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The influence of printing angle on color and translucency of 3D printed resins for dental restorations

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ABSTRACT

Objectives: To evaluate the influence of printing orientation on color and translucency of 3D printing restorative resins.
Methods: Four 3D printing resin systems in the available shades (DFT-Detax Freeprint Temp- A1, A2,A3; FP-Formlabs Permanent Crown- A2,A3,B1,C2; FT- Formlabs Temporary CB- A2,A3,B1,C2; GCT-GC Temporary-Light, Medium) were evaluated. Three samples (10 × 10 × 1.2 mm) from each material were printed at two different printing orientations (0° and 90°) and polished to 1.00 ± 0,01 mm of thickness. Spectral reflectance was measured against black background using a calibrated spectroradiometer, CIE D65 standard illuminant and the 45°/0°geometry. Color and translucency differences were evaluated using CIEDE2000 metric (ΔE_{00}) and 50:50% perceptibility (PT_{00} and TPT_{00}) and acceptability (AT_{00} and TAT_{00}) thresholds.
Results: In general, color changes due to printing orientation at (0° and 90°) were mainly produced by ΔL^* or ΔC^* . ΔE_{00} were above PT_{00} for all DFT shades, FP-B1, FP-C2, FT-A2 and FT-B1. Only for DFT-1, ΔE_{00} was above AT_{00}. ΔRTP_{00} values were above TPT_{00} for DFT-A1, DFT-A3, FP-B1 and FT-B1, but lower than TAT_{00}. The direction of the changes in translucency (ΔRTP_{00}) depends on the material and shade.
Significance: The selection of building orientation (0° and 90°) for the 3D printed resins influence the visual color and translucency and therefore their esthetic appearance. These aspects should be considered when printing dental restorations using the evaluated materials.

1. Introduction

The use of temporary restorations is an important interim stage in a prosthodontic treatment. Temporary restorations assist on the therapeutic and functional effectiveness of the treatment, providing biological protection to the prepared tooth, stabilizing occlusal relationships, and simulating the final esthetic appearance of the restoration [1]. Thus, like definitive restorative materials, temporary crown and bridge materials should fulfill adequate mechanical requirements [2,3] and esthetic standards [4], which depend on the ability of the material to match the shape and shade of the natural dentition [5]. Resin materials are the most commonly used for this purpose. 3D printing restorative materials are gaining popularity mostly because of the reduction in material waste and the production of multiple restorations with no increasing manufacturing time [6,7].

Color and optical properties are particularly crucial to mimic the appearance of natural teeth [8]. A recent study [9] showed that 3D printing polymers for dental restorations are not yet adequately evaluated and characterized in relation to these properties. 3D printing restorative polymers still have limitations, compared to conventional or milled resins, on colorimetric behavior, such as: stain susceptibility [1,10–12], color stability after termocycling [4] or water storage [13], color stability with variations in post-curing time [14–16], and color masking ability [4]. Stability and changes in translucency for 3D printing polymers were evaluated using relative translucency parameter (RPT) [4] or translucency parameter (TP) [13,16]. Another factor that could influence the colorimetric behavior of these resins is the printing orientation of the resin structures [17]. Printing angle, printing orientation or build direction, meaning the layer construction orientation, is an important parameter in the initial steps of additive manufacturing (AM) procedures. It has been proven to influence printing accuracy [18] and mechanical properties such as flexural strength [19–22], flexural modulus [19,20] and compressive strength [3] of 3D printing restorative resins.

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A recent study [17] showed that printing angle modifies color stability and stainability of 3D printed resins. However, limitations of the study included that it did not analyze the cause of the influence of printing orientation on the color changes in the 3D printing restorative resin.

Color differences in dentistry are usually evaluated using the CIEDE2000 color difference formula (ΔE_{00}) [23], based on color CIELAB color space. ΔE_{00} incorporates specific corrections for the no uniformity of CIELAB color space and is currently recommended by CIE [24] and ISO/TR 28642 [25]. The esthetic success of dental restorations depends on the visual perception by the observer rather than statistical differences between color measurements [8]. Visual thresholds for color discrimination are well-established quality control tools in research and industry. Thus, according to the latest Guidance on color measurements, published by the International Organization for Standardization ISO/TR 28642:2016 [25], color variation should be assessed based on comparisons with 50:50% thresholds.

The translucency of a material may be characterized by the translucency parameter (TP) [26,27]. It has been defined as the color difference of a material that is optically uniform throughout its thickness and which is in optical contact with ideal white (Rg = 1) and black background (Rg = 0). Under these conditions, TP values of 0 and 100 would correspond to completely opaque and completely transparent materials, respectively [28]. However, when the backgrounds used are not ideal, referred to the color of the backings used in the color difference determinations, the relative translucency parameter (RTP) is required [29]. In this case, there will be a change in scale, being the maximum possible TP obtained the color difference between the backings used. Moreover, the use of ΔE_{00} metric has been suggested for TP calculations [30,31]. Translucency variation should be assessed based on comparisons with reliable 50:50% translucency thresholds [31].

