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Research Article

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Translucency and Polymerization Ability of Contemporary Resin Composites

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Abstract
Objective: The present study aimed to characterize the translucency and polymerization ability of commercially available contemporary resin composites. Methods: The resin composites considered in this study were Forma (Enamel, Body, and Dentin; Ultradent), Empress Direct (Enamel and Dentin; Ivoclar/Vivadent), Sirius-Z (Enamel and Dentin; DFL), and Orion (Enamel and Dentin; DFL). All photoactivation procedures were performed using the same light source (Valo Cordless, Ultradent, 20 s). The translucency parameter (TP) was determined with a benchtop spectrophotometer (X-Rite, SP60), and the degree of conversion (DC) as a function of thickness was assessed by Fourier transform infrared spectroscopy (FTIR) immediately after photoactivation and again after 1 h. The results were analyzed using analysis of variance (ANOVA) and Tukey's tests. Pearson's correlation tests were employed to investigate the relationship between opacity and polymerization ability. Results: Regarding TP, the values obtained among the enamel shades were similar, but a significant variation was observed in dentin shades (p = 0.0023). The degree of conversion (DC) was dependent on the material tested (p = 0.0021 for immediate evaluation and p = 0.0043 for readings taken after 1 h) and the analysis depth (p = 0.0002 for immediate evaluation and p = 0.0038 for readings taken after 1 h). However, the relationship between these two factors was dependent on the time of evaluation. Forma and Empress Direct resin composites exhibited lower polymerization potential for dentin shades. The relationship between opacity and polymerization potential was significant for the baseline evaluation but not significant when considering DC values taken after 1hour. In conclusion, regardless of the brand, enamel shades demonstrated similar TP and curing potential. Conversely, there was a large variation in these parameters for dentin shades. A delayed polymerization can offset slow initial polymerization depending on the resin composite.

Keywords:
esthetic; nanotechnology; resin composite; translucency; polymerization; operative dentistry

1. Introduction

Resin composites are essentially composed of ceramic particles (inorganic fillers) coated with a bonding agent (silane) and held together by a resin matrix formulated from a mixture of methacrylate-based monomers [1,2]. Despite several modifications in material formulations, shade selection remains one of the most challenging steps in restorative treatment when using resin composites [3].

The color of a natural tooth is determined by the interaction between enamel and dentin with light during refraction and reflection [4]. Therefore, it is essential for restorative materials to mimic the degree of translucency of dental tissues [5]. Some studies have indicated that the inorganic filler particles in resin composites are primarily responsible for transmitting and scattering light, resulting in translucency similar to, or different from, that of the restored tooth [6,7].

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The color information obtained in scientific studies is generally complex and often has little or no clinical application. Another difficulty for clinical application is the wide variety of brands available for reproducing enamel or dentin layers with different degrees of translucency [8,9]. The incorrect use of these layers often leads to professional frustration, patient dissatisfaction, and the need for early replacement of the restorations [10,11].

Therefore, it is essential to conduct studies to determine the optical properties of materials to guide their acquisition and/or use in clinical practice and to assess the polymerization capacity of these materials as a function of depth [12,13]. Additionally, one might question whether more opaque materials could create depth-related polymerization difficulties. Accordingly, this study aimed to [1] characterize the translucency and [2] asses the polymerization ability of resin composites currently available in the market. The null hypotheses were that there is no significant difference in (i) the translucency and (ii) polymerization ability among different commercially available contemporary resin composites.

2. Materials and Methods

2.1. Evaluation of Optical Properties

The materials used in the present study are listed in Table 1. Six disk-shaped specimens were made for each group using a cylindrical metal mold with an 8 mm internal diameter and 2 mm thickness. After composite placement, the top surface was covered with a polyester strip and leveled by applying pressure with a glass plate. The specimens were light-activated for 30 s from the top surface using a broad-spectrum (385 to 515 nm) light-emitting diode curing unit (Valo, Ultradent, USA) operated in high irradiance mode at 1200 mW/cm^2, measured with a portable radiometer (LED radiometer, Demetron–Kerr, Middleton, WI, USA). Afterward, both surfaces of all samples were polished (Buehler, Lake Bluff, IL, USA) with 2000- and 4000-grit SiC papers under continuous water cooling. The thickness was then checked with a digital caliper with 0.01 mm resolution (Digimatic Caliper, Mitutoyo, Tokyo, Japan).

