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Exploring the optical behavior and relative translucency parameter of CAD-CAM resin-based composites, polymer-infiltrated ceramic network, and feldspar porcelain

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ABSTRACT

Objectives: To evaluate and compare the optical properties and relative translucency parameter of CAD-CAM restorative materials.

Methods: Four CAD-CAM materials were evaluated: Lava Ultimate (LU), Grandio Blocs (GB), VITA Enamic (VE), and VITA Mark II (VM). Disk-shaped samples in shade A2-HT were prepared (n = 10) and polished to 1.00 ± 0.01 mm of thickness. Scattering (S), absorption (K), albedo (*a*) coefficient, transmittance (T%), light reflectivity (RI), infinite optical thickness (X_∞), and radiative transfer coefficients (μ_a, and μ'_S) were calculated using Kubelka-Munk method and Thennadil's semi-empirical approach. Root Mean Square Error (*RMSE*) and Goodness of Fit (GFC) were used as performance optical behavior. Translucency differences were evaluated using the relative translucency parameter (RTP_{00}) and 50:50 % translucency perceptibility and acceptability thresholds (TPT_{00} and TAT_{00}).

Results: The spectral distribution of S, K, T%, RI, and X_∞ was wavelength-dependent. GFC and *RMSE* values indicated good spectral behavior matches and good comparative spectral values for RI in LU-GB, LU-VE, and GB-VE, and for K in VE-VM. VM displayed the highest scattering values across the wavelengths, while VE and VM showed lower absorption at shorter wavelengths. LU and GB had the highest transmittance. The X_∞ values indicated that all 1.0 mm thick materials could be influenced by the background. No good spectral match and no good comparative spectral values were found between CAD-CAM materials and anterior bovine maxillary specimens. VM had the lowest RTP_{00} values with perceptible and unacceptable differences compared to CAD-CAM materials evaluated.

Significance: Understanding the optical behavior of different CAD-CAM materials was essential for guiding clinicians in material selection and optimizing their clinical performance. The findings confirm that the different compositions and microstructure impact the optical properties and translucency of CAD-CAM restorative materials.

1. Introduction

Modern dentistry has made noteworthy progress due to the rapid development of computer-aided design and computer-aided manufacturing (CAD-CAM) technology [1]. With the increasing demand for aesthetics, shorter treatment times, and technological advancements, several restorative materials have been developed [2–4]. CAD-CAM materials that do not require additional crystallization or sintering post-milling steps have gained popularity due to their easy and fast chairside fabrication [3].

According to the composition, CAD-CAM restorative materials can be categorized into glass-ceramics, resin-matrix ceramics (RMCs), and polycrystalline ceramics [1,5]. The CAD-CAM fine-structure feldspar ceramics (e.g., VITA Mark II) have evolved from traditional feldspar porcelain glass-ceramic and remain widely used [1]. RMCs represent a novel group of CAD-CAM materials and are further classified into

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resin-based composites (RBCs; e.g., Lava Ultimate and Grandio Blocs) and polymer-infiltrated ceramic network (PICN; e.g., VITA Enamic) [1, 5]. The PICN materials combine the mechanical strength and color stability of ceramics with improved flexural resiliency, reduced wear on opposing teeth, better polishability, and easier intraoral repairs of composites [1,2,6,7].

The optical properties of CAD-CAM restorative materials may differ from conventional materials due to variations in fabrication and processing methods, microstructure, and particle size [8,9]. Despite similarities in composition to traditional materials, CAD-CAM materials exhibit enhanced performance due to their manufacturing process [10]. The controlled pressure and heating during the industrial polymerization of RMCs CAD-CAM materials, especially the RBCs, increase the degree of conversion and improve physical properties [9,11]. This process avoids the known negative effects of polymerization shrinkage stress in composites [12]. The physical-mechanical properties of restorative materials play a fundamental role in their clinical performance and long-term restoration success [6]. However, the esthetic outcome depends mainly on their optical properties, which must faithfully replicate those of adjacent teeth [6,13].

The final aesthetic appearance of natural teeth is determined by a complex combination of structural layers (e.g., enamel, dentin, and pulp) [7,13,14]. Attaining color and optical properties that mimic natural teeth is highly desirable yet challenging, especially in the anterior region [13,15]. A comprehensive understanding of the color behavior, perception, and appearance of dental materials, obtained by learning about optical characterization, can aid clinicians in selecting the appropriate material for natural-looking esthetic indirect restorations [15,16]. The measurement of the reflectance spectrum of an object is a reliable method for describing color as it is independent of illumination and viewing conditions [14]. However, when discussing the full esthetic outcome of CAD-CAM materials, it is crucial to consider and determine the light scattering, absorption, and transmittance to know their inherent optical properties [6,15,17,18]. This knowledge helps predict how light interacts with restorative materials, influencing their blending with surrounding tissues and contributing to perceived color and translucency [19]. This information can provide valuable insights into the behavior of restorative materials, particularly for aesthetic restorations.

The final color and translucency of a dental restorative material are characterized by two wavelength-dependent main processes: scattering and absorption of light as it passes through a biomaterial [20,21]. When an incident light transmits through a material, it would be multiply scattered by the small-size particles before it emerges and reaches an observer, with some of the light being absorbed and reflected [22,23]. The light reflectivity of restorative materials indicates their reflectance when opaque and can be used to determine the intrinsic color of the material independent of the background [24,25].