So far, there is no information about the effect of printing orientation on color and translucency of 3D printed resins, justifying the need for further studies. This information is important for the successful management of these materials, and to satisfy the increasing esthetic demands of patients. Therefore, the purpose of this study was to evaluate the influence of printing orientation on color and translucency of 3D printing restorative resins, testing the hypotheses that printing orientation has no influence on (1) color of 3D printed restorative resins, considering the color perceptibility threshold (PT_{00}), and (2) relative translucency parameter of 3D printing restorative resins considering the translucency perceptibility threshold (TPT_{00}).

2. Materials and methods

2.1. Tested materials and samples preparation

Four polymer-based 3D printing resins indicated for fixed restorations were selected for the study (Table 1). The resins were printed using the 3D printer recommended by each material's manufacturer.

Square-shaped specimens (10 mm × 10 mm x 1.2 mm) were designed (n = 3) (Fig. 1) using an open-source CAD software (Autodesk Fusion 360, Autodesk Inc., San Rafael, California, USA) and saved as a standard tessellation language (STL) file, which was used to manufacture the specimens from all the evaluated materials. The STL file was exported to a 3D printer slicer software program: Preform Software (Formlabs Inc.,35 Medford, Somerville, MA 02143, United States) for Formlabs Temporary CB and Formlabs Permanent Crown resins (Fig. 2-A), and Asiga Composer Software (Asiga HQ, Alexandria, NSK, Australia) for Detax Freeprint Temp resin and GC TempPrint resin (Fig. 3-A). Sufficient specimen support structures were added (Figs. 2-B, 3-B, 3-C), and the specimens were prepared for printing using the manufacturer stablished parameters for exposure time, 50 µm layer thickness and two different printing orientations, 0° and 90°, to the building platform surface. Printing followed the manufacturer recommended instructions.

After printing, the specimens were carefully post-processed according to the manufacturer´s instructions, as follows (Fig. 4):

- Detax Freeprint Temp resin specimens were carefully removed from the building platform using a scraper, pre-cleaned with 99,9% isopropyl alcohol for 3 min in a sonic bath, and the support structures were removed using low speed rotary instruments (Marathon N3S S07, Supershu). Another cleaning procedure using 99,9% isopropyl alcohol for 3 min in a sonic bath was performed and dried with compressed air. Post-curing was performed with a xenon flash curing unit Otoflash G171-N2 (NK Optik GmbH Baierbrunn, Germany) with 2 × 2000 flashes under inert gas conditions (nitrogen).
- GC TempPrint resin specimens were carefully removed from the building platform using a scraper, pre-cleaned with 99.9% isopropyl alcohol, cleaned for 2 min in an sonic water bath, and dried with compressed air. A second rinse was done using fresh isopropanol and a sonic water bath. Post-curing was performed using Otoflash G171-N2 (NK Optik GmbH Baierbrunn, Germany) with 2 × 400 flashes under nitrogen. The support structures were removed with a nipper and a carbide bur, and a final post-curing was performed under the same conditions.
- Formlabs resins specimens were cleaned before removal from the building platform using FormWash (Formlabs Inc., Somerville, MA, USA) with 99.9% isopropyl alcohol for 3 min. The specimens were carefully removed from the building platform using a scraper. A second rinse was performed using fresh isopropanol to completely remove uncured monomers remaining on the surface. The specimens were dried with compressed air. Post-curing was performed using FormCure (Formlabs Inc., Somerville, MA, USA) for 20 min at 60 °C. After cooling, the support structures were removed using low speed rotary instruments (Marathon N3S S07, Supershu). The

Table 1
Information about the polymer-based 3D-printing resins evaluated in the study.

Resin	Manufacturer	Shades	Printer	Lot number
DFT- Detax Freeprint Temp	DETAX GmbH, Ettlingen, Germany	A1, A2, A3	Asiga Max UV[a]	A1: 240202 A2: 240204 A3: 240201
FT- Formlabs Temporary CB	Formlabs Inc., Somerville, MA, USA	B1, A2, A3, C2	3D Form 3B+[b]	B1: 600282 A2: 600134 A3: 600130 C2: 600126
FP- Formlabs Permanent Crown	Formlabs Inc., Somerville, MA, USA	B1, A2, A3, C2	3D Form 3B+	B1: 600167 A2: 600165 A3: 600164 C2: 600193
GCT- GC TempPrint	GC Corporation, Tokyo, Japan	Medium Light	Asiga Max UV[a]	Light: 2012081 Medium: 2010091

[a] Digital light processing (DLP) printer. Asiga HQ, Alexandria, NSK, Australia.
[b] Stereolithography (SLA) printer. Formlabs Inc.,35 Medford, Somerville, MA 02143, United States.

