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Masking ability of indirect restorative systems on tooth-colored resin substrates

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ABSTRACT

Objective. To evaluate the masking ability of different indirect restorative systems (IRS) on tooth-colored resin substrates.

Methods. A1-shaded specimens from 5 IRS (LDC–IPS e.max® CAD; YZW-Zenostar Zr Translucent; PICN-Enamic; YLD-T-IPS e.max® ZirCAD + IPS e.max Ceram; CAD-on-Zenostar Zr Translucent + Crystall./Connect + IPS e.max® CAD) were fabricated. Specimens (n = 5) were cemented with a resin luting agent (Variolink® N; shade White) on three different shades (ND3, ND8 and ND9) of a tooth-colored resin substrate (IPS Natural Die Material). Spectral reflectance and color coordinates were measured using a spectroradiometer under standardized lighting conditions (CIE D65 illumination) and optical geometry 0/45°. Color differences (ΔE^*_{ab} and ΔE_{00}) from cemented specimens and CIELAB- and CIEDE2000-based translucency parameter (TP and TP_{00}) from non-cemented specimens were calculated. Data was statistically analyzed using one-way ANOVA and Tukey's tests ($\alpha = 0.05$). ΔE values were also analyzed using perceptibility (PT = 1.22 ΔE^*_{ab} units; 0.81 ΔE_{00} units) and acceptability (AT = 2.66 ΔE^*_{ab} units; 1.77 ΔE_{00} units) thresholds.

Results. The cemented specimens of CAD-on, LDC, YZW and PICN on different substrates (ND3–ND8, ND3–ND9 and ND8–ND9) showed different ΔE^*_{ab} and ΔE_{00} values ($p \le 0.05$), which were above AT. YLD-T showed ΔE^*_{ab} and ΔE_{00} values below AT for all comparisons. Lowest and highest TP and TP_{00} values were obtained for YLD-T and PICN, respectively ($p \le 0.05$).

Significance. Resin-cemented YLD-T on different tooth-colored substrates showed less translucency as well as smaller color differences (below acceptability threshold), indicating the best masking ability among evaluated systems.

1. Introduction

Considering dental color appearance, natural-looking restorations require adequate shade matching and blending optical properties from adjacent natural teeth [1,2]. The final appearance of esthetic indirect restorations is influenced by factors such as composition and microstructure [2,3] optical properties [4] and layering of the ceramic systems [5], surface texture and material thickness [6,7], and color and opacity of luting

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agents [6,7]. In addition, the tooth preparation (substrate) color is major factor influencing on final color and appearance of indirect restorations [1,8].

In clinical situations requiring restoration of non-vital discolored teeth or metal abutment structures, dentists are confronted to choose materials to mask the underlying color producing an adequate esthetic restoration. That is one of the greatest challenges in esthetic dentistry [8,9]. Additionally, the ceramic framework translucency was recognized as a key factor determining the optical characteristics of all-ceramic restorations [10].

There are many CAD–CAM ceramic systems combining strength and esthetics to cover different clinical situations. Lithium disilicate-based glass-ceramic has generated considerable interest for restorative dentistry mostly because of adequate strength (350–450 MPa) [8] and optical properties [4]. Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) is still the strongest and toughness ceramic ever used in dentistry [8,11] but its limited translucency [12] and the veneer porcelain chipping [11] are major disadvantages for veneered Y-TZP systems [13]. To avoid such problems, monolithic zirconia restorations using highly-translucent Y-TZP were introduced to dentistry as an alternative to porcelain-fused-to-zirconia restorations [14–16]. In addition, in 2011, a new technique was developed (CAD-on) to produce multilayered all-ceramic restorations (zirconia framework and lithium disilicate-based veneer fused together using a glass-ceramic) manufactured using the CAD–CAM technology [17,18]. A polymer-infiltrated ceramic-network (PICN) material with a dominant ceramic-network interconnected to a polymer-based matrix was introduced as an attempt to combine good material properties from polymers and ceramics [19,20].