The Radiative Transfer Equation (RTE) produces unambiguous values of reduce scattering and absorption coefficients (μ_a and μ'_S), but the measurement process is challenging and there is no analytical solution, requiring a complex and computationally intensive approach [26]. An alternative approach in the field of optics consists in using the two-flux model, which, under some specific approximations, is an angularly integrated solution of the RTE. A simplified one-dimensional model is the two-flux Kubelka-Munk (K-M) reflectance theory [27,28], which is still widely used due to its relative simplicity in analyzing translucent materials. This model allows for the calculations of scattering and absorption coefficients (S and K) by considering the reflectance over the thickness of the material and the reflectance of the backing [28]. Thus, this model enables the extraction of spectral absorption and scattering coefficients of a given material with known thickness through straightforward analytical calculations, employing only two optical measurements: the reflectance factors of the layer in optical contact with a white background and with a black background, provided the spectral reflectance factor of the black and white backgrounds are known. This reflectance model has been successfully applied to explore the optical behavior of human dentine and enamel, bovine enamel-dentine structures [29–33], and dental materials, such as resin composites,[17,18] zirconia ceramics [31–33], multi-colored CAD-CAM PICN material [6], and 3D-printed dental restorative resins [16].

The relationship between K–M and the transport coefficients has been previously examined by several researchers [34–37] using the RTE as the starting point. A study [36] summarized different values found in the literature by introducing the parameters x and y for the scattering ($S = y\mu'_s - x\mu_a$). In general form for these coefficients: $K = 2\mu_a$, Gate [34] gives x = 0 and y = 3/4, and Star et al. [35] give x = 1/4 and y = 3/4. Thennadil [36], using a semi-empirical approach, found the same result as Gate [34] when the incident beam is diffuse. Sandoval and Kim [37] found results that align with Star et al. [35], but S obtained has an additional term that is proportional to the product μ_ag.

Translucency is related to the ability of a material to transmit light through it, which depends on factors such as scattering and absorption as well as on its thickness [21,23]. The translucency of dental materials can be evaluated using the translucency parameter (TP) by quantifying the color difference of an optically uniform material at a specific thickness against ideal white and black backgrounds [38]. However, if the backgrounds used are not ideal for determining the color difference, the relative translucency parameter (RTP) is required [39]. In this case, there is a change in scale since the maximum possible RTP is the color difference between the backgrounds used. In addition, the use of the CIEDE2000 color difference formula (ΔE_{00}) has been proposed for RTP calculations (RTP_{00}) [40,41].

To date, limited information is available on the optical properties and relative translucency parameter of CAD-CAM feldspar porcelain, RBCs, and single-shaded PICN material. This study aimed to apply the two-flux K-M model to evaluate optical properties and to calculate the CIELAB color coordinates to assess the relative translucency parameter (RTP_{00}) of four different CAD-CAM materials. The study tested the hypotheses that the composition and microstructure of the CAD-CAM materials have an influence on (1) K-M scattering and absorption coefficients, transmittance (T%), light reflectivity (RI), and infinite optical thickness (X_∞) spectral behavior; and (2) relative translucency parameter (RTP_{00}) values of CAD-CAM materials, considering translucency thresholds.

2. Materials and methods

2.1. Specimen preparation

The information on the materials used in this study are detailed in Table 1. Prefabricated CAD-CAM blocks from Lava Ultimate (3 M ESPE, St. Paul, MN, USA), Grandio Blocs (VOCO GmbH, Cuxhaven, Germany), VITA Enamic (VITA Zahnfabrik, Bad Sackingen, Germany), and VITA Mark II (VITA Zahnfabrik) were machined into 7.5 mm diameter cylinders and sliced into disks (n = 10/material) of 1.05 mm ± 0.05 mm thickness using a diamond disk at low speed (250 rpm) in a precision cutting machine (ISOMET1000, Buehler, USA). Then, the specimens were polished in a rotary polishing machine (Aropol 2 V; Arotec indústria e comércio, Brazil) using a sequence of #600, #1200, #1500, and #2000-grit silicon carbide abrasive papers under water cooling. Each specimen was measured with a digital caliper (Mitutoyo Digimatic Caliper 150 mm, Mitutoyo Co., Japan) to ensure a final thickness of 1.00 mm ± 0.01 mm. The specimens were ultrasonically cleaned in distilled water for 20 min and then stored at 37ºC for 24 h before reflectance measurements.

2.2. Spectral reflectance measurement

The spectral reflectance of all samples was measured using a calibrated spectrophotometer (CM-2600d, Konica Minolta, USA) with the CIE d/8° illuminating/measuring geometry and the software program OnColor V5 (Cyberchrome Inc., SC, USA). Standard white (L* = 99.58, a* = −0.09, and b* = −0.02) and black (L* = 15.25, a* = −0.12, and b* = −0.67) backgrounds (CM-A145 calibration plate, Konica Minolta) were used to measure the spectral reflectance at 10 nm intervals in the visible range (400–700 nm) [15] with a focus measuring diameter of 3.0 mm (CM-A147 target mask, Konica Minolta). Three short-term repeated measurements were performed on each specimen and the data were averaged.

