y = \left(\frac{L^* + 16}{116}\right)^3 \times Y_n \quad (2)$$

For simulated object colours, the specified white stimulus normally chosen is one that has the appearance of a perfect reflecting diffuser, normalized by a common factor so that Y_n is equal to 100.[24] Y values of the specimens recorded on black (Y_b) and white (Y_w) backgrounds were used to calculate the contrast ratio (CR) as follows:[7,25,26]

$$\mathrm{CR} = \frac{Y_b}{Y_w} \quad (3)$$

CR values range from 0.0 (transparent material) to 1.0 (totally opaque material).

2.4. Opalescence parameter (OP)

The values from a^* and b^* coordinates recorded (VITA Easyshade® Advance, Vita Zahnfabrik, Germany) from the ceramic specimens placed on a black (B) and a white (W) backgrounds were also used to estimate the opalescence parameter (OP) according to the following equation:[27,28]

$$\mathrm{OP} = \sqrt{(a_B^* - a_W^*)^2 + (b_B^* - b_W^*)} \quad (4)$$

2.5. Statistical analysis

To determine the level of similarity of two different distributions of transmittance, the VAF (variance accounting for) coefficient with Cauchy–Schwarz inequality was used as follows:

$$\mathrm{VAF} = \frac{\left(\sum_{k=400}^{780} a_k b_k\right)^2}{\left(\sum_{k=400}^{780} a_k^2\right)\left(\sum_{k=400}^{780} b_k^2\right)} \quad (5)$$

where a_k is the value of each transmittance curve (for each wavelength) and b_k is the equivalent for another specimen measurement. The closer this coefficient gets to unity (100%), the more similar the curves will be. The VAF coefficient has been used to compare spectral behaviour of optical properties of biomaterials.[4,29–31]

Data from the optical properties ($T\%$ at 400 nm, at 525 nm and at 780 nm; TP; CR; and OP) were statistically analysed using analysis of variance (ANOVA) and the difference between groups were evaluated by Tukey's multiple comparison test ($\alpha = 0.05$). The Bonferroni correction was applied, increasing the level of significance ($\alpha = 0.001$). All statistical analyses were performed using a standard statistical software package (Origin 8.0, OriginLab® Corporation, Northampton, MA, USA). In addition, TP and CR were evaluated by Pearson correlation to determine the coefficient of determination (r-squared value).

3. Results

3.1. Direct transmittance (T%)

The wavelength distribution of transmittance ($T\%$ curves) for all ceramics in shades A1, A2 and A3 are shown in Fig. 1A–C. The transmittance values of some ceramic systems are dependent on the wavelength. The spectral behaviour showed a slight and constant increase up to approximately 550 nm, then some ceramics changed the behaviour as the wavelength gets longer. The spectral behaviour of $T\%$ (Fig. 1) was very similar when all shades (A1, A2 and A3) were compared within each ceramic system ($95.97 \le \mathrm{VAF} \le 99.99$).

Considering the VAF coefficients (Table 2), the spectral behaviour of ceramics emLT–emHT and EmpLT–EmpHT are very similar for shades A1 (97.40% and 99.36%), A2 (99.91% and 99.58%) and A3 (99.17% and 99.60%), respectively. The spectral behaviour of both e.max ceramics (emLT and emHT) presented significant differences when compared with other ceramics (Table 2).

Considering shade A1 (Fig. 1A and Table 3), ceramics PaC and MII showed similar values for $T\%_{400\ \mathrm{nm}}$ ($p > 0.001$), with EmpHT and emLT presented the greatest and the lowest values, respectively. Ceramics emHTA1 and PaCA1, and EmpLTA1 and MIIA1 showed similar values ($p > 0.001$) for $T\%_{525\ \mathrm{nm}}$. At longer wavelengths (780 nm), emHTA1 presented the highest $T\%$ values. The ceramics emLTA1 and EmpHTA1, as well as the ceramics EmpLTA1, PaCA1 and MIIA1 did not show significant differences ($p > 0.001$) for $T\%_{780\ \mathrm{nm}}$ (Table 3).

Considering shade A2 (Fig. 1B and Table 3), ceramics emLT and EmpHT showed the lowest and the highest values, respectively, for $T\%_{400\ \mathrm{nm}}$. Similar $T\%_{525\ \mathrm{nm}}$ values were found for ceramics emLTA2 and MIIA2, and for ceramics emHTA2, EmpLTA2 and PaCA2 ($p > 0.001$). Ceramic emHTA2 showed the highest value for $T\%_{780\ \mathrm{nm}}$ while MIIA2, PaCA2 and EmpLTA2 were statistically similar ($p > 0.001$) and showed the lowest values for $T\%_{780\ \mathrm{nm}}$ (Table 3).