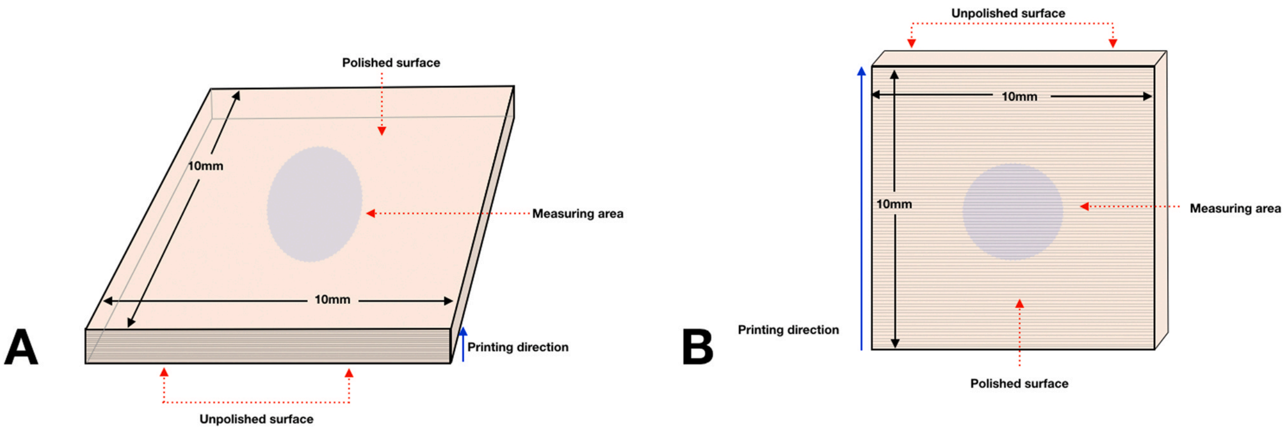

Fig. 1. A- Specimen size, printing orientation (0° or horizontal printing) and polished surface. B- Specimen size, printing orientation (90° or vertical printing) and polished surface.

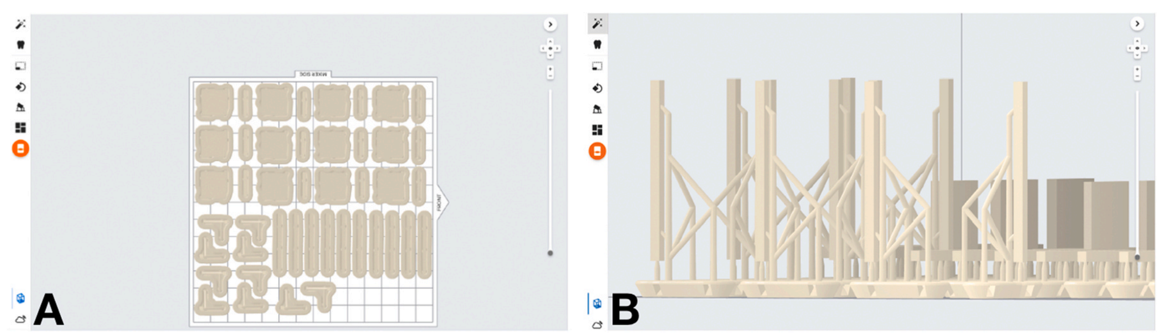

Fig. 2. Cad design for FT and FP specimens in Formlabs Preform Software. A: Top view. 0° and 90° square-shape samples for color measurements. B: Front view. Supporting structures for the 3D printed specimens.

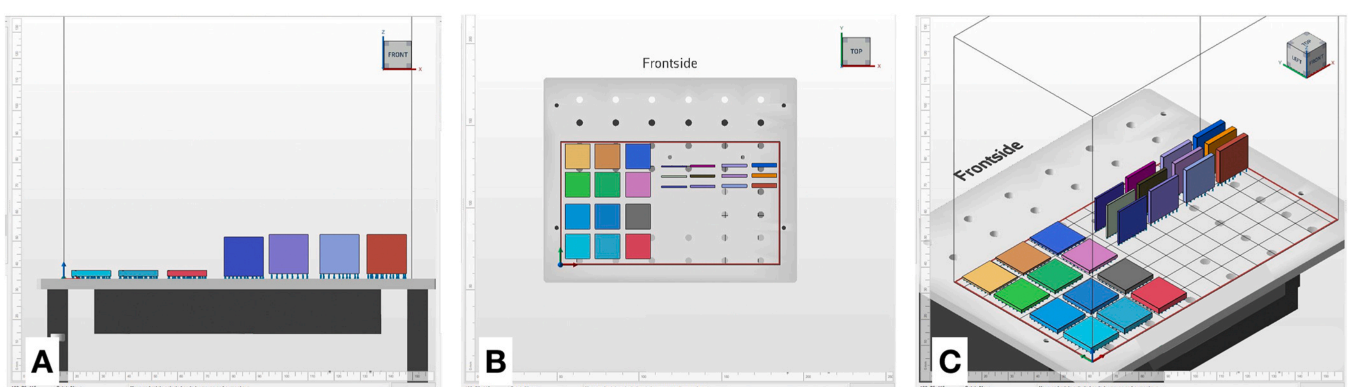

Fig. 3. Cad design for DFT and GC specimens in Asiga Composer Software. A: Front view. 0° and 90° square-shape samples for color measurements. B: Top view. Supporting structures for the 3D printed specimens. C: View before printing.

surface residue was removed using Perlablast Micro (Bego GmbH & Co., Bremen, Germany) and a second post-curing process was perform in FormCure for 20 min at 60 °C.