2.3. Optical properties

The Kubelka-Munk scattering (S), absorption (K), transmittance (T %), light reflectivity (RI), and infinite optical thickness (X_∞) were calculated algebraically following the implementation suggested by Mikhail et al. [42]. These optical parameters are wavelength-dependent, showing variations across the visible spectrum. The absorption coefficient (μ_a) and reduced scattering coefficient (μ'_S) were derived from S and K based on the approach carried out by Thennadil [36].

$$S = \frac{3}{4}\mu'_s$$

$$\frac{K}{S} = \frac{8}{3}\frac{\mu_a}{\mu'_s}$$

where S, K, μ_a, and μ'_S are expressed in units of mm^{-1}.

Finally, the albedo coefficient was employed to assess how absorption and scattering processes contribute to the extinction attenuation of light when passing through an analyzed CAD-CAM material sample:

$$a = \frac{\mu'_S}{\mu'_S + \mu_a}$$

2.4. Relative translucency parameter (RTP_{00})

To calculate the RTP_{00}, the spectral reflectance values were converted into CIELAB color coordinates using the CIE 2° Standard Observer and the CIE D65 illuminant standards. RTP_{00} values were obtained by calculating the CIEDE2000 color difference between the color coordinates values over black and white backgrounds [40,43]:

$$RTP_{00} = \left[\left(\frac{L'_B - L'_W}{k_L S_L}\right)^2 + \left(\frac{C'_B - C'_W}{k_C S_C}\right)^2 + \left(\frac{H'_B - H'_W}{k_H S_H}\right)^2 + R_T\left(\frac{C'_B - C'_W}{k_C S_C}\right)\left(\frac{H'_B - H'_W}{k_H S_H}\right)\right]^{1/2}$$

where the subscripts “B” and “W” denote the lightness (L′), chroma (C′), and hue (H′) of the specimens over the black and the white backgrounds, respectively. R_T is the rotation function that accounts for the interaction between chroma and hue differences in the blue region of color space. The weighting functions S_L, S_C, and S_H adjust the total color difference for variation in the location of the color difference specimen over the B and W backgrounds in L′, a′, and b′ coordinates and the parametric factors K_L, K_C, and K_H are correction terms for experimental conditions. In this study, the parametric factors of the CIEDE2000 color difference formula were set to 1.

Values of translucency differences (ΔRTP_{00}) were evaluated and compared using previously reported data of 50:50 % RTP_{00} perceptibility ($TPT_{00} = 0.62$) and acceptability ($TAT_{00} = 2.62$) thresholds [40].

Table 1
CAD-CAM materials evaluated.

Classification	Materials and codes	Manufacturers	Compositions (% in weight)[*]	Lot n.°
RBCs[a]	Lava Ultimate HT[c] A2 (LU)	3 M ESPE	Agglomerated nanoparticles of silica and zirconia (80 %), highly cross-linked polymer matrix composed of Bis-GMA, UDMA, Bis-EMA, and TEGDMA (20 %). Particle sizes: 20-nm silica; 4- to 11-nm zirconia	NC50092
	Grandio Blocs HT[c] A2 (GB)	VOCO GmbH	Nanohybrid filler particles of nanosilica and barium glass (86 %) dispersed in an organic polymeric matrix composed of UDMA and DMA (14 %)	2248461
PICN[b]	VITA Enamic HT[c] A2 (VE)	VITA Zahnfabrik	Polymer-infiltrated feldspathic ceramic network (86 % ceramic), resin polymer composed of UDMA and TEGDMA (14 %)	89270
Feldspar porcelain	VITA Mark II HT[c] A2 (VM)	VITA Zahnfabrik	SiO_2 (56 −64 %), Al_2O_3 (20 −23 %), Na_2O (6 −9.0 %), K_2O (6 −8.0 %), CaO (0.3 −0.6 %), TiO_2 (0 −0.1 %)	94600

[*] Information given by the respective manufacturers.
[a] Resin-based composites;
[b] Polymer-infiltrated ceramic network;
[c] High-translucency level.

2.5. Data analyses

Two performance metrics were used to evaluate the level of similarity between the spectral behavior of all optical properties: the Root Mean Square Error (*RMSE*) and the Goodness-of-Fit coefficient (GFC) [44,45]. *RMSE* evaluates the absolute differences between two spectral signals focusing on the magnitude of the difference and is not independent of scale factors. A *RMSE* = 0 indicates a perfect match, while higher values of *RMSE* correspond to increasing disagreement/variation between the two analyzed spectral curves. *RMSE* is calculated as follows:

$$RMSE = \sqrt[2]{\frac{1}{n}\sum_{j=1}^{n}\left(R_1(\lambda_j) - R_2(\lambda_j)\right)^2}$$

where $R_1(\lambda_j)$ and $R_2(\lambda_j)$ are the spectral curves of two materials being compared at their correspondent wavelength. As reported by Imai et al. [45], a *RMSE* of around 2.0 % indicates a good comparative of metrics spectral quality.