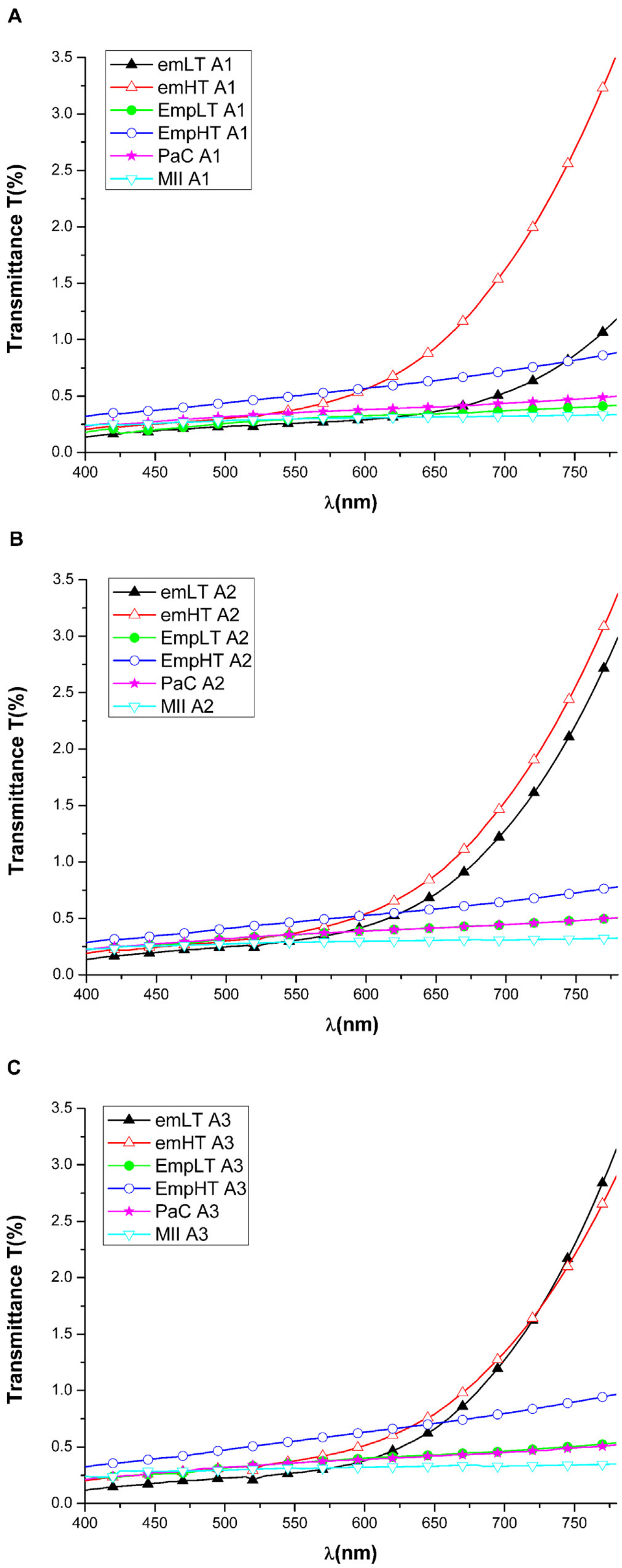

Fig. 1 – Wavelength distribution of transmittance *T*(%) for shades A1 (A), A2 (B) and A3 (C).

Considering shade A3 (Fig. 1C and Table 3), ceramics emLT and EmpHT showed the lowest and the highest values, respectively, for $T\%_{400\ nm}$. Ceramics emLTA3, emHTA3, PaCA3 and MIIA3 showed the lowest values ($p > 0.001$) for $T\%_{525\ nm}$. Ceramic emLTA3 showed the highest value for $T\%_{780\ nm}$, while EmpLTA3, EmpHTA3, PaCA3 and MIIA3 were statistically similar ($p > 0.001$) and showed the lowest values for $T\%_{780\ nm}$ (Table 3).

3.2. *Translucency parameter (TP)*

For A1 shade, ceramics EmpHT and PaC showed the highest TP values (21.59 and 21.16, respectively) and emLT showed the lowest TP value (16.79) (Table 3, Fig. 2). Ceramics EmpHT and PaC showed the greatest TP values and the ceramics emLT and MII showed the lowest TP values for shades A2 and A3, in addition to emHT for the later (Table 3, Fig. 2).