The original methodology was described and published in reference [3]. Optical data were obtained according to the L'a'b' color system in SCI mode using a zero-calibration box (L* = 0.0; a* = 00 and b* = 0.0) with a spectrophotometer equipped with an integrating sphere (X-Rite SP60, Grand Rapids, Michigan, USA). Illumination and viewing settings complied with the CIE/10º diffuse geometry for observers and the D65 standard illuminant. The translucency of each material was quantitatively evaluated by calculating the translucency parameter (TP), according to the Formula (1):

$$TP = [(L * w - L * b)^2 + (a * w - a * b)^2 + (b * w - b * b)^2]^{1/2} \quad (1)$$

where "w" refers to the color values for each sample measured on a white background and "b" on a black background. The analyses were performed with the samples placed on a black background (Ceramic Color Standard, Ceram Research Ltd., Stoke-on-Trent, Staffordshire, UK) with L* = 8.6, a* = −0.7 and b* = −1.5, and on a white background (Ceramic Color Standard, Ceram Research Ltd.) with L* = 93.7, a* = 1.2 and b* = 0.8.

2.2. Evaluation of the Degree of Conversion as a Function of Depth

The degree of conversion (DC) of each material was determined in the top (0.1 mm) and bottom (2 mm) regions. Plastic molds with the specified thicknesses and a 6 mm diameter were used, and the reading was performed by Fourier transform infrared spectroscopy (FTIR) using the attenuated total reflectance technique (Alpha; Bruker Optics, Ettlingen, Germany; with 16 scans and 4 cm^{-1} resolution). For the spectral analysis, the vibrational modes of the carbon chains at the peaks of ~1638 cm^{-1} (aliphatic bonds) and peaks at ~1608 cm^{-1} (aromatic bonds) were considered before and after the photoactivation process. Thus, the DC (%) was determined by the Formula (2):

$$DC = 100 \times \left\{ 1 - \left[\frac{\frac{C = C_{pol}}{aromatic_{pol}}}{\frac{C = C_{npol}}{aromatic_{npol}}} \right] \right\} \quad (2)$$

where DC means a degree of conversion; C=C$_{pol}$ denotes the value of the absorption peak area of the aliphatic C=C bonds of the polymerized sample, aromatic$_{pol}$ denotes the value of the absorption peak area of the aromatic ring of the polymerized sample; C=C$_{npol}$ denotes the value of the absorption peak area of the aliphatic C=C bonds of the unpolymerized sample, and aromatic$_{npol}$ denotes the value of the absorption peak area of the aromatic ring of the unpolymerized sample. The analysis was performed immediately after the photoactivation procedure and repeated after 1 h.

2.3. Statistical Analysis

For each variable-response tested, data were analyzed with the Anderson–Darling and Kolmogorov–Smirnov tests to check normality and equal variance. The opacity values were submitted to analysis of variance and Tukey's test (95%). The conversion values as a function material and depth of evaluation were submitted to two-way ANOVA and Tukey's test (95%). The relationship

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Table 1: Restorative resin composites used in the study. Basic formulation obtained from the manufacturers.