The GFC is a metric that represents the cosine of the angle formed between two samples compared in the high-dimensional vector space of spectral curves. This metric remains unaffected by scale factors, making it suitable for evaluating the spectral behavior based on the shape of the curves being compared. The GFC = 1 indicates a perfect match. Values of GFC greater than or equal to 0.999 and 0.9999 correspond to very good and excellent spectral matches, respectively. The GFC is calculated following the equation:

$$GFC = \frac{\left|\sum_{j=i}^{n} R_1(\lambda_j)\cdot R_2(\lambda_j)\right|}{\left|\sum_{j=i}^{n}\left[R_1(\lambda_j)\right]^2\right|^{\frac{1}{2}}\cdot\left|\sum_{j=i}^{n}\left[R_2(\lambda_j)\right]^2\right|^{\frac{1}{2}}}$$

where $R_1(\lambda_j)$ and $R_2(\lambda_j)$ are the spectral curves of two materials being compared at their correspondent wavelength.

3. Results

Fig. 1**a-d** depict the spectral distribution of scattering and absorption coefficients (S and K), transmittance (T%), and albedo coefficient (*a*) as a function of wavelength for the CAD-CAM restorative materials evaluated. Fig. 2**a-b** show the spectral distribution of light reflectivity (RI) and infinite optical thickness (X_∞). Table 2 presents the *RMSE* and GFC values among the evaluated CAD-CAM materials. The GFC values between LU and GB, and between VE and VM, exhibited good spectral behavior matches (GFC $\geq$ 0.999) for all optical properties. However, only *RMSE* values $\leq$ 2 % were observed when comparing LU-GB, LU-VE, and GB-VE for RI, and VE-VM for K.

S for VE and VM displayed a continuous and smooth decrease as wavelength increased. In contrast, LU and GB exhibited an abrupt decrease in the scattering coefficient from 420 to 700 nm. VM showed the greater S values for all wavelengths (Fig. 1**a**). The spectral distribution pattern of K for all CAD-CAM materials evaluated indicated a decrease with wavelength, with smaller values observed for longer wavelengths (Fig. 1**b**). The VITA materials VE and VM demonstrated lower K for short and medium wavelengths compared to the other specimens.

CAD-CAM samples evaluated showed albedo coefficient values ranging from 0.62 to 0.89 (Fig. 1**c**). The *a* values of less than the unit (*a* < 1) and next to 1 indicate that scattering is the most relevant optical extinction that occurs when light interacts with the medium. This phenomenon was more significant for VM, which shows values between 0.79 and 0.89 across all wavelengths. Transmittance T% (Fig. 1**d**) increased with wavelength, with LU and GB exhibiting a ramp-up of T% up to 450 nm, while VE and VM showed a smoother increase. All materials had transmi ttance values below 60 % for all wavelengths.

Light reflectivity (RI) values of all CAD-CAM materials increased as the wavelength increased (Fig. 2**a**). The RI values ranged from 0.20 to 0.38 for LU and GB, 0.23 to 0.38 for VE, and 0.30 to 0.45 for VM. The comparison between the CAD-CAM materials showed a *RMSE* of around 2 % and a GFC $\geq$ 0.999 for LU-GB, LU-VE, and GB-VE, indicating a good spectral match and good comparative spectral values for these dental