The bottom side of the specimens (the closer to the printing platform) was polished (Fig. 1) under water using a sequence of silicon carbide (SiC) papers of decreasing grit (500–800–1200–2000–4000). Specimen thickness was controlled during the polishing process using a digital caliper with an accuracy of 0.01 mm (Mitutoyo, Europe GmbH, Germany) to a final thickness of 1.00 mm ± 0.01 mm. The specimens were classified and stored in the dark.

2.2. Spectral reflectance and color measurement

A spectroradiometer (PR 670- Photo Research, Chatsworth, CA), a fiber-coupled Xe-Arc light source (70050–300, Newport Corporation, Irvine, CA, USA) and a spectrally calibrated reflectance standard (SRS-3, Photo Research, Syracuse, NY, USA) were used to measure the spectral reflectance of the specimens in the range 380–780 nm, with a focus measuring aperture of 1°, at the center of each sample (Fig. 1). The spectroradiometer was placed 40 cm away from the samples with the illuminating/measuring geometry corresponding to CIE 45°/0°. The spectral reflectance of all specimens was measured against white ($L^* = 94.2$, $a^* = 1.3$, and $b^* = 1.7$) and

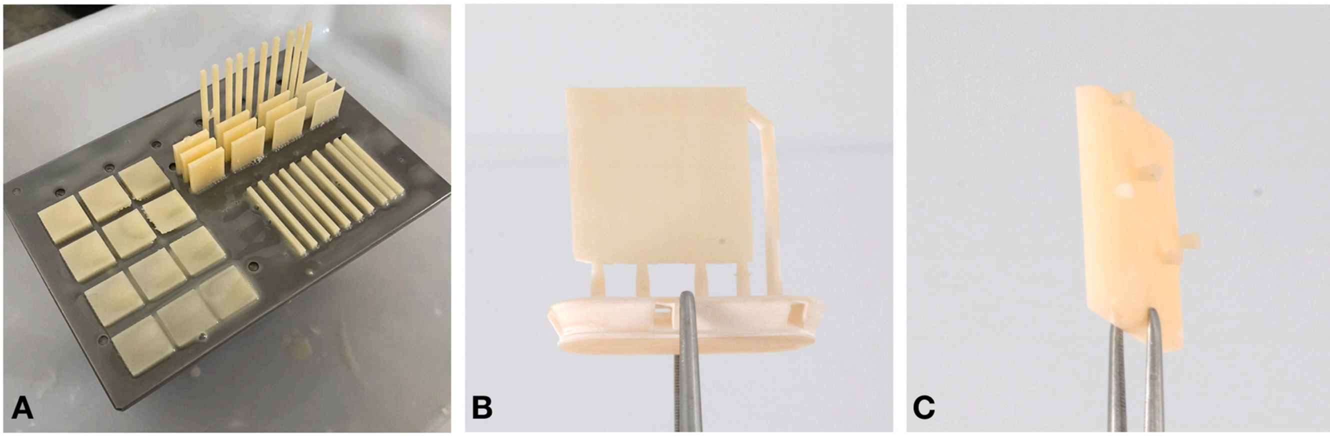

Fig. 4. A: 0° and 90° specimens printed using Asiga Max UV printer. B: 90° specimens printed using Formlabs 3D Form 3B+. C: 0° specimens printed using Formlabs 3D Form 3B+.

black (L* = 3.1, a* = 0.7, and b* = 2.4) 50 mm × 50 mm ceramic tile backgrounds (Ceram, Staffordshire, United Kingdom).

Saturated sucrose solution having a refraction index of approximately 1.5 was placed at the optical contact between the specimen and the background [32,33]. Three short-term repeated reflectance measurements without replacement were performed.

2.3. Color differences

The CIEDE2000 color difference (ΔE_{00}) was calculated as follows [25,26]:

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

where $\Delta L'$, $\Delta C'$and, $\Delta H'$ are metric differences between the corresponding values of the samples, computed on the basis of uniform color space used in CIEDE2000. Parametric factors (k_L, k_C and k_H) were set to 1 for CIEDE2000.

Color differences were evaluated using the published data of 50:50% color perceptibility (PT_{00} =0.81) and acceptability (AT_{00} =1.81) thresholds [34].

2.4. Relative translucency parameter

The relative translucency parameter (RTP_{00}) was determined by calculating the color difference between readings over the black and the white backgrounds according to the ΔE_{00} color difference formula [23,24,31]:

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

where the subscripts "B" and "W" refer to lightness (L′), chroma (C′) and hue (H′) of the specimens over the black and the white backgrounds, respectively. Parametric factors (k_L, k_C and k_H) were set to 1 (RTP_{00} (1:1:1)).