Resin	Brand	Shades	Composition
Forma	Ultradent	A2 Enamel A2 Body A2 Dentin	Bisphenol-A Diglycidyl Dimethacrylate (Bis-GMA), Triethylene Glycol Dimethacrylate (TEGDMA), Ethoxylated Bisphenol-A Diglycidyl Dimethacrylate (Bis-EMA), and Urethane Dimethacrylate (UDMA). Inorganic filler based on zirconia/silica and barium glass (0.7 μm). 68% by volume for dentin shades, and 56% for enamel shades.
Empress Direct	Ivoclar/ Vivadent	A2 Enamel A2 Dentin	Nanohybrid Bis-GMA, UDMA, cycloaliphatic dimethacrylate, propoxylated bisphenol-A dimethacrylate. Barium glass filler particles, ytterbium trifluoride, mixed oxide trifluoride, mixed oxides, and silica dioxide. The average particle size ranges from 40 nm to 3000 nm, with an average of 55 nm.
Sirius-Z	DFL	A2 Enamel A2 Dentin	Bisphenol-A Diglycidyl Dimethacrylate (Bis-GMA), Triethylene Glycol Dimethacrylate (TEGDMA), Ethoxylated Bisphenol-A Diglycidyl Dimethacrylate (Bis-EMA), and Urethane Dimethacrylate (UDMA). Average particle size of 0.7 μm (63% by volume, 78% by weight). Particle size range: 0.01–4.5 μm
Orion	DFL	A2 Enamel A2 Dentin	Bisphenol-A Diglycidyl Dimethacrylate (Bis-GMA), Triethylene Glycol Dimethacrylate (TEGDMA), Ethoxylated Bisphenol-A Diglycidyl Dimethacrylate (Bis-EMA), and Urethane Dimethacrylate (UDMA). Average particle size of 0.7 μm (64% by volume, 79% by weight). Particle size range: 0.04–2.8 μm.

between TP and the polymerization ratio was evaluated by Pearson's correlation coefficient (95%) with values obtained immediately and after 1 h by spectroscopic measurements. All statistical analysis was carried out using the Jamovi software (Version 2.5, The Jamovi Project, Sydney, Australia).

3. Results

Figure 1 shows the mean TP according to the materials used. Differences were observed ($p = 0.0023$) when considering the dentin shades, with the highest opacity values for Forma Dentin and Empress Direct Dentin. The Body resin had similar opacity to that of the Orion and Sirius-Z resins in the Dentin version. No considerable differences in opacity were observed for the enamel resins.

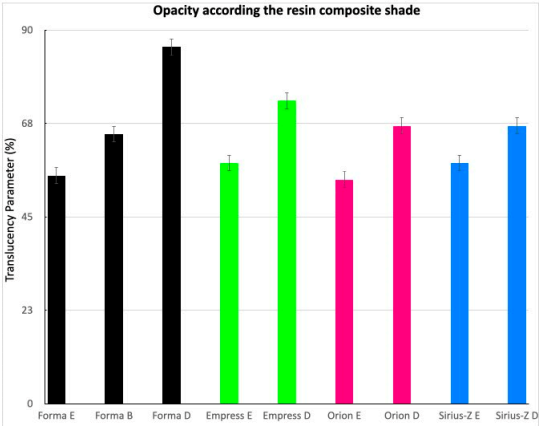


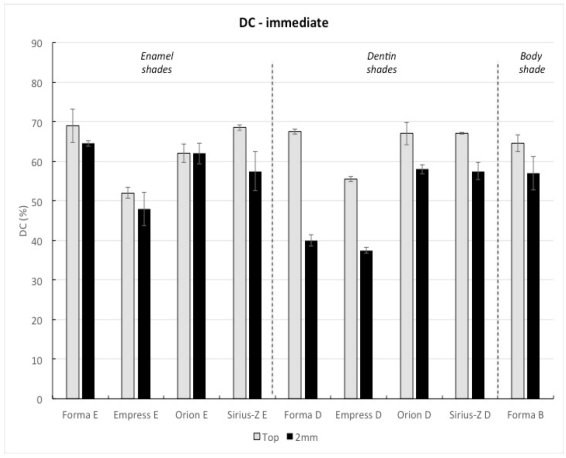
Figure 1: Opacity according to each resin composite for enamel, dentin, and body shades.

When considering the immediate values, the degree of conversion was dependent on the material tested ($p = 0.0021$) and the analysis' depth ($p = 0.0002$), without integration between these two factors ($p = 0.0389$). For each resin composite evaluated immediately after the photoactivation procedure (Figure 2a), the DC in the top region remained around 60–70%. On the other hand, at a depth of 2 mm, a proportional decrease in conversion was generally observed. Forma Dentin and Empress Dentin resins showed a lower DC than that of the other resins (30–40%). When considering the readings taken 1hour after the photoactivation procedure (Figure 2b), the degree of conversion was dependent on the material tested ($p = 0.0043$) and the analysis' depth ($p = 0.0038$), and the integration between the two factors ($p = 0.0024$).