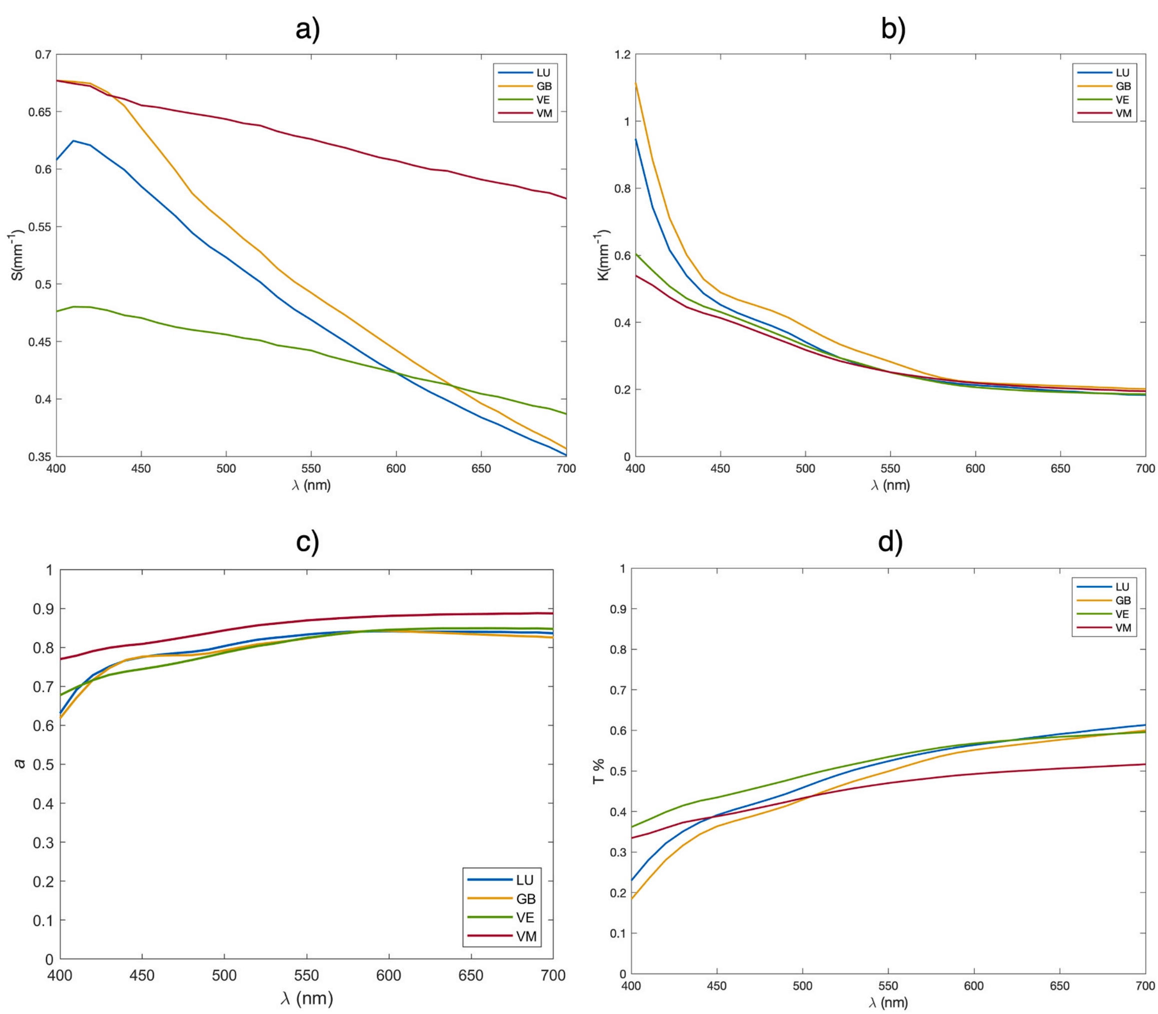

Fig. 1. Mean values of the spectral distribution of the Kubelka-Munk a) scattering coefficient (S); b) absorption coefficient (K); c) albedo coefficient (*a*); and d) the transmittance (T%).

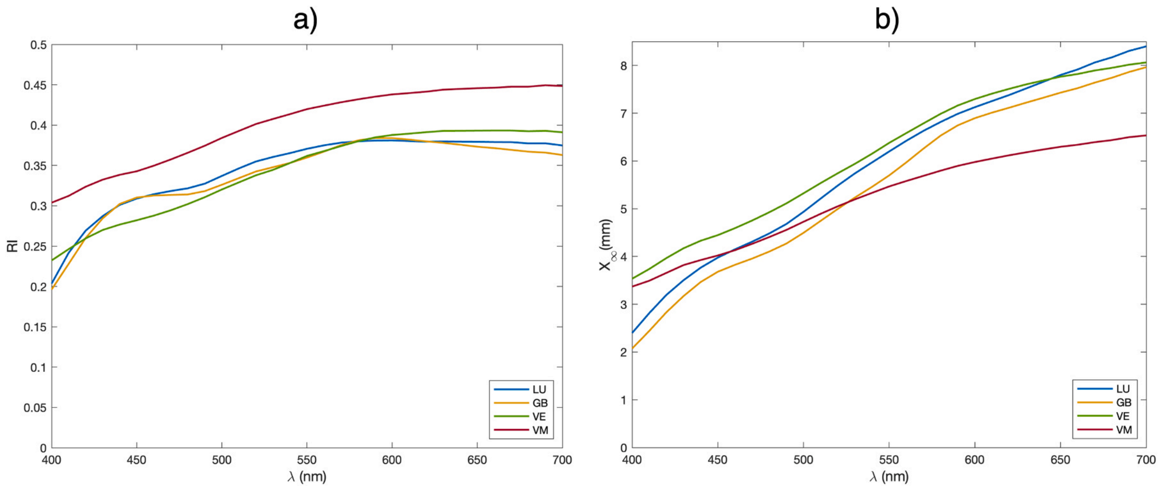

Fig. 2. Mean values of the spectral distribution of the Kubelka-Munk a) light reflectivity (RI); and b) infinite optical thickness (X_{∞}) of all materials.

Table 2
RMSE and GFC metrics between evaluated CAD-CAM materials.

Optical Properties		LU-GB	LU-VE	LU-VM	GB-VE	GB-VM	VE-VM
S	*RMSE*	0.0327	0.0716	0.1569	0.1019	0.1388	0.1872
	GFC	0.9998	0.9934	0.9914	0.9907	0.9884	0.9998
K	*RMSE*	0.0521	0.0748	0.0916	0.1228	0.1398	0.0195
	GFC	0.9993	0.9876	0.9805	0.9821	0.9734	0.9990
T%	*RMSE*	0.0255	0.0405	0.0634	0.0628	0.0609	0.0641
	GFC	0.9996	0.9974	0.9962	0.9948	0.9933	0.9999
RI	*RMSE*	0.0081	0.0160	0.0573	0.0169	0.0637	0.0586
	GFC	0.9999	0.9992	0.9992	0.9991	0.9990	0.9994
X_{∞}	*RMSE*	0.3821	0.4173	1.0254	0.7068	0.8297	1.0377
	GFC	0.9997	0.9990	0.9947	0.9969	0.9927	0.9990

Abbreviations: LU, Lava Ultimate; GB, Grandio Blocs; VE, VITA Enamic; VM, VITA Mark II; Scattering (S); Absorption (K);
Transmittance (T%); Light reflectivity (RI); Infinite optical thickness (X_{∞}).