3.3. *Contrast ratio (CR)*

Ceramic emLT showed the greatest CR value for A1 shade. Ceramics emLT and MII showed the greatest CR value for A2 and A3 shades. Ceramics EmpHT and PaC showed the lowest CR values, irrespective of the shade (A1, A2 or A3) (Table 3 and Fig. 3).

TP and CR showed a strong correlation ($r^2 = -0.97$) for all ceramics examined in the present study (Fig. 4), meaning, as the TP decreases, CR increases. This correlation was confirmed for each ceramic system: emLT ($r^2 = -0.97$), emHT ($r^2 = -0.93$), EmpLT ($r^2 = -0.94$), EmpHT ($r^2 = -0.96$), PaC ($r^2 = -0.92$) and MII ($r^2 = -0.97$).

3.4. *Opalescence parameter (OP)*

Ceramics emLT and MII showed, respectively, the greatest and the lowest OP values for A1 shade. Ceramics emHT and MII showed the lowest OP values for A2 shade. Ceramics EmpLT

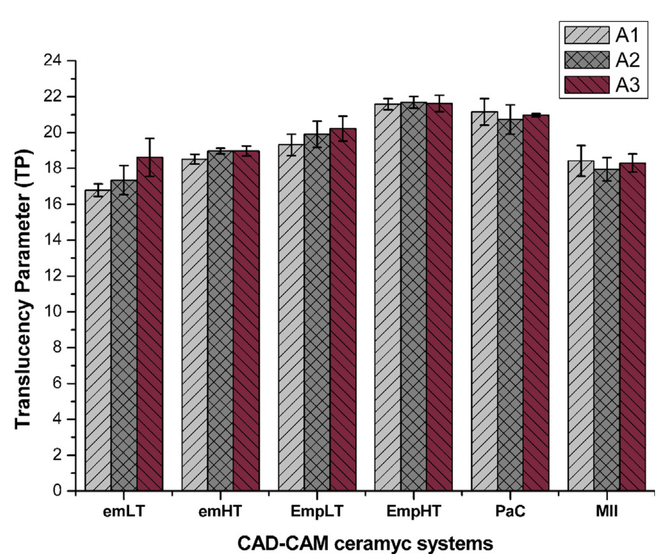

Fig. 2 – Mean and standard deviation values of translucency parameter (TP) of CAD–CAM ceramic systems for shades A1, A2 and A3.

Table 2 – VAF values* of transmittance spectral behaviour for all CAD–CAM ceramic evaluated in A1, A2 and A3 shades.

Ceramic groups		VAF values of transmittance spectrum					
		emLT (%)	emHT (%)	EmpLT (%)	EmpHT (%)	PaC (%)	MII (%)
VAF for A1 shade	emLT		97.40	79.94	85.33	79.17	70.95
	emHT	97.40		68.36	75.15	67.22	57.55
	EmpLT	79.94	68.36		99.36	99.85	98.08
	EmpHT	85.33	75.15	99.36		99.14	95.99
	PaC	79.17	67.22	99.85	99.14		98.78
	MII	70.95	57.55	98.08	95.99	98.78	
VAF for A2 shade	emLT		99.91	65.78	71.46	65.50	55.48
	emHT	99.91		68.06	73.68	67.77	57.75
	EmpLT	65.78	68.06		99.58	99.99	98.40
	EmpHT	71.46	73.68	99.58		99.52	96.53
	PaC	65.50	67.77	99.99	99.52		98.55
	MII	55.48	57.75	98.40	96.53	98.55	
VAF for A3 shade	emLT		99.17	64.48	70.01	63.18	51.79
	emHT	99.17		72.73	77.87	71.48	60.35
	EmpLT	64.48	72.73		99.60	99.95	97.49
	EmpHT	70.01	77.87	99.60		99.35	95.38
	PaC	63.18	71.48	99.95	99.35		98.05
	MII	51.79	60.35	97.49	95.38	98.05	

* VAF values: The closer this coefficient gets to unity (100%), the more similar the curves will be.

and emHT showed, respectively, the greatest and the lowest OP values for A3 shade (Table 3 and Fig. 5).

4. Discussion

This study presented the transmittance spectral behaviour of ceramics according to the wavelength distribution and evaluated optical properties, such as TP, CR, OP and T%. The results of this study confirmed a strong correlation between TP and CR,[7,16,20] yet suggesting a different optical behaviour for the ceramics evaluated, confirming both experimental hypotheses.