The relative translucency parameter difference (ΔRTP_{00})was calculated as follows [23,24]:

$$\Delta RTP_{00} = RTP_{00_2} - RTP_{00_1} \quad (3)$$

Translucency differences were finally evaluated using published data of 50:50% translucency perceptibility (TPT_{00} =0.62) and acceptability (TAT_{00} =2.62) thresholds [31].

2.5. Statistical analysis

Levene's test for homogeneity of variance (α = 0.05) was used. Since equal variances for the CIELAB color coordinates (L*, a*, b*), the polar color coordinates (chroma, C*; hue angle, h°) and RPT groups could not be assumed, the Kruskal-Wallis test was applied to analyze the differences between the printing orientations. The Mann–Whitney U test was used for pairwise comparisons with Bonferroni correction ($p < 0.001$). All statistical tests were performed with dedicated software (SPSS Statistics 20.0.0, IBM, Armonk, NY).

3. Results

Table 2 shows the color coordinates and RTP values for the resin specimens printed at 0° and 90°, evaluated over black background. Fig. 5 shows the color difference values for the resin specimens printed at 0° and 90°, compared to the perceptibility (PT_{00}) and acceptability (AT_{00}) thresholds. In addition, the magnitudes of lightness, chroma and hue components in total CIEDE2000 color difference are depicted by the height of colored fragments in the bars. Color differences are mainly produced by lightness differences, except for DFT-A2, FP-A3 and FT-A2, which presented color differences mainly produced by chroma differences. Only GCT-M showed color differences produced by hue differences but with low value (0.23 units).

For CIELAB color coordinates, statistically significant differences between 0° and 90° printing ($p < 0.005$) were found for DFT-A1, DFT-A2 and DFT-A3 resins. Color difference values for DFT resins were higher than PT_{00} (DFT-A1 (ΔE_{00} =2.94), DFT-A2 (ΔE_{00} =1.67) and DFT-A3 (ΔE_{00} =1.64)) but only DFT-A1 presented a color difference higher than the acceptability threshold. In addition, DFT showed the greatest color differences between 0° and 90° printing orientation compared to the other 3D printing resins evaluated.

Only the shade B1(ΔE_{00} =1.13) from FP showed a color difference higher than PT_{00}, but below AT_{00}. For this shade, the color coordinate L* showed statistically significant differences ($p < 0.001$). FP-A3 showed statistically significant differences in b* and C*. For FP-C2, all color coordinates showed statistically significant differences, except for a*, while FP-A2 did not show any statistically significant difference for the color coordinates.

For Formlabs Temporary CB (FT) only the shades B1 and A2 showed color differences above PT_{00} but lower than acceptability threshold. For FT-B1 and FT-C2, statistical differences ($p < 0.001$) were found only for L* coordinate, and no statistical differences were found for FT-A3 ($p \geq 0.001$). Finally, FT-A2 showed statistically significant differences for b, C* and h° color coordinates ($p < 0.001$).

GC Temp Print resins (GCT), in both Light (GCT-L, ΔE_{00} =0.29) and Medium (GCT-M, ΔE_{00} =0.24) shades, showed color differences lower

Table 2
Average and standard deviation (SD) values of the CIELAB color coordinates (L*, a* and b*), chroma (C*) and hue angle (h º) evaluated on black background, and Relative Translucency Parameter RTP00, for the resin specimens printed at 0° and 90°.