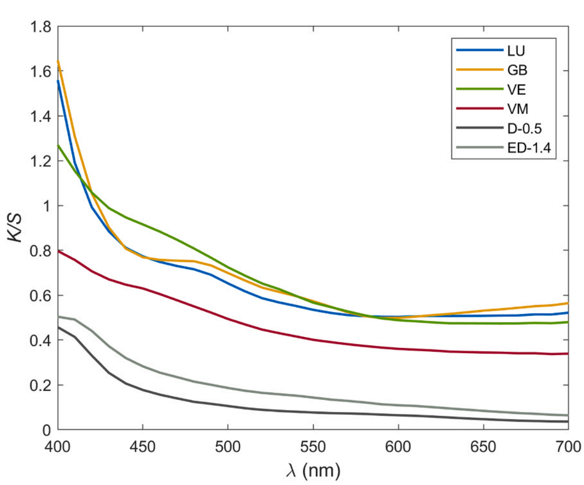

Fig. 3. Mean values of the spectral distribution of K/S ratio for all study materials and for bovine dentin and enamel-dentin structures.

ceramics for light reflectivity.

The infinite optical thickness (X_{∞}) values were wavelength-dependent for all samples and increased as the wavelength increased. Thus, the CAD-CAM materials studied are more opaque at lower wavelengths than at higher wavelengths (Fig. 2**b**). This result is less pronounced for CAD-CAM fine-structure feldspar ceramic (VM).

Fig. 3 displays the ratio of the absorption and scattering effects (K/S) of the CAD-CAM materials versus the K/S ratio for 1.4-mm thick enamel/dentin specimens and 0.5-mm thick dentin specimens from anterior bovine maxillary teeth obtained in a recent study from our laboratory [33] using the same method. The K/S ratio showed a GFC ≥ 0.999 for LU-GB and VM-VE, indicating a good spectral match for these dental ceramics. On the other hand, no good spectral match and no good comparative spectral values were found between CAD-CAM materials and anterior bovine maxillary specimens (GFC < 0.984 and *RMSE*>>2 %). Finally, the value of the ratio less than 1 shows the greatest effect of scattering, which is more pronounced in bovine dental structures compared to CAD-CAM materials.

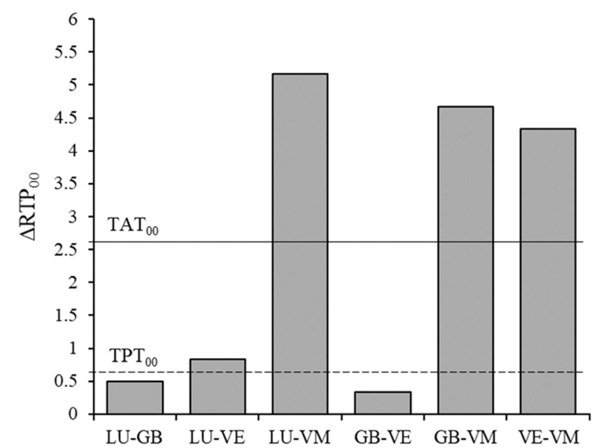

Fig. 4. Mean values of relative translucency parameter differences (ΔRTP_{00}) between CAD-CAM materials. TPT_{00}, translucency perceptibility; TAT_{00}, translucency acceptability; LU, Lava Ultimate; GB, Grandio Blocs; VE, VITA Enamic; and VM, VITA Mark II.

Regarding RTP_{00}, LU and GB exhibited higher translucency values (20.74 ± 0.37 and 20.24 ± 0.90, respectively), followed by VE (19.91 ± 0.61), while VM had the lowest translucency (15.58 ± 0.23). Fig. 4 illustrates the mean ΔRTP_{00} values among the CAD-CAM materials evaluated and their comparison with the TPT_{00} and TAT_{00} thresholds. The differences between LU-GB and GB-VE remained below the TPT_{00}. The ΔRTP_{00} between LU and VE was slightly perceptible but clinically acceptable. The ΔRTP_{00} values between Vita Mark II (VM) and all other materials were deemed unacceptable (>2.62).

4. Discussion

In the present study, optical properties and the relative translucency parameter of CAD-CAM resin-based composites, polymer-infiltrated ceramic network, and feldspar porcelain were analyzed and compared between them. No good spectral behavior match were found (GFC $\leq$ 0.999) in S, K, and T%, RI, and X_∞ except between RBCs (LU-GB) and VITA materials (VE-VM) specimens. The RI data showed similar spectral behavior for all CAD-CAM materials (GFC $\geq$ 0.999), but only good comparative spectral values for the comparison between LU-GB, LU-VE, and GB-VE, ($RMSE$ < 2.0 %). Therefore, the first hypothesis was accepted.