Different parameters have been used to evaluate the masking ability of restorative materials, such as: contrast ratio (CR) [21,22] and translucency parameter (TP) [9,10,21–25]. In addition, CIELAB color space and its associated CIELAB (ΔE^*_{ab}) and CIEDE2000 (ΔE_{00}) total color difference formulas have been extensively used for color research in dentistry and, as a consequence, ΔE^*_{ab} [7,9,10,24,26–29] or ΔE_{00} [23,25] have been also used to evaluate the masking ability of restorative materials cemented on colored substrates. Yet, the International Organization for Standardization (ISO/TR 28642:2016) [30] states that color differences should be assessed on the basis of 50:50% acceptability (AT: $\Delta E^*_{ab} = 2.66$ and $\Delta E_{00} = 1.77$) and 50:50% perceptibility (PT: $\Delta E^*_{ab} = 1.22$ and $\Delta E_{00} = 0.81$) thresholds [31]. Thus, if the color difference between two specimens is at or below PT, it represents an excellent match; if the difference is between PT and AT, it represents an acceptable match; and if the difference is above AT, it represents an unacceptable match.

As the masking ability of indirect restorative systems (IRS) is critical for acceptable esthetic restorations on discolored substrates, the objective of this study was to evaluate the masking ability of IRS on different tooth-colored resin substrates using CIELAB (ΔE^*_{ab}) and CIEDE2000 (ΔE_{00}) metrics for color differences and the translucency parameters (CIELAB-based *TP* and CIEDE2000-based TP_{00}) for measuring the translucency of non-cemented IRS specimens. The hypotheses tested were that (1) color differences from same IRS cemented on different color of substrate are not acceptable (above AT), and (2) translucency varies with structural characteristics.

2. Material and methods

This *in-vitro* study used five indirect restorative systems (Table 1) being three monolithic structures (LDC, YZW and PICN), one bilayer structure (YLD-T) and one trilayer structure (CAD-on).

2.1. *Specimens preparation*

Plate-shaped specimens (n = 20; 1.5 mm thick; and shade A1) were fabricated from pre-sintered CAD–CAM ceramic blocks (IPS e.max® CAD, IPS e.max® ZirCAD and VITA Enamic®) and disc (Zenostar Zr Translucent) using a water-cooled precision cutting machine (Minitom, Struers Inc., Ballerup, Denmark) and diamond disc. Ceramic specimens were polished (Strues Abramin, Copenhagen, Denmark) using a sequence grit of silicon carbide abraded papers (#600, 800, 1200) under constant water irrigation.

For the CAD-on specimens, Zenostar Zr Translucent plates (thickness: 0.7 mm) were sintered (Zirkonofen 600/V2 furnace, ZirkonZahn, Gais, South Tyrol, Italy) according to the manufacturer's instructions. These zirconia plates were glass fused (IPS e.max CAD Crystall./Connect) to 0.7 mm thick plates of IPS e.max CAD HT. For this, the fusion glass capsule containing powder and liquid was vibrated (Ivomix, Ivoclar Vivadent, Schann, Liechtenstein) for 10 s, opened, and the material was applied to the surface of the IPS e.max® CAD HT plate that was immediately positioned onto the zirconia plate. The three-layer structure was placed under a load of 750 g and the excess glass was removed with a brush. Glass fusion and glass-ceramic (IPS e.max® CAD HT) crystallization were performed simultaneously using a Programat EP5000 furnace (Ivoclar Vivadent, Schann, Liechtenstein) following manufacturer's instructions [17,18].