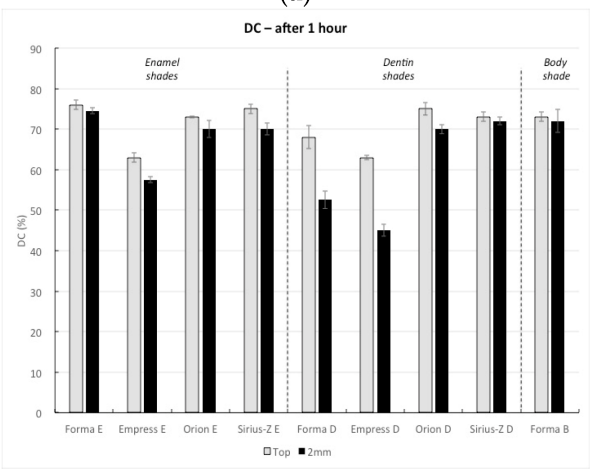
Figure 3 shows the mean values of the increase in DC after 1 h of photoactivation, and the increase occurred, in most cases, at the base of the increment (2 mm).

The polymerization potential as a function of each material and the evaluation time is presented in Figure 4, considering the mean DC values obtained by the base/top ratio in each situation. With the exception of the Forma Dentin and Empress Direct Dentin resins, all other materials showed polymerization potential higher than 90% after 1 h of activation.

Figure 5a shows the relationship between the translucency parameter and polymerization potential when considering the conversion values obtained immediately after photoactivation—where an inversely proportional and statistically significant correlation can be observed ($p = 0.0012$)—and after 1 h of photoactivation (Figure 5b) was not significant ($p = 0.025$).



(a)



(b)

Figure 2: Degree of conversion for composite materials: (**a**) immediate after photoactivation; (**b**) 1 h after photoactivation. The dotted lines indicate differences in opacity levels according to the nomenclature used by manufacturers.

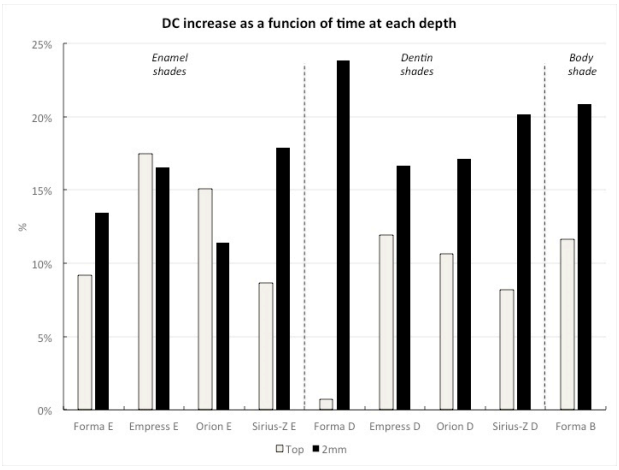


Figure 3: Mean values of the increase in the degree of conversion (DC) after 1 h of photoactivation at the base surface. The dotted lines indicate differences in opacity levels according to the nomenclature used by manufacturers.

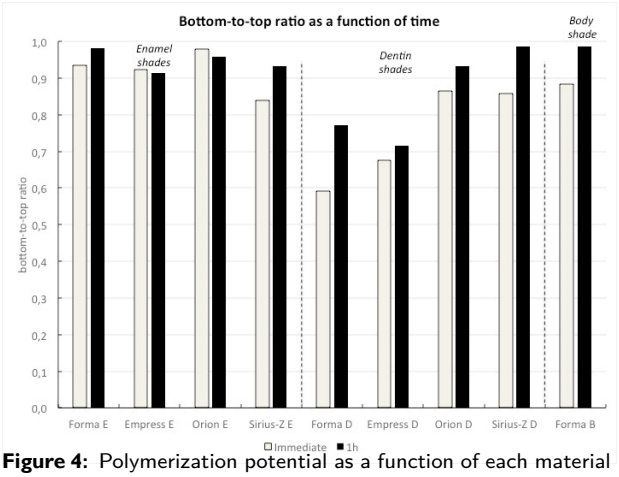


Figure 4: Polymerization potential as a function of each material and the evaluation time, considering the mean degree of conversion (DC) values obtained by the base/top ratio. The dotted lines indicate differences in opacity levels according to the nomenclature used by manufacturers.