Translucency is recognized as one of the primary factors in evaluating dental aesthetics [46]. It is a significant optical property of restorative materials, allowing them to mimic surrounding structures, with the so-called blending effect, or in some cases, to mask discolored substrates to obtain a natural appearance [6,41,47]. The translucency of dental materials can be assessed by direct transmission, total transmission, or spectral reflectance [2,48]. This study used the CIEDE2000 color difference formula to calculate the RTP_{00} and 50:50 % translucency perceptibility and acceptability thresholds adopted to interpret translucency differences. In this study, given that no ISO standard is available for evaluating translucency in dentistry, a 1.0 mm thickness was set for all samples to compare the translucency among different material types. The findings revealed that RTP_{00} values varied between materials, showing ΔRTP_{00} values below the perceptibility threshold only for comparisons between the RBCs (LU-GB) and the RBC (GB) and PICN (VE). Therefore, the second hypothesis was also partially accepted.

Comparing translucency values between dental materials and their interpretation within clinical perceptibility and acceptability thresholds is crucial to provide information on how different materials may exhibit similar or different behavior under standard conditions [40,49]. This knowledge is essential for selecting restorative materials for clinical cases from an aesthetic standpoint [49]. The resin-based composites Lava Ultimate and Grandio Blocs exhibited the highest RTP_{00} values, with no perceptible ΔRTP_{00} between them. The feldspar porcelain VITA Mark II had the lowest translucency values, exhibiting unacceptable ΔRTP_{00} with all other CAD-CAM materials. The PICN VITA Enamic showed translucency differences below the perceptibility compared to Grandio Blocs and noticeable but acceptable differences with Lava Ultimate. Thus, higher RTP_{00} values were noted for materials with resin matrix content.

It must be considered that all samples were prepared from CAD-CAM blocks with the same high-translucency level (HT), A2 shade, and thickness of 1.0 ± 0.1 mm. Thus, the findings align with previous reports on the influence of numerous factors, such as crystalline structure, grain size, pigments, opacifiers, thickness, resin polymerization, and the number, size, and distribution of defects and porosity on the translucency of restorative materials [46,50–56].

Differences in refractive indices between the reinforcing fillers or opacifying compounds and the polymeric matrix lead to increased opacity levels due to multiple reflections and refractions at the interface between the matrix phases [55,57]. Previous studies have shown that the refractive index of enamel ranges from 1.52 to 1.63, while dentin has lower values, ranging from 1.43 to 1.57 [58]. The refractive indices for Bis-GMA, UDMA, TEGDMA, Bis-EMA, Al_2O_3, and TiO_2 are 1.55, 1.48, 1.53, 1.55, 1.77, and 2.49, respectively [53,57]. Therefore, RBCs contain fillers with lower refractive indices with values closer to dental tissues than Al_2O_3 and TiO_2, which are components of VM, making feldspar porcelain the most scattering and least translucent material. This finding was unexpected, as feldspathic porcelain is recognized for its ability to mimic the color and translucency of natural teeth [8,59]. The disparity may be attributed to the inherent differences between veneered porcelain and VM monolithic feldspar porcelain restorations. Veneered porcelain restorations typically employ a multi-layered approach to enhance aesthetics by incorporating various colors and translucency levels in opaque, dentin, and enamel layers [59], whereas monolithic restorations lack this layered complexity.

The main optical properties that determine the visible match between a restorative material and natural teeth are the absorption and scattering characteristics of light reflected on the surface and within the substrate [31,46]. The scattering coefficient of a resin-based composite is mainly determined by the particle size, with larger particles leading to increased scattering when their diameter is equal to or exceeds the wavelength of the incident light [18,60]. Absorption is associated with the resin matrix and the colorant pigments used [22]. Nanoscale and nanofiller particles with diameters smaller than the visible light wavelength result in reduced scattering and absorbance, enhancing light transmission and translucency [54,57,60]. Overall, the S and K coefficients and T% of the RBCs Lava Ultimate and Grandio Blocs, and the ones among VITA Enamic and VITA Mark II exhibited similar spectral behavior (GFC $\geq$ 0.999). This indicates that when compared, these materials mainly scatter and absorb light in shorter wavelengths, with maximum transmittance occurring at longer wavelengths. Despite showing similar spectral behavior, the mean values of their optical properties differed notably, probably due to varying particle sizes.

It has been reported that bovine and human dentin exhibit similar optical behavior within the visible spectrum [31], likely due to their homogeneity and comparable microstructures [61]. Based on the findings of this study and considering the difference in thickness between the CAD-CAM samples and dental tissue specimens (Fig. 3), the ratio of the absorption and scattering effects significantly differs between bovine tooth structures and all the CAD-CAM materials studied (GFC < 0.984 and $RMSE$>>2 %), with K/S values lower for dental structures for all wavelengths. This indicates that scattering contributes more significantly to the extinction of light in dental tissues than in the CAD-CAM materials tested. This disparity can be attributed to the dense hydroxyapatite crystals in enamel and the tubular structure and collagen matrix network in dentin [62]. Therefore, dental tissues have a structure that differs considerably from the glassy mineral and resin-matrix content of the materials [1,46,62].

Albedo coefficient (a) values higher than 0.5 and lower than 1.0 indicate that scattering is the most predominant light attenuation phenomenon when light interacts with a material (Espinar 2023) [16]. In this study, the values of a ranged from 0.62 to 0.89 for the evaluated CAD-CAM materials. These results suggest a significant presence of scattering in the light transmittance of these materials, which could be related to the different filler content and particle size. When light encounters an obstacle (e.g. particles) within a medium, a scattering event occurs, altering the direction of light propagation (Espinar 2023) [16]. The presence of additional particles causes new scattering events, further changing the direction of light propagation. Consequently, scattering is influenced by the wavelength of irradiation, the refractive indices of the medium, the particle causing scattering, as well as the particle size and its cross-section [16,50,63].