The bilayer ceramic structure (YLD-T), simulating a conventional ceramic restoration, was fabricated using a plate (thickness: 0.7 mm) of IPS e.max® ZirCAD veneered by a layer (thickness: 0.8 mm) of IPS e.max Ceram. The zirconia plate was fabricated as described for CAD-on. The IPS e.max Ceram layer was obtained by the traditional layering technique (powder/liquid). Before application of the ceramic veneer, a thin layer of IPS e.max ZirLiner (Ivoclar Vivadent, Schann, Liechtenstein) was applied onto the zirconia plate and sintered using a Programat EP5000 furnace, according to the manufacturer's instructions. Treated zirconia plate was placed in a silicon matrix (Zetaplus, Zhermack SpA, Badia Polesine, Italy) for ceramic application. IPS e.max Ceram powder and liquid were mixed and applied with a brush onto the treated zirconia surface followed by sonic vibration. Excess ceramic liquid was removed using absorbent paper. The structure was carefully removed from the matrix and placed into the furnace for sintering, following manufacturer's instructions. YLD-T specimens were polished using a sequence grit of silicon carbide abraded papers (#600, 800, 1200) under constant water irrigation.

Table 1 – Description of materials used in the study.

Groups	Materials[a]	Thickness	Composition	Indications
LDC	IPS e.max® CAD LT	1.5 mm	Lithium disilicate-based glass-ceramics	Monolithic structure
YZW	Zenostar Zr Translucent	1.5 mm	Yttria tetragonal zirconia polycrystal	Monolithic structure
PICN	VITA Enamic® HT	1.5 mm	Polymeric-infiltrated ceramic-network	Monolithic structure
YLD-T	IPS e.max® ZirCAD	0.7 mm	Yttria tetragonal zirconia polycrystal	Framework ceramic
	IPS e.max Ceram	0.8 mm	Feldspathic ceramic	Veneering ceramic
CAD-on	Zenostar Zr Translucent	0.7 mm	Yttria tetragonal zirconia polycrystal	Framework ceramic
	IPS e.max CAD Crystall./Connect	0.1 mm	Glass-ceramic	Fusion glass
	IPS e.max® CAD HT	0.7 mm	Lithium disilicate-based glass-ceramics	Veneering ceramic

All information was provided by manufacturers.

[a] Except for VITA Enamic (Vita Zahnfabrik, Bad Säckingen, Germany), all materials are from Ivoclar Vivadent (Schann, Liechtenstein).

Handling, preparation, shrinkage percentage calculation (before cutting) and heat treatments (sintering or crystallization) of each ceramic system was performed by the same trained operator following manufacturers' recommendations. Final thickness of specimens was verified with a digital caliper (Digimatic caliper, Mitutoyo Corp., Tokyo, Japan).

2.2. *Substrate preparation*

A light-activated resin-based composite material (IPS Natural Die Material, Ivoclar Vivadent, Schann, Liechtenstein) was used as substrate to simulate tooth-colored preparations. Three different shades (ND3, ND8 and ND9) of this material were used for each IRS (n = 15; and 2.5 mm thick) because of the following reasons:

ND3 — imitates standard dentin (control shade);

ND8 — imitates severely discolored/non-vital tooth preparation; and

ND9 — imitates metallic structures.

A Teflon matrix (14 mm × 14 mm × 2.5 mm) was used to fabricate the substrate plates. The material was packed into the matrix and covered by a mylar strip and a glass slide (thickness: 1 mm). Material was light activated through the glass slide using a curing unit (Radii-cal, SDI, Bayswater, Victoria, Australia; 1200 mW/cm^2) for 40 s. Plate was removed from matrix and light activated for 40 s from the bottom side.