As previously reported, a dental spectrophotometer (Vita Easyshade) was used to obtain the values for L^*, a^* and b^* coordinates, which were used to estimate the optical parameters,[7,28,32] except for T% that cannot be evaluated with this spectrophotometer, therefore another equipment was used (Lamba 20—Perkin Elmer). Therefore, this should be taken in consideration to evaluate the results from the present study.

There are important relationships between chemical composition, atomic structure, fabrication process, microstructure and properties of dental ceramics.[8] However, in a previous study,[15] L^*, a^*, b^* and TP values did not show significant differences between samples of lithium

Table 3 – Mean and SD values of transmittance (T%), translucency parameter (TP), contrast ratio (CR) and opalescence parameter (OP) for all experimental groups.

Ceramic groups	Optical parameters					
	$T\,(\%)_{400\,nm}$	$T\,(\%)_{525\,nm}$	$T\,(\%)_{780\,nm}$	TP	CR (%)	OP
emLT A1	0.14 ± 0.01a	0.24 ± 0.01a	1.18 ± 0.13b	16.79 ± 0.35a	0.64 ± 0.01c	6.59 ± 0.39d
emHT A1	0.20 ± 0.01c	0.33 ± 0.01c	3.53 ± 0.34c	18.51 ± 0.27b	0.59 ± 0.01b	4.41 ± 0.12b
EmpLT A1	0.18 ± 0.01b	0.28 ± 0.01b	0.42 ± 0.02a	19.32 ± 0.60b	0.59 ± 0.01b	5.88 ± 0.15c
EmpHT A1	0.32 ± 0.01e	0.47 ± 0.02d	0.89 ± 0.06b	21.59 ± 0.31c	0.53 ± 0.01a	4.38 ± 0.15b
PaC A1	0.23 ± 0.01d	0.34 ± 0.01c	0.50 ± 0.02a	21.16 ± 0.74c	0.53 ± 0.01a	4.39 ± 0.40b
MII A1	0.24 ± 0.02d	0.29 ± 0.02b	0.34 ± 0.02a	18.43 ± 0.86b	0.59 ± 0.02b	3.01 ± 0.07a
emLT A2	0.14 ± 0.02a	0.26 ± 0.01a	2.99 ± 0.17c	17.35 ± 0.81a	0.62 ± 0.02c	6.58 ± 0.51c,d
emHT A2	0.19 ± 0.01b	0.32 ± 0.01b	3.38 ± 0.32d	18.97 ± 0.16b,c	0.58 ± 0.01b	4.86 ± 0.08a
EmpLT A2	0.23 ± 0.02c	0.34 ± 0.03b	0.54 ± 0.05a,b	19.91 ± 0.73c,d	0.58 ± 0.01b	7.05 ± 0.16d
EmpHT A2	0.29 ± 0.03d	0.47 ± 0.04c	0.79 ± 0.08b	21.69 ± 0.33e	0.52 ± 0.01a	6.07 ± 0.30b,c
PaC A2	0.22 ± 0.01b,c	0.34 ± 0.01b	0.51 ± 0.03a	20.73 ± 0.81d,e	0.54 ± 0.01a	6.02 ± 0.18b
MII A2	0.23 ± 0.01c	0.28 ± 0.01a	0.33 ± 0.01a	17.95 ± 0.65a,b	0.61 ± 0.01c	4.42 ± 0.22a
emLT A3	0.12 ± 0.02a	0.33 ± 0.06a	3.14 ± 0.25c	18.62 ± 1.06a	0.60 ± 0.02c	6.96 ± 0.22c
emHT A3	0.20 ± 0.01b	0.33 ± 0.01a	2.90 ± 0.40b	18.98 ± 0.28a	0.57 ± 0.01b	5.24 ± 0.14a
EmpLT A3	0.25 ± 0.02c	0.40 ± 0.04b	0.54 ± 0.10a	20.22 ± 0.69b	0.56 ± 0.02b	7.64 ± 0.10d
EmpHT A3	0.32 ± 0.03d	0.52 ± 0.05c	0.77 ± 0.13a	21.63 ± 0.46c	0.53 ± 0.01a	6.89 ± 0.11c
PaC A3	0.21 ± 0.01b,c	0.35 ± 0.01a,b	0.52 ± 0.01a	20.98 ± 0.09b,c	0.54 ± 0.01a	6.33 ± 0.13b
MII A3	0.24 ± 0.02b,c	0.30 ± 0.02a	0.35 ± 0.02a	18.31 ± 0.51a	0.60 ± 0.01c	6.15 ± 0.21b

Different letters show statistical differences of mean values within same shade and parameter (column) ($p < 0.001$; Bonferroni correction).