The resin-based composites Lava Ultimate and Grandio Blocs had the highest RTP_{00} values among all the materials. Lava Ultimate is composed of 80 % (by weight) nanoceramic particles of silica and zirconia in 20 nm and 4–11 nm sizes, respectively, embedded in a polymer matrix of Bis-GMA, UDMA, Bis-EMA, and TEGDMA. Grandio Blocs contains 86 % nanohybrid particles of nanosilica and barium glass in a polymer matrix of UDMA and DMA (14 % by weight). VITA Mark II exhibited the lowest RTP_{00} value. The CAD-CAM feldspar porcelain mainly comprises SiO_2 (silica) and Al_2O_3 (alumina). The a values for VM were closer to 1.0, indicating that this material exhibits significant light scattering as an attenuating factor for all wavelengths, likely due to its higher silica and alumina content and the absence of a resinous matrix.

The underlying substrate shade can influence the perceived color of restorative material by the way light is scattered and absorbed [64]. If the substrate is dark, the material might need a specific thickness to achieve the desired balance of translucency and opacity for better natural-looking. The infinite optical thickness (X_∞) is the minimum thickness at which a translucent material, backed by a black background, will attain its light reflectivity and become nearly opaque [24]. When restoration thicknesses exceed X_{∞}, the material absorbs or scatters all incident light, eliminating the background influence [16,64]. The X_{∞} results indicated that all materials were opaquer at lower wavelengths (400–500 nm) compared to higher wavelengths (600–700 nm), with VITA Mark II showing a less pronounced effect of X_{∞} at larger wavelengths. The 1.0 mm thick specimens of all materials were significantly thinner compared to the infinite optical thickness at visible wavelengths. Although they appeared more opaque at lower wavelengths, the X_{∞} values ranged from LU 2.40 to 4.94 mm; GB 2.07 to 4.50 mm; VE 3.53 to 5.32 mm, and VM 3.37 to 4.73 mm. Therefore, the results indicate that the evaluated CAD-CAM materials with a 1.0 mm thickness could not exhibit their inherent color without being influenced by the background.

The spectral reflectance of all samples was measured using a spectrophotometer to determine the optical properties of the CAD-CAM materials. According to ISO/TR 28642:2016 [65], spectrophotometers are widely regarded for their accuracy and reliability in evaluating spectral reflectance and transmittance of materials, especially in controlled laboratory settings where factors like consistent light source and sample positioning can be ensured. The data obtained is then used to calculate optical properties such as scattering, absorption, transmittance, and light reflectivity using K-M equations [15,46]. It is worth highlighting that the spectrophotometer utilized in this study has an integrating sphere that includes the scattered light and ensures uniform illumination of the specimen. This methodology aligns with established practices in the field, as evidenced by previous studies [15,20,30,46,60,66].

The study highlights differences in the optical behavior and relative translucency parameter among the CAD-CAM materials, which in turn generally differ from those of dental tissues [31,33]. However, the absorption coefficient of all CAD-CAM materials decreased as the wavelength increased, similar to the trend in natural tissues. VITA Mark II showed the highest scattering at all wavelengths, resembling the strong scattering observed in dentin [62], higher light reflectivity, and lower translucency, which may be advantageous for anterior restorations requiring a masking effect. Resin-based composites demonstrated superior transmittance and translucency, making them suitable for aesthetic dental restorations. VITA Enamic exhibited translucency comparable to RBCs materials and optical behavior similar to feldspar porcelain, albeit with different values from the latter, offering a balanced clinical application among the materials studied. It is crucial to note that the clinical recommendations mentioned are somewhat restricted extrapolations as only optical properties were taken into account. When choosing and using a restorative material, several other factors, including physical, chemical, mechanical, and biological properties, must be considered. These findings highlight the importance of selecting materials based on specific clinical requirements, emphasizing the necessity for personalized approaches in restorative dentistry.

This study has certain limitations. Only one sample thickness was investigated. It is important to note that the final thickness of an indirect restoration can vary based on the clinical situation, and consequently, the relative translucency may differ from the study's findings. The CAD-CAM materials evaluated were chosen as representatives of their classification. Dental materials with the same classification from other manufacturers may exhibit comparable spectral behavior, although the values of the optical properties may differ if modifications in particle sizes and microstructure are made. Lastly, as an in vitro study, the results cannot be directly applied to real clinical scenarios, as the interaction of the materials with different background shades and dental substrates, such as enamel and dentin, was not considered.

5. Conclusion

Considering the aforementioned study limitations, it was concluded that the spectral behavior of S, K, T%, RI, X_{∞}, and albedo coefficient in the evaluated CAD-CAM resin-based composites, polymer-infiltrated ceramic network, and feldspar porcelain differed significantly from each other and from bovine dental structure. Thus, their optical properties were wavelength-dependent and influenced by their compositions and microstructure features. Scattering was identified as the most relevant light extinction phenomenon, although it was less significant compared to dental structures. CAD-CAM feldspar porcelain exhibited the lowest translucency, with ΔRTP_{00} values exceeding the acceptability threshold.

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