2.3. *Cementation procedure*

Bonding surfaces of LDC and PICN specimens were etched with 10% hydrofluoric acid (HF — Condac porcelana, FGM, Joinville, SC, Brazil) for 20 s (LDC) and 30 s (PICN). Bonding surfaces of YZW, YLD-T and CAD-on specimens were sandblasted (Basic classic, Renfert, Ribeirão Preto, Brazil) using aluminum oxide particles (Cobra 25 μm, Renfert, Ribeirão Preto, Brazil) for 20 s with 2 bar pressure. The tip of sandblasting unit was placed perpendicular and 10 mm far from specimens. Specimens were sonically cleaned (Vitasonic II, Vita Zahnfabrik, Bad Säckingen, Germany) in distilled water for 5 min and air-dried. A thin layer of adhesive (Tetric N-Bond®, Ivoclar Vivadent, Schann, Liechtenstein) was applied on the bonding surface of substrates and specimens. Components from the dual-cured cement (White shade; Variolink® N, Ivoclar Vivadent, Schann, Liechtenstein) were mixed and subsequently applied on the treated surface of specimens, which were placed onto the substrates. A load (750 g) was applied on the structures and cement excess was removed with a microbrush (FGM, Joinville, SC, Brazil). Cement was light activated using a curing unit (Radii-cal, SDI, Bayswater, Victoria, Australia; 1200 mW/cm^2) for 40 s from each side [18].

2.4. *Reflectance and color measurements*

The relative spectral reflectance (between 380–780 nm at 2 nm interval) was measured against white and black backgrounds for each specimen of IRS and against white background for each specimen of IRS cemented on different substrates. This procedure was performed using a non-contact spectroradiometer (SpectraScan PR-670, Photo Research, Chatsworth CA, USA), a fiber-coupled Xe-Arc light source (Oriol Research, Newport Corporation, USA) and a Spectrally Calibrated Reflectance Standard (SRS-3, PhotoResearch, USA). CIELAB coordinates from white and black ceramic tile backgrounds were $L^* = 94.70$, $a^* = 0.06$ and $b^* = 3.85$; and $L^* = 22.74$, $a^* = -0.38$ and $b^* = -1.67$, respectively. Spectral reflectance values were converted into CIE L*a*b* color coordinates using the CIE 2° Standard Observer and the CIE D65 Standard Illuminant. The illuminating/measuring geometry corresponded to CIE 45°/0° [32]. Three short-term repeated measurements without replacement were performed for each sample and the results were averaged.

CIELAB color coordinates against white background were used to evaluate color from all IRS.

2.5. *Color differences*

Color differences (ΔE) values between specimens of the same IRS (n = 15) cemented on different substrates (ND3: $L^* = 71.70 \pm 0.58$, $a^* = 2.13 \pm 0.16$, $b^* = 27.86 \pm 0.65$; ND8: $L^* = 61.16 \pm 0.83$, $a^* = 5.68 \pm 0.19$, $b^* = 23.37 \pm 0.66$; and ND9: $L^* = 47.69 \pm 1.30$, $a^* = 1.16 \pm 0.11$, $b^* = 11.35 \pm 0.48$) were calculated using CIELAB color difference metric (ΔE^*_{ab}) [32]:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

where ΔL^*, Δa^* and Δb^* are the respectively axes differences for a pair of samples; and CIEDE2000 color difference metric (ΔE_{00}), according to following equation [32,33]:

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{K_C S_C}\right)\left(\frac{\Delta H'}{K_H S_H}\right)} \quad (2)$$

where $\Delta L'$, $\Delta C'$, and $\Delta H'$ are the differences in coordinates (lightness, chroma, and hue, respectively) for a pair of samples in CIEDE2000. R_T is the so-called rotation function that accounts for the interaction between chroma and hue differences in the blue region. S_L, S_C, S_H are the weighting functions that adjust the total color difference for variation in the location of the color difference pair in L', a', b' coordinates. Finally, the parametric factors (K_L, K_C, K_H), are correction terms for experimental conditions [32,33]. In the present study, parametric factors of the CIEDE2000 color difference formula were all set to 1 ($K_L = 1, K_C = 1, K_H = 1$). Discontinuities due to mean hue computation and hue-difference computation were considered to calculate the CIEDE2000 color difference metric [34].