Sample	Printing Angle (º)	L* (SD)	a* (SD)	b* (SD)	C* (SD)	hº (SD)	RTP_{00} (SD)
DFT-A1	90	69,10 (0,48) †	-1,39 (0,07) †	9,39 (0,08) †	9,50 (0,07) †	98,42 (0,45) †	14,08 (0,52)
DFT-A1	0	71,71 (0,54) †	-1,95 (0,26) †	6,79 (0,38) †	7,07 (0,34)†	106,08 (2,61) †	13,44 (0,41)
DFT-A2	90	67,85 (0,26) †	-0,21 (0,18)	11,70 (0,57)	11,71 (0,57)	91,08 (0,95)	14,58 (0,21) †
DFT-A2	0	68,71 (0,23) †	-0,72 (0,25)	9,72 (1,01)	9,75 (1,00)	94,42 (1,81)	14,19 (0,12) †
DFT-A3	90	65,94 (0,13) †	0,32 (0,16) †	12,76 (0,28) †	12,76 (0,28) †	88,58 (0,70) †	14,64 (0,22) †
DFT-A3	0	67,52 (0,65) †	-0,12 (0,23) †	11,46 (0,54) †	11,46 (0,53) †	90,66 (1,23) †	13,86 (0,06) †
FP-A2	90	69,25 (0,23)	-0,63 (0,07)	10,88 (0,22)	10,90 (0,22)	93,33 (0,41)	12,99 (0,04) †
FP-A2	0	68,69 (0,27)	-0,77 (0,13)	10,93 (0,30)	10,96 (0,29)	94,03 (0,78)	13,29 (0,18) †
FP-A3	90	66,69 (0,35)	-0,78 (0,09)	11,74 (0,21) †	11,76 (0,20) †	93,79 (0,49)	13,85 (0,40)
FP-A3	0	66,86 (0,06)	-0,77 (0,05)	11,24 (0,19) †	11,27 (0,19) †	93,90 (0,33)	13,98 (0,08)
FP-B1	90	70,05 (0,18) †	-1,83 (0,04)	5,12 (0,32)	5,44 (0,31)	109,68 (0,78)	14,36 (0,05) †
FP-B1	0	71,42 (0,15) †	-1,73 (0,08)	4,61 (0,12)	4,93 (0,12)	110,60 (0,84)	13,62 (0,10) †
FP-C2	90	66,72 (0,31) †	-1,19 (0,04)	9,58 (0,10) †	9,65 (0,10) †	97,10 (0,23) †	12,80 (0,10) †
FP-C2	0	65,87 (0,24) †	-1,22 (0,01)	9,17 (0,14) †	9,25 (0,14) †	97,60 (0,14) †	13,22 (0,09) †
FT-A2	90	69,52 (0,25)	-0,70 (0,11)	12,54 (0,16) †	12,56 (0,16) †	93,19 (0,51) †	12,34 (0,12) †
FT-A2	0	69,66 (0,30)	-0,84 (0,11)	10,93 (0,28) †	10,96 (0,27) †	94,43 (0,68) †	12,82 (0,24) †
FT-A3	90	66,53 (0,29)	-0,81 (0,05)	11,75 (0,19)	11,78 (0,19)	93,96 (0,27)	14,13 (0,11)
FT-A3	0	66,72 (0,37)	-0,87 (0,03)	11,84 (0,39)	11,87 (0,38)	94,19 (0,25)	13,86 (0,18)
FT-B1	90	72,06 (0,45) †	-1,58 (0,03)	5,00 (0,04)	5,24 (0,03)	107,52 (0,46)	12,94 (0,27) †
FT-B1	0	70,98 (0,33) †	-1,58 (0,06)	4,95 (0,32)	5,20 (0,31)	107,74 (1,25)	13,62 (0,33) †
FT-C2	90	65,01 (0,19) †	-1,36 (0,03)	9,68 (0,23)	9,77 (0,23)	98,03 (0,33)	13,60 (0,25)
FT-C2	0	65,38 (0,09) †	-1,35 (0,06)	9,61 (0,19)	9,71 (0,19)	97,97 (0,28)	13,36 (0,09)
GCT-L	90	73,47 (0,06)	-1,33 (0,01)	6,49 (0,18)	6,62 (0,18)	101,60 (0,28)	9,77 (0,33)
GCT-L	0	73,78 (0,40)	-1,33 (0,14)	6,71 (0,31)	6,85 (0,28)	101,29 (1,67)	10,07 (0,15)
GCT-M	90	73,10 (0,26)	0,78 (0,09)	10,81 (0,18)	10,84 (0,18)	85,89 (0,44)	9,32 (0,27)
GCT-M	0	73,16 (0,20)	0,95 (0,09)	10,76 (0,13)	10,80 (0,14)	84,98 (0,44)	9,43 (0,16)

† The difference in color coordinate or RTP00 values for the tested resin printed at 0° and 90° is statistically significant.

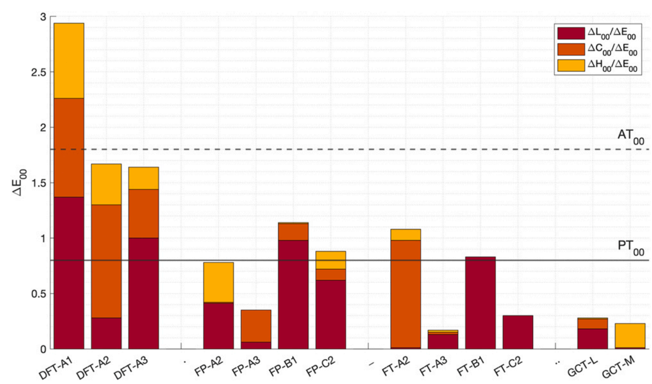

Fig. 5. Color difference (ΔE_{00}) values for the resin structures printed at 0° and 90°, compared to the perceptibility (PT_{00}) and acceptability (AT_{00}) thresholds. The magnitudes of lightness, chroma and hue components in total CIEDE2000 color difference are depicted by the height of colored fragments in the bars.