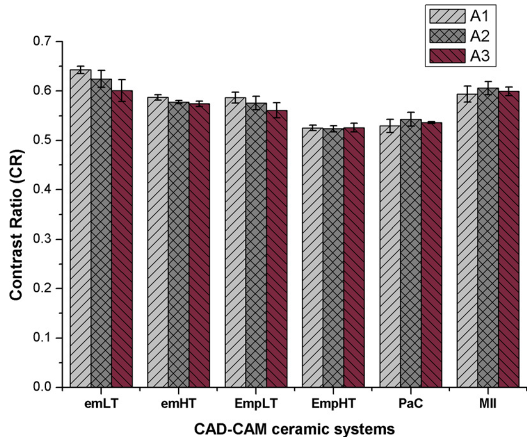

Fig. 3 – Mean and standard deviation values of contrast ratio (CR) of CAD–CAM ceramic systems for shades A1, A2 and A3.

disilicate-based ceramics, manufactured by different fabrication process (IPS e.max Press and IPS e.max CAD), which indicates that different fabrication techniques may not affect the translucency of such ceramic materials. In addition, sintered all-ceramic restorations are now being replaced by heat-pressed or machined all-ceramic restorations with better-controlled processing steps.[33]

The spectral distribution of direct transmittance ($T\%$ curves) for all shades of CAD–CAM ceramic systems showed that the value for this parameter increases as the wavelength increased from 400 nm to 780 nm (Fig. 1). This behaviour demonstrates the transmittance dependency of the wavelength, agreeing with previous studies.[11,34,35]

When light passes through a translucent material, is reduced by the scattering of small-sized particles, such as filler particles and porosity voids. The portion of incident light that emerges as diffuse transmission is essential for colour perception and appearance of dental ceramics.[11,36] The

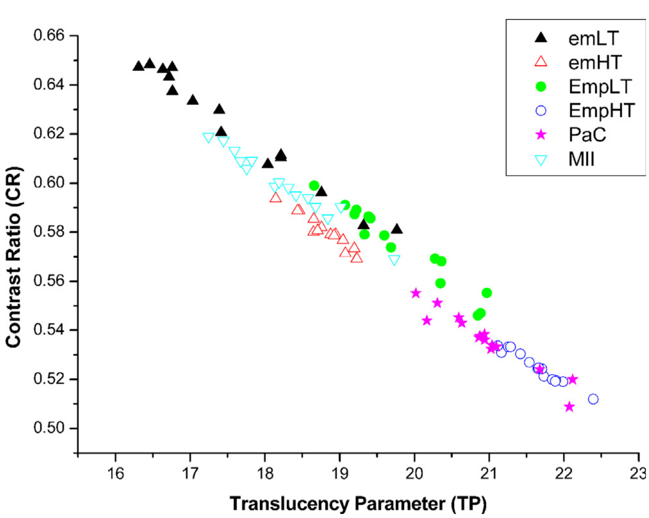

Fig. 4 – Correlation between TP and CR of CAD–CAM ceramic systems.

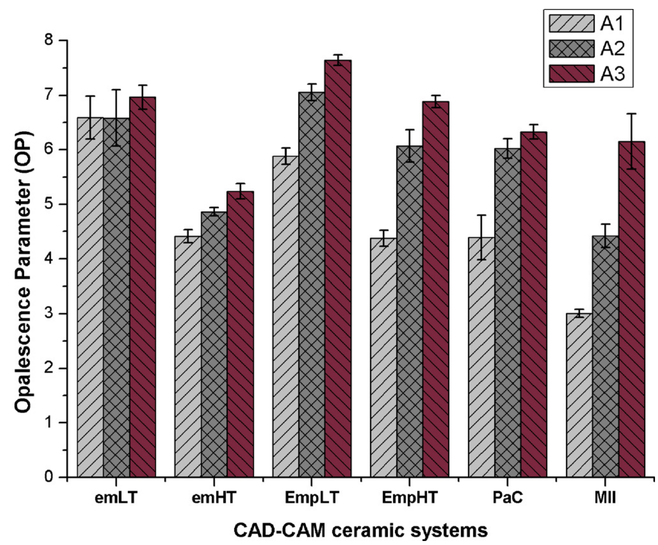

Fig. 5 – Mean and standard deviation values of opalescence parameter (OP) of CAD–CAM ceramic systems for shades A1, A2 and A3.