Color differences were analyzed through comparisons with 50:50% perceptibility (PT = 1.22 ΔE^*_{ab} units and 0.81 ΔE_{00} units) and 50:50% acceptability (AT = 2.66 ΔE^*_{ab} units and 1.77 ΔE_{00} units) thresholds, as determined for dental ceramics using TSK fuzzy approximation [31].

2.6. *Translucency parameter*

Translucency parameter (TP) values were determined for all specimens from IRS (n = 5), according to the following CIELAB-based equation [35]:

$$TP = \sqrt{(L^*_B - L^*_W)^2 + (a^*_B - a^*_W)^2 + (b^*_B - b^*_W)^2} \quad (3)$$

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

In addition, the TP was also calculated using CIEDE2000 color difference metric [6,36]:

$$TP_{00} = \sqrt{\left(\frac{L'_B - L'_W}{K_L S_L}\right)^2 + \left(\frac{C'_B - C'_W}{K_C S_C}\right)^2 + \left(\frac{H'_B - H'_W}{K_H S_H}\right)^2 + R_T\left(\frac{C'_B - C'_W}{K_C S_C}\right)\left(\frac{H'_B - H'_W}{K_H S_H}\right)} \quad (4)$$

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. All the other parameters are the same as Eq. (2).

2.7. *Statistical analysis*

Translucency parameter values (TP and TP_{00}) for non-cemented specimens from different IRS, and color difference values (ΔE^*_{ab} and ΔE_{00}) between the specimens from same IRS cemented on different substrates were statistically analyzed using one-way analysis of variance (one-way ANOVA) and Tukey's multiple comparison tests ($\alpha = 0.05$). The statistical analyses were performed using a standard statistical software package (SPSS 16.0, Chicago, USA).

3. Results

CIELAB color coordinates of IRS are shown in Fig. 1. Fig. 2(a and b) show mean and standard deviation values of translucency parameter (TP and TP_{00}) for different indirect restorative systems. The behavior of all systems was similar for both translucency parameters. PICN and YLD-T showed, respectively, the greatest and the lowest TP values ($p \leq 0.05$). In addition, LDC and CAD-on showed similar TP values ($p > 0.05$) (Fig. 2(a and b)).

Table 2 shows mean and standard deviation values of color differences (ΔE^*_{ab} and ΔE_{00}) between specimens of the same IRS cemented on different substrates (ND3–ND8, ND3–ND9 and ND8–ND9). The behavior of all systems was similar for both color difference metrics. Groups LDC, YZW, PICN and CAD-on cemented on different substrates (ND3–ND8, ND3–ND9 and ND8–ND9) showed different ΔE_{00} values ($p \leq 0.05$) for all comparisons. In addition, all these values were above AT (Table 2 and Fig. 3(a and b)). The lowest and the greatest ΔE values were registered for ND3–ND8 and ND3–ND9,