4. Discussion

Understanding translucency characteristics and polymerization ability is crucial for promoting restorative treatments with satisfactory esthetic characteristics and longevity. In the current study, "enamel" resins exhibit similar translucency values; however, "dentin" resins showed significant differences among different commercial brands. Thus, the null hypothesis was rejected. The term "dentin" refers to materials with a higher opacity index, i.e., lower translucency, which are typically used when there is a need to conceal the dental substrate or restore more opaque areas. However, such materials lack specific standardization. These differences may arise from several factors, including the number of pigments employed in each material, the type and size of filler particles, and the variations in their refractive indices compared to those of the resin matrix [14–16].

The degree of conversion (%) was calculated by determining the proportion of carbon double bonds converted into single bonds, as per Kim and Watts 2008 [17]. However, spectroscopic measurements actually assess the amount of C=C bonds still available, which can vary among commercially available materials due to a wide variety of factors. These factors include the monomers employed in the resin matrix formulation, their quantities, and the percentage of silane covering the filler particles capable of establishing C-C bonds [18]. In other words, comparing absolute conversion values among different commercial materials is not meaningful. Therefore, the

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present study considered absolute conversion values only for the same material in different situations, such as the influence of time or thickness, and comparisons among different brands, as well as other aspects like polymerization potential—calculated by the ratio between the values obtained at 2 mm thickness compared to the data obtained from the top of the samples [3].

In the evaluation of baseline DC, it is evident that Forma and Empress Direct resins in the Dentin version exhibit a loss of polymerization potential, likely associated with their lower translucency. This is supported by Pearson's correlation coefficient, indicating an inversely proportional relationship between opacity and bottom-to-top polymerization ratio when initial values are considered. It is noteworthy that Empress Direct composite resin is formulated with a photoinitiator system called Evocerin™, which differs from the systems used in most commercially available materials that often rely on camphor quinone and amine and are based on shorter wavelengths. However, while this material may offer aesthetic benefits in terms of color stability, studies have pointed out that alternative photoinitiators absorbing energy at lower wavelengths result in lower polymerization depth values due to greater light scattering in the near-ultraviolet wavelength region [19,20].

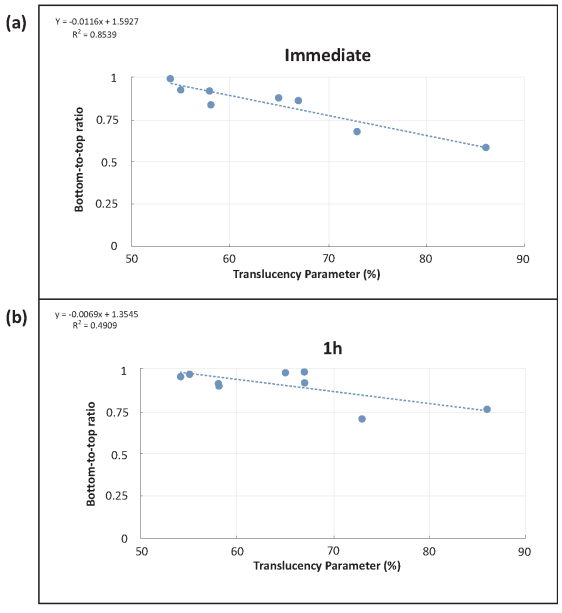

Figure 5: Relationship between translucency parameter and polymerization potential (**a**) immediate after photoactivation; (**b**) 1 h after photoactivation.