Rayleigh scattering theory, which applies for small particles, describe that higher scattering occurs at lower wavelengths.[11,35] Thus, the decrease in the transmittance at lower wavelengths (Fig. 1) could be caused by a higher scattering of light in the ceramic materials, which was previously suggested for dental porcelains.[11]

The spectral behaviour of $T\%$ was very similar when all shades (A1, A2 and A3) were compared within each ceramic system ($95.97 \leq \text{VAF} \leq 99.99$), suggesting that the transmittance spectral behaviour depends on the material microstructure and composition.

The transmittance values of emLT was the lowest of all ceramics ($p > 0.05$), irrespective of the shade (A1, A2 or A3) at $T\%_{400\ \text{nm}}$, maintaining similar behaviour at $T\%_{525\ \text{nm}}$. Such behaviour changed considerably at $T\%_{780\ \text{nm}}$ (Table 3). This result suggests that the transmittance cannot be adequately estimated from few values at some specific wavelengths.

The translucency parameter (TP) is a standardized method to calculate translucency considering the entire visible spectrum. For materials commonly viewed in reflection, the TP can be established as the colour difference between a specified thickness of material on black and white backings. However, such a colour difference, is valid only for the illuminant and observer used in the colour calculations.[5] In previous study, TP values of 1 mm thick human dentine and human enamel (employing a spectrophotometer with 3 mm round aperture) were 16.4 and 18.7, respectively.[37] Such values are consistent with the ones found in the present study, meaning: lithium disilicate-base glass–ceramics (from 16.79 to 18.98), feldspathic ceramics (17.95–18.43) and leucite reinforced glass–ceramics (from 19.32 to 21.69). The chemical composition and the microstructure, mainly the average particle size, may explain the differences in TP values.

The relative amount, nature, shape and particle size distribution of the crystalline phase(s) and porosity directly influence the mechanical and optical properties of ceramic material.[8,33] Greater crystalline content results in higher flexural strength but also can decrease translucency.[33] Leucite-based and feldspathic ceramics are aluminosilicate consisting of amorphous and crystalline phases. IPS e.max® CAD system is a lithium disilicate-based glass ceramic ($Li_2Si_2O_5$) with a crystalline content of about 65% and a flexural strength of 262 ± 88 MPa. Leucite-reinforced glass–ceramics ($KAlSi_2O_6$), such as IPS Empress® CAD and Paradigm™ C have a crystalline content of about 35% and a flexural strength of about 160 MPa. Feldspar can have different chemical composition [(Na,K).$AlSi_3O_8$] resulting in different crystalline structures. VITA Mark II is a sanidine ($KAlSi_3O_8$) reinforced feldspathic ceramic (a crystalline content of about 30% and a flexural strength of 122 ± 13 MPa).[33] VAF values of T% from EmpLT, EmpHT, PaC and MII (95.38–98.78%) (Table 2) confirm that crystalline content influences the optical properties.

Systems which present LT and HT options showed different values of translucency (Table 3) probably because of crystalline formation. Lithium disilicate ceramics, in partially crystallized state, can present two crystal nuclei: lithium metasilicate (Li_2SiO_3) and lithium disilicate ($Li_2Si_2O_5$). The translucency of these ceramics can be adjusted by varying the crystallization heat treatment, which dictates crystalline content and crystal size. Thus HT ceramic exhibits crystals of 1.5 × 0.8 μm in a glassy matrix, whereas LT ceramic exhibits smaller crystals (0.8 × 0.2 μm) interlocked in a high density matrix.[33]

Additionally, matching refractive indexes of the crystalline phase and glass matrix is also important for controlling the translucency and the inherent appearance of the ceramic material. This may be the reason for the TP values of MII.

Contrast ratio calculation involves the reflectance values of a specific thickness of material over black and white backgrounds. Previous studies[16,18–20] showed higher CR values than the ones from the present study, which is probably due to the use of different measuring devices and ceramic materials.

TP and CR showed a strong correlation: as TP decreases, CR increases. This correlation was showed in previous studies.[7,16,20] Nogueira and Della Bona also showed a strong correlation between CR and TP ($r^2 = -0.97$) and a lower correlation between CR and $T\%_{525\ nm}$ (direct transmittance at 525 nm) ($r^2 = 0.85$) when CAD–CAM ceramic system were evaluated.[7] Spink et al. evaluated different ceramic systems and showed a no-linear relationship between CR and T% (average percent of total transmission) ($r^2 = 0.80$). However, when one of the experimental groups was excluded because it was too opaque for CR measurement, although it showed a T% value of 15.25 ± 0.46, the correlation increased ($r^2 = 0.97$). They concluded that CR, which measures diffuse reflectance, does not detect small changes in light transmission, when materials present high scattering and absorption coefficients. CR could be used only for ceramic materials with a percent of total transmission of at least 50%.[20]