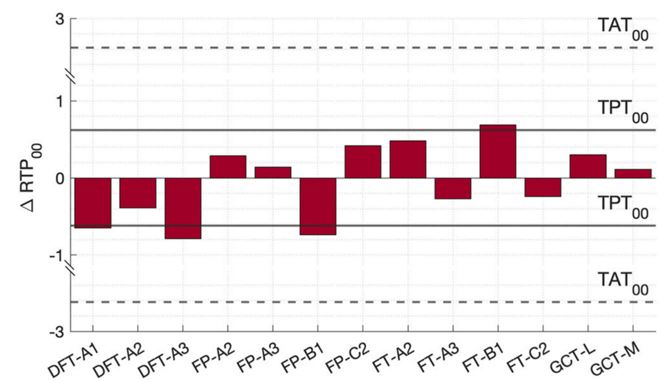

Fig. 6. Relative translucency parameter difference ($\Delta RTP_{00} = RTP_{90º} - RTP_{0º}$) values between resins printed at 0° and 90°. Negative ΔRTP_{00} values indicate that $RTP_{90º} < RTP_{0º}$. Positive ΔRTP_{00} values indicate that $RTP_{90º} > RTP_{0º}$.

than the perceptibility threshold. ΔE_{00} values were very similar in both shades, but slightly higher in GCT-L. No significant differences were found for all color coordinates between 0° and 90° GCT specimens.

Significant differences were found for RTP_{00} (Table 2) between specimens printed at 0° and 90°, except for DFT-A1, FP-A3, FT-A3, FT-C2 and GCT materials (GCT-M and GCT-L). Fig. 6 presents translucency difference ($\Delta RTP_{00} = RTP_{90º} - RTP_{0º}$) values for the resins specimens printed at 0° and 90°, compared to the translucency perceptibility (TPT_{00}) and acceptability (TAT_{00}) thresholds[31]. Only DFT-A1 ($\Delta RTP_{00} = 0.65$), DFT-A3 ($\Delta RTP_{00} = 0.79$), FP-B1 ($\Delta RTP_{00} = 0.74$) and FT-B1 ($\Delta RTP_{00} = 0.69$) showed translucency differences above TPT_{00}. All experimental groups showed translucency differences lower than TAT_{00}.

4. Discussion

Color matching between restorations and natural teeth is essential when temporary restorations are used for long term dental treatments [5]. Thus, it is critical to understand how 3D printing materials behave in terms of color and translucency with changes in the printing procedure in order to produce predictable dental restorations and to optimize these properties in materials development.

Visual color difference thresholds are a well-established quality control tool for color selection in dentistry [8]. According to the Guidance on color measurements ISO/TR 28642:2016 [25], color differences should be assessed based on comparisons with 50:50% thresholds. In the present study, color differences were evaluated using the visual thresholds determined by Paravina et al. [34] for CIEDE2000 metric. The results of this study showed that color differences between 0° and 90° printing orientation were higher than the color perceptibility threshold (PT_{00}) for more than half of the 3D printed resins evaluated (DFT-A1, DFT-A2, DFT-A3, FP-B1, FP-C2, FT-A2, FT-B1). This means that the perceived color can be affected in certain situations by printing orientation and, therefore, the first null hypothesis was partially rejected. In addition, statistically significant differences were found between CIELAB coordinates values for DFT resin printed at 0° and 90°

($p < 0.005$), and for some shades from other resins, supporting this result. The scarce scientific evidence in this topic supported the formulation of a null hypothesis and challenges comparisons between studies.

Based on the results of this study, dentists must take caution on printing the evaluated materials and shades for dental restorations, as the printing orientation (0°/90°) can have an influence on the final color of the restoration. This is particularly relevant for DFT because the color difference values are greater than other evaluated resins, and DFT-A1 color change depending on printing orientation can be considered unacceptable by an average observer.

Differences in lightness or chroma were the primary cause for the color differences observed in the present study, which considered different printing orientations (Fig. 5). Except to DFT, visually perceptible differences were always found only for bright shades (FP-B1, FT-B1, FT-A2), which is probably associated with differences in chemical composition to increase lightness. Moreover, diverse color difference magnitudes were observed for the evaluated 3D printing resin systems, which could be related to differences in chemical composition, printing technique, photopolymerization mechanism and photoinitiators [35].

Optical properties are associated with absorption and scattering of light emerging on the surface and inside the medium. The perceived color and translucency are intimately related with light-scattering [36,37]. Considering resin-based composites, scattering is mostly determined by particles size and shape, while absorption is associated with the resin matrix and the presence and nature of colorant pigments [38–40]. Drawing an analogy with resin-based composites, differences in chemical composition between the evaluated 3D printing resins could explain their different behavior in terms of color and translucency with variations in printing orientation.

The strategy behind the 3D photopolymerization consists on the light irradiation through a reservoir (vat) filled with photocurable materials, resulting in photopolymerization of the liquid monomers/oligomers at a predetermined location, straight on the building platform [35]. A photoinitiator system is required to convert photolytic energy into the reactive species (radical or cation) which can drive the chain growth via radical or cationic mechanism [35]. This strategy is translated into two streams: SLA, where a movable photon source is used to activate photopolymerization of the photocurable resin with point-by-point exposure and successively print solid layers one on top of the other, and DLP, where a light source illuminates each layer all-at-once from the bottom of the resin bath, and the building platform is dipped into the resin from above [35]. The materials evaluated in the present study are designed for different printing techniques (Table 1) and probably present different monomer/oligomer type, monomer molecular weight, type of photoinitiators and photopolymerization mechanism (radical/cationic/combined). Therefore, the exact chemical composition of the resins was requested to the manufacturers, but no detailed information was obtained. Thus, the specific relation between the chemical composition and optical behavior could not be depicted.