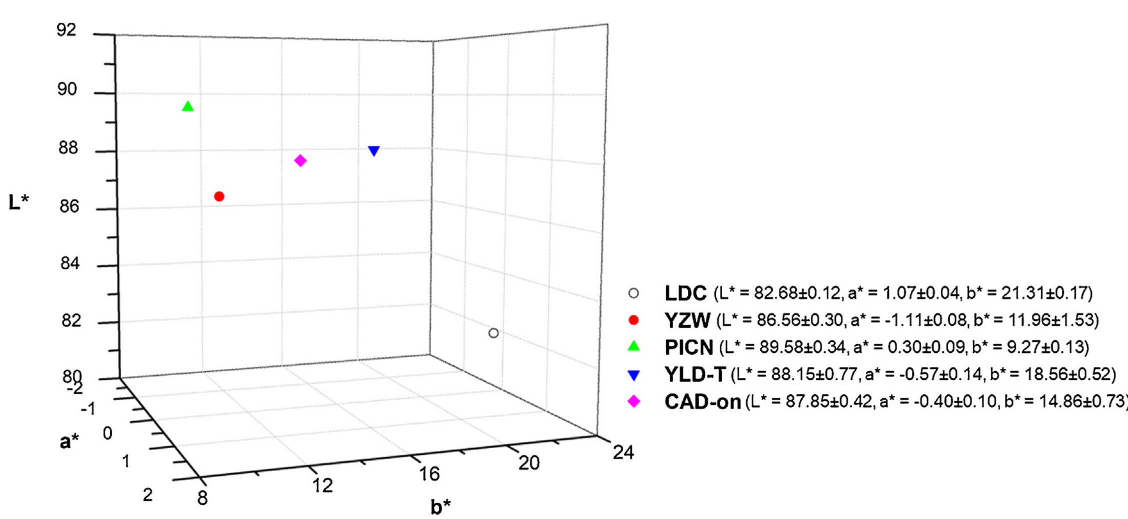

Fig. 1 – Distribution of mean values for the CIELAB color coordinates of each indirect restorative system (IRS), indicated in the figure legend.