OP values were obtained following the methodology proposed by Ardu et al., using a dental spectrophotometer, which is useful for clinical practice.[28] Shiraishi et al. reported OP values (5.27–12.11) for 1 mm thick porcelains, which are a little higher than the ones found in the present study.[38] Porcelains with higher OP values were associated with increasing amounts of some oxides, such as: ZrO_2, Y_2O_3, SnO_2 and V_2O_5. The higher the chromatic shade, the higher the content of these oxides. A strong correlation was found between ZrO_2 and Y_2O_3 concentrations and OP values ($r^2 = 0.74$ and $r^2 = 0.85$, respectively).[38]

The findings of the present study suggest that optical properties are influenced by the material microstructure and composition. Because colour and other optical properties are important for shade matching and aesthetic appearance in dentistry, studies on colour should include additional, seldom reported, optical properties, such as scattering and absorption of light. In addition, the monolithic ceramic samples used in this study are not representative of most ceramic restorations, which are typically multilayer structures bonded to another substrate. Therefore, future studies should investigate the optical properties considering the material microstructure and composition, combining optical properties and using multilayer structures bonded to different substrates.

5. Conclusions

Within the limitations of this study, results suggested that the microstructure of CAD–CAM ceramic systems influences their optical properties. In addition, TP and CR showed a strong correlation for all ceramic systems evaluated. Yet, the light transmittance behaviour of the ceramics was dependent on the wavelength, which should be fully explored on reporting this optical property.

Conflict of interest statement

The authors report no conflict of interest.

Acknowledgments

The authors acknowledge funding support from CNPq do Brasil (304995/2013-4) and CAPES do Brasil (PNPD 42009014007P4).

REFERENCES

1. Davidowitz G, Kotick PG. The use of CAD/CAM in dentistry. *Dental Clinics of North America* 2011;**55**:559–70.
2. Raptis NV, Michalakis KX, Hirayama H. Optical behavior of current ceramic systems. *International Journal of Periodontics and Restorative Dentistry* 2006;**26**:31–41.
3. Friebel M, Povel K, Cappius HJ, Helfmann J, Meinke M. Optical properties of dental restorative materials in the wavelength range 400 to 700 nm for the simulation of color perception. *Journal of Biomedical Optics* 2009;**14**:054029.
4. Pecho OE, Ghinea R, Ionescu AM, Cardona Jde L, Paravina RD, Perez MM. Color and translucency of zirconia ceramics, human dentine and bovine dentine. *Journal of Dentistry* 2012;**40**:e34–40.
5. Paravina RD, Powers JH, editors. *Esthetic color training in dentistry*. Maryland: Elsevier Mosby; 2004.
6. Commission Internationale de ÍEclairage. CIE technical report: colorimetry. *CIE Pub no.* 15.3. Vienna, Austria: CIE Central Bureau; 2004.