Translucency is a conditioning factor in the final esthetic appearance of dental restorations. It has been usually characterized through the translucency parameter (TP) [26,27] and assessed by comparison with reliable 50:50% translucency perceptibility and acceptability thresholds determined according to CIELAB and CIEDE2000 color difference formulas [31]. In the present study, the translucency of 3D printing resins was evaluated through RTP [4] and compared with the translucency thresholds [31] ($TPT_{00} = 0.62$ and $TAT_{00} = 2.62$) to assess translucency differences. As DFT-A1, DFT-A3, FP-B1 and FT-B1 resins showed translucency difference values higher than TPT_{00}, the second hypothesis was partially rejected. Nevertheless, the present study did not find a distinct pattern for the translucency variation based on the printing orientation. The changes were dependent on the material and shade. While DFT resins showed higher translucency (RTP) at 90°, GCT resins showed the opposite behavior. Furthermore, FT and FP resins showed different behavior depending on the shade. While FP-B1, FT-A3 and FT-C2 resins were more translucent at 90°, the other shades presented higher translucency when they were printed at 0°. These aspects should be considered when printing dental restorations using the evaluated materials.

Translucency of other resin-based dental restorative materials is ultimately determined by the difference between the refractive indices (n) of the filler and the organic matrix [41]. Thus, the differences between the n of the components in each resin when it is polymerized could entail differences in translucency (RTP) for the different 3D printing resins evaluated. However, in the present study, translucency differences were calculated for specimens from the same resin type and shade (so with the same n) but printed at different angles. Therefore, translucency differences were probably due to the effect of the orientation of the overlapping layers during the printing process.

Printed specimens are generally composed of several layers having possibly distinct refractive indices [42]. The layers and the interfaces forming a multilayer specimen are each responsible for the reflection and the transmission of light [42]. Light may be scattered and/or absorbed in the layers, as well as reflected and transmitted at the interfaces between layers of distinct refractive indices [44]. Different overall scattering/absorption values from the overlapping layers and different overall reflectance/transmittance values from the interfaces in 0° and 90° specimens could explain the differences in translucency from the same resin depending on printing angle. Different chemical composition in resins from different brands and shades could entail different scattering/absorption values in the layers and different reflectance/transmittance values at the interfaces, and therefore different variations in RTP depending on printing orientation. This could explain the different magnitudes of the translucency differences due to printing orientation for the evaluated materials.

Different monomer content in the formulation of 3D printing resins has been proved to determine variations in their mechanical properties [43]. Moreover, 3D printing resins revealed certain anisotropy (understood as different behavior for different printing orientations) regarding their mechanical properties [44]. This properties-composition relation and the anisotropic behavior are in agreement with our results concerning color and translucency. Thus, the selection of building orientation has an impact not only on the mechanical behavior of the resin-based 3D printed restorations, but also in their esthetic appearance.

Tayaheri et al. [18] analyzed the degree of conversion across the thickness of the specimens printed at 0° and 90°. Polymerization at the "top" (close to the printing platform) of 3D printed bars appeared to be slightly higher than at the "base". Since the color measuring area is at the flat surface of the square specimens (Fig. 1), these over-polymerized layers will be present in the measuring area of 0° specimens, but not in 90° specimens. The presence or absence of layers with higher degree of conversion at the measuring area of the specimens depending on printing angle could explain differences in the interaction of light [42], and thereby differences in the final color and translucency of the printed resin. Further studies could be performed to identify the relationship between color and translucency, and the degree of conversion of 3D-printing resins.

Lucena et al. [45] showed significant differences in translucency, scattering, absorption and transmittance between different thicknesses of the same resin-based composite material. Thus, it could be expected that color and translucency differences depending on printing orientation in 3D printed resins may change with variations in material thickness. Therefore, we suggest further studies considering different material thicknesses and evaluating optical properties (scattering, absorption, transmittance) that determine color and translucency of 3D printed resins.

A potential clinical limitation of the present study is that provisional crown and bridges do not have square geometrical shape, but rounded asymmetrical morphology, which could determine a different behavior of 3D printed resins in terms of color and translucency with variations in thickness and printing orientation, suggesting further studies on this topic.

In vitro studies like the present work allow a better understanding of the intrinsic properties of materials and how they are influenced by different factors, which is of outmost importance to enhance and optimize these properties in materials development, improving their behavior and predictability for clinical use.

5. Conclusions

Within the limitations of this study, it can be concluded that: (1) color and translucency of the 3D printing restorative resins is influenced by the printing orientation, which may result in visually perceptible color and translucency differences; (2) lightness and chroma differences were the main determinants for the color differences. The direction of such differences depends on the material and shade. Therefore, the selection of the building orientation (0° or 90°) affects the final esthetic appearance of the 3D printed resins. These aspects should be considered when printing dental restorations.

Data availability

The data that support the findings of this study are included in it. The documents are available on request from the corresponding author.

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