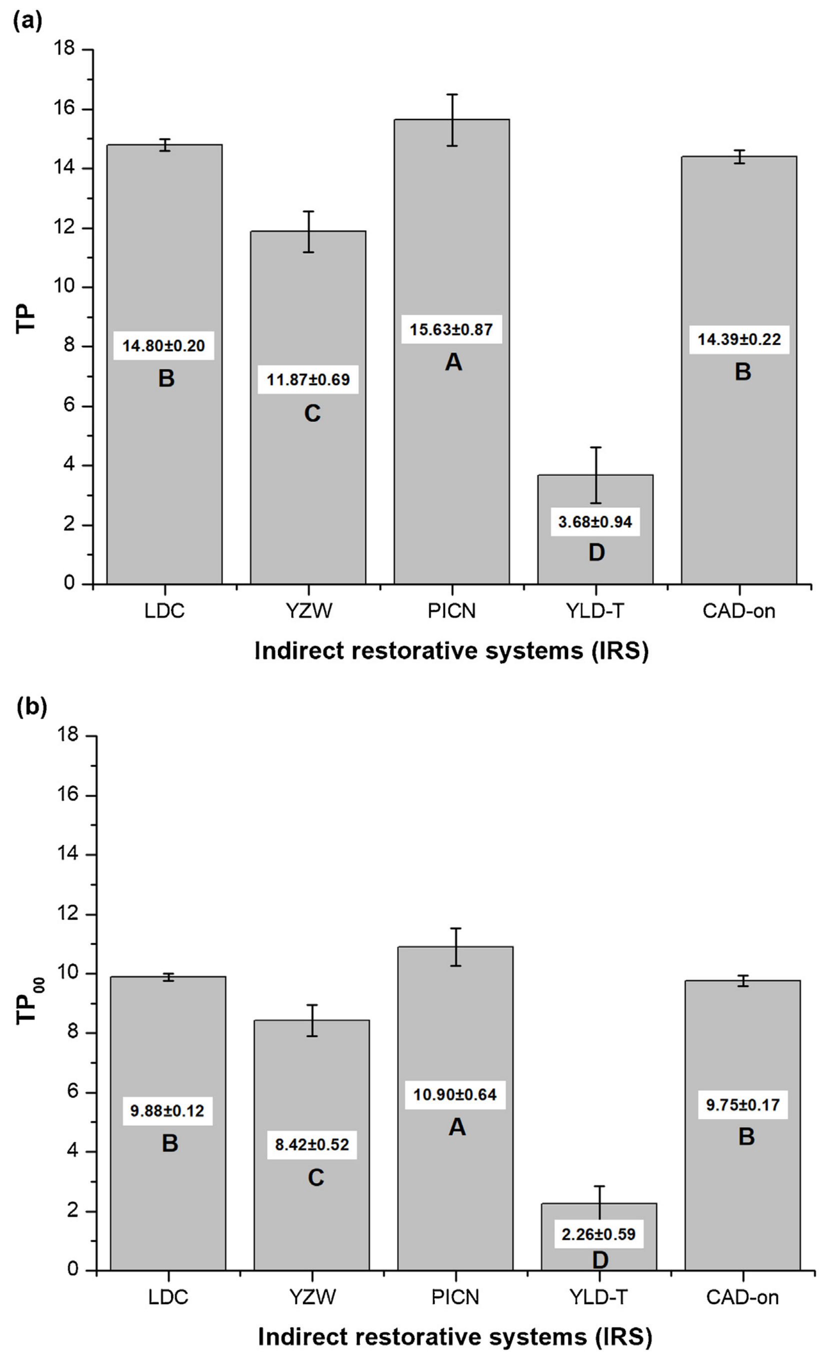

Fig. 2 – Mean and standard deviation values of (a) CIELAB-based translucency parameter (*TP*) and (b) CIEDE2000-based translucency parameter (TP_{00}) for different indirect restorative systems. Different capital letters show statistical differences for mean values of *TP* or TP_{00} (one-way ANOVA and Tukey's tests; $p \leq 0.05$).

respectively ($p \leq 0.05$) (Table 2). YLD-T showed ΔE^*_{ab} and ΔE_{00} values below AT for all comparisons (ND3–ND8, ND3–ND9 and ND8–ND9) with some of them not statistically different ($p > 0.05$) (Table 2 and Fig. 3(a and b)).

4. Discussion

The present study was designed to evaluate the masking ability of indirect restorative systems manufactured by CAD–CAM technology, except for the veneer layer of YLD-T structure. Therefore, monolithic (LDC — lithium disilicate-based glass-ceramics, YZW — zirconia, and PICN — polymer-infiltrated ceramic-network), bilayer (YLD-T — zirconia framework veneered with feldspathic ceramic) and trilayer (CAD-on — zirconia framework and lithium disilicate-based veneer fused with a glass-ceramic) restorative systems were cemented to tooth-colored resin-based composite substrates. The study design was an attempt to mimic clinical challenges of preparations with different shades that need to be masked by an

Table 2 – Mean and standard deviation values of color differences (ΔE^*_{ab} and ΔE_{00}) between specimens from the same indirect restorative systems cemented on different tooth-colored substrates (ND3, ND8 and ND9).

Substrates	Color differences	Indirect restorative systems				
		LDC	YZW	PICN	YLD-T	CAD-on
ND3–ND8	ΔE^*_{ab}	4.21 ± 0.30C	4.16 ± 0.74C	5.16 ± 0.49C	1.75 ± 1.18AB[a]	4.61 ± 0.36C
	ΔE_{00}	2.74 ± 0.18c	3.02 ± 0.54c	3.86 ± 0.32c	1.12 ± 0.61b[a]	3.18 ± 0.25c
ND3–ND9	ΔE^*_{ab}	9.74 ± 0.48A	8.73 ± 0.51A	11.51 ± 0.29A	2.42 ± 1.32A[a]	9.93 ± 1.11A
	ΔE_{00}	7.20 ± 0.41a	6.91 ± 0.33a	8.68 ± 0.20a	1.70 ± 0.64a[a]	7.30 ± 0.79a
ND8–ND9	ΔE^*_{ab}	5.80 ± 0.40B	5.22 ± 0.74B	6.77 ± 0.37B	1.47 ± 0.65B[a]	5.94 ± 0.99B
	ΔE_{00}	5.00 ± 0.36b	4.66 ± 0.36b	5.74 ± 0.26b	1.04 ± 0.35b[a]	4.94 ± 0.63b

Statistical groupings resulted from one-way ANOVA and Tukey's tests ($p \leq 0.05$).
Different capital letters show statistical differences for mean ΔE^*_{ab} values between the same IRS cemented on different substrates (column) ($p \leq 0.05$).
Different lowercase letters show statistical differences for mean ΔE_{00} values between the same IRS cemented on different substrates (column) ($p \leq 0.05$).
[a] Mean values of ΔE below acceptability thresholds (AT = 2.66 ΔE^*_{ab} units and 1.77 ΔE_{00} units) (Paravina et al. [31]).

indirect restoration. A previous study [26] used same substrate material to evaluate the influence of different shades of the substrate on the final color of glass-ceramic structures, but used try-in pastes as luting agents.