According to the present study (Figure 3), the conversion values obtained in the analysis performed after 1 h of photoactivation were higher than those obtained immediately after the process. The photoactivation process initiates polymerization, which occurs rapidly within the first few seconds and gradually slows down due to the increased viscosity and reduction in the number of remaining C=C bonds as the process continues [2]. However, this process can continue slowly over the next few hours, known as late polymerization or "dark curing," depending on the speed of each material evaluated [21]. Thus, materials with initially low conversion values tend to show a proportional increase in conversion over time. The post-curing process, however, may not achieve values that are acceptable or close to those obtained with other materials. For example, Forma Dentin resin showed a 25% increase in the polymerization ratio but remained below 80%, which is considered less than ideal according to the literature [22]. Additionally, it is known that polymers formed slowly are generally more linear and susceptible to degradation by hydrolysis [23–26].

"Enamel" resins classified as having high polymerization potential exceeded 90% for all commercial brands tested, a benchmark not achieved by materials with lower translucency. This raises concerns because a reduced decrease of conversion (DC) with depth can compromise restoration integrity, potentially impacting mechanical properties and leading to fractures or early degradation of marginal areas in proximal restorations [27–29]. Moreover, it is crucial to note that these high values were achieved using a photo activator device of high light quality and high light collimating capacity, which may not be universally available to clinicians [30,31].

Among the materials with lower translucency evaluated, Orion and Sirius-Z resins in the dentin version achieved polymerization potentials compatible with 90%. While this performance could be attributed to the efficiency of the photoinitiator/co-initiator system [3], it's noteworthy that Forma Body resin, despite having similar opacity to Orion and Sirius-Z Dentin resins, also demonstrated high activation capacity. This underscores that the primary factor influencing polymerization potential is the degree of translucency and the consequent ability to transmit light. Thus, the present study offers clinicians accurate measurement of the polymerization capacity among the different materials. However, further research using commercially available materials is necessary and fundamental to understanding their optical characteristics. Being a laboratory study, some limitations can be highlighted, such as the necessity to evaluate these materials in clinical outcomes. It is important to comprehensively understand the material's optical characteristics, durability in clinical settings, and overall suitability for diverse patient aesthetics needs.

5. Conclusions

Despite the limitations of this study, it can be concluded that:

- "Enamel" resins exhibit similar opacity among different commercial brands tested, with the polymerization potential exceeding 90%, a benchmark not achieved by all materials with lower translucency. Therefore, the decrease in the degree of conversion (DC) with depth may adversely affect restorative treatments, potentially compromising mechanical properties and leading to early degradation.
- In assessing baseline DC, it is evident that the Forma and Empress Direct resins in the dentin version show a loss of polymerization potential, which is probably associated with their lower translucency. Conversely, Orion and Sirius-Z resins in the dentin version were able to achieve a high degree of polymerization.
- There was a correlation between translucency and polymerization potential when baseline DC was considered. However, this relationship was not significant for conversion values after 1 h. These findings indicate that depending on the resin composite, delayed polymerization processes may compensate for slow initial polymerization.

List of Abbreviations

TP	Translucency Parameter
DC	Degree Of Conversion
FTIR	Fourier Transform Infrared Spectroscopy
Bis-GMA	Bisphenol-A Diglycidyl Dimethacrylate
TEGDMA	Triethylene Glycol Dimethacrylate
Bis-EMA	Ethoxylated Bisphenol-A Diglycidyl Dimethacrylate
UDMA	Urethane Dimethacrylate

Author Contributions

Conceptualization and supervision, L.F.J.S. and L.M.C.; methodology, V.O.G.J.; B.A.B.M.; C.S.; validation, V.O.G.J.; L.F.J.S. and L.M.C.; formal analysis, L.F.J.S.; investigation, B.A.B.M. and C.S.; resources, B.A.B.M.; C.S. and M.C.N.; data curation L.F.J.S. and L.M.C.; writing—original draft preparation, B.A.B.M. and C.S.; writing—review and editing, V.O.G.J.; M.C.N.; L.F.J.S. and L.M.C.; project administration, L.F.J.S. and L.M.C.; funding acquisition, L.F.J.S. and L.M.C. All authors have read and agreed to the published version of the manuscript.

Availability of Data and Materials

All data available are presented in the study in the Result section of the manuscript.

Consent for publication

Not applicable.

Conflicts of Interest

All authors declare that they have no conflicts of interest.

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