7. Nogueira AD, Della Bona A. The effect of a coupling medium on color and translucency of CAD–CAM ceramics. *Journal of Dentistry* 2013;**41**:e18–23.
8. Della Bona A. Bonding to ceramics: scientific evidences for clinical dentistry. Sao Paulo: Artes Medicas; 2009.
9. Sakaguchi RL, Powers JM. Fundamentals of materials science. In: Sakaguchi RL, Powers JM, editors. *Craig's restorative dental materials*. 13th ed. Philadelphia: Elsevier Mosby; 2012. p. 33–81.
10. Baldissara P, Llukacej A, Ciocca L, Valandro FL, Scotti R. Translucency of zirconia copings made with different CAD/CAM systems. *Journal of Prosthetic Dentistry* 2010;**104**:6–12.
11. Brodbelt RH, O'Brien WJ, Fan PL. Translucency of dental porcelains. *Journal of Dental Research* 1980;**59**:70–5.
12. Johnston WM, Ma T, Kienle BH. Translucency parameter of colorants for maxillofacial prostheses. *The International Journal of Prosthodontics* 1995;**8**:79–86.
13. Li Q, Yu H, Wang YN. Spectrophotometric evaluation of the optical influence of core build-up composites on all-ceramic materials. *Dental Materials* 2009;**25**:158–65.
14. Perez MM, Ghinea R, Ugarte-Alvan LI, Pulgar R, Paravina RD. Color and translucency in silorane-based resin composite compared to universal and nanofilled composites. *Journal of Dentistry* 2010;**38**:e110–6.
15. Bagis B, Turgut S. Optical properties of current ceramics systems for laminate veneers. *Journal of Dentistry* 2013;**41**:e24–30.
16. Barizon KTL, Bergeron C, Vargas MA, Qian F, Cobb DS, Gratton DG, *et al*. Ceramic materials for porcelain veneers. Part I: Correlation between translucency parameters and contrast ratio. *Journal of Prosthetic Dentistry* 2013;**110**:397–401.
17. Powers JM, Dennison JB, Lepeak PJ. Parameters that affect the color of direct restorative resins. *Journal of Dental Research* 1978;**57**:876–80.
18. Heffernan MJ, Aquilino SA, Diaz-Arnold AM, Haselton DR, Stanford CM, Vargas MA. Relative translucency of six all-ceramic systems. Part I: Core materials. *Journal of Prosthetic Dentistry* 2002;**88**:4–9.
19. Shono NN, Al Nahedh HN. Contrast ratio and masking ability of three ceramic veneering materials. *Operative Dentistry* 2012;**37**:406–16.
20. Spink LS, Rungruanganut P, Megremis S, Kelly JR. Comparison of an absolute and surrogate measure of relative translucency in dental ceramics. *Dental Materials* 2013;**29**:702–7.
21. Lee YK, Lu H, Powers JM. Measurement of opalescence of resin composites. *Dental Materials* 2005;**21**:1068–74.
22. Cho MS, Yu B, Lee YK. Opalescence of all-ceramic core and veneer materials. *Dental Materials* 2009;**25**:695–702.
23. Brainard DH. Color appearance and color difference specification. In: Shevell SK, editor. *The science of color*. Oxford: Elsevier; 2003.
24. Shanda J. CIE colorimetry. *Colorimetry - understanding the CIE system*. Vol 3. New Jersey: John Wiley & Sons, Inc.; 2007 p. 62.
25. Miyagawa Y, Powers JM, O'Brien WJ. Optical properties of direct restorative materials. *Journal of Dental Research* 1981;**60**:890–4.
26. Chu FCS, Chow TW, Chai J. Contrast ratios and masking ability of three types of ceramic veneers. *Journal of Prosthetic Dentistry* 2007;**98**:359–64.
27. Lee YK, Lu H, Powers JM. Changes in opalescence and fluorescence properties of resin composites after accelerated aging. *Dental Materials* 2006;**22**:653–60.
28. Ardu S, Feilzer AJ, Devigus A, Krejci I. Quantitative clinical evaluation of esthetic properties of incisors. *Dental Materials* 2008;**24**:333–40.
29. Perez MDM, Perez-Ocon F, Lucena-Martin C, Pulgar R. Stability and reproducibility of radiometric properties of light curing units (LCUs). Part I: QTH LCUs. *Dental Materials Journal* 2008;**27**:284–91.
30. Perez MDM, Perez-Ocon F, Lucena-Martin C, Pulgar R. Stability and reproducibility of radiometric properties of light curing units (LCUs). Part II: LED LCUs. *Dental Materials Journal* 2008;**27**:292–9.
31. Cardona JC, Ionescu AM, Gomez-Sotomayor R, Gonzalez-Andrades M, Campos A, Alaminos M, *et al*. Transparency in a fibrin and fibrin-agarose corneal stroma substitute generated by tissue engineering. *Cornea* 2011;**30**:1428–35.
32. Lehmann KM, Igiel C, Schmidtmann I, Scheller H. Four color-measuring devices compared with a spectrophotometric reference system. *Journal of Dentistry* 2010;**38**:e65–70.
33. Sakaguchi RL, Powers JM. Restorative materials—ceramics. In: Sakaguchi RL, Powers JM, editors. *Craig's restorative dental materials*. 13th ed. Philadelphia: Elsevier Mosby; 2012p. 253–75.
34. O'Keefe KL, Pease PL, Herrin HK. Variables affecting the spectral transmittance of light through porcelain veneer samples. *The Journal of Prosthetic Dentistry* 1991;**66**:434–8.
35. Arikawa H, Fujii K, Kanie T, Inoue K. Light transmittance characteristics of light-cured composite resins. *Dental Materials* 1998;**14**:405–11.
36. Lee YK. Influence of scattering/absorption characteristics on the color of resin composites. *Dental Materials* 2007;**23**:124–31.
37. Yu B, Ahn JS, Lee YK. Measurement of translucency of tooth enamel and dentin. *Acta Odontologica Scandinavica* 2009;**67**:57–64.
38. Shiraishi T, Wood DJ, Shinozaki N, Van Noort R. Optical properties of base dentin ceramics for all-ceramic restorations. *Dental Materials* 2011;**27**:165–72.