In the present study, color measurements were done using a spectroradiometer. The great advantage of this device is the ability to provide non-contact color measurements, which is obtained under similar viewing conditions as human visual assessments (perceived color) [37]. Most studies on masking ability of different dental materials have used dental spectrophotometers for color measurements [23,26–28]. However, inherent features of human teeth (curved, sometimes narrow, surfaces) challenge these contact-type color measuring devices, which may provide inadequate color readings mostly because of a considerable fraction of light that hits the tooth surface is lost [37,38]. A recent study [39] comparing tooth color measurements obtained by using two devices (a spectroradiometer and a dental spectrophotometer) showed that the combination of a spectroradiometer and CIEDE2000 color difference most closely represents the visual perception of color.

Previous reports have used contrast ratio (CR) [21,22] and TP [9,10,21–25] to evaluate the masking ability of non-cemented specimens and color differences using CIELAB (ΔE^*_{ab}) [7,9,10,24,26–29] or CIEDE2000 (ΔE_{00}) metrics [23,25] for specimens cemented on colored substrates. According to the ISO standard [30], the masking potential of dental materials should be evaluated using TP (color difference against white and black backgrounds). Whenever 1 mm-thick composite or 0.3 mm-thick ceramic shows a TP value below PT ($\Delta E^*_{ab} = 1.2$) it represents an excellent masking potential; a TP value between PT ($\Delta E^*_{ab} = 1.2$) and AT ($\Delta E^*_{ab} = 2.7$) represents an acceptable masking potential; and a TP value above AT ($\Delta E^*_{ab} = 2.7$) represents an unacceptable masking potential [30]. Nevertheless, this standard has some limitations. Materials have to be placed on ideal black and white backgrounds to obtain TP values. These "colors" are opposing extremes and the color difference obtained could be greater than usually involved in dental treatments, such as: vital tooth and non-vital discolored tooth preparations, or vital tooth preparation and a metallic structure (metal post and core or implant abutment), or between a non-vital discolored tooth preparation and a metallic structure. Therefore, the present study showed that TP and TP_{00} values of non-cemented specimens from the evaluated IRS (Fig. 2) were greater than ΔE^*_{ab} and ΔE_{00} values of same specimens cemented on different substrates (ND3–ND8, ND3–ND9, and ND8–ND9) (Fig. 3), regardless of the parameters used (color difference metrics or translucency parameters), which showed similar behavior (Figs. 2 and 3). In addition, TP values ($TP = 3.68$–15.63; and $TP_{00} = 2.26$–10.90) (Fig. 2) were above AT (2.66 ΔE^*_{ab} units and 1.77 ΔE_{00} units) [31]. Therefore, none of the evaluated IRS would be able to mask discolored substrates, according to ISO [30]. However, when the restorative structures were cemented on tooth-colored substrates, simulating a clinical situation, only YLD-T showed ΔE^*_{ab} and ΔE_{00} values below AT for all comparisons (ND3–ND8, ND3–ND9 and ND8–ND9) (Table 2 and Fig. 3), meaning, substrate color influenced on the esthetic appearance of resin-bonded IRS, excepted for YLD-T, partially accepting the first study hypothesis.

Notwithstanding, using color difference thresholds (PT and AT) to evaluate masking ability from TP values could present limitations. TP values are dependent on the white and black backgrounds used for color measurements, and it is difficult to obtain perfect white and black backgrounds (as suggested in TP formulation) or having backgrounds with the exact same color coordinates at different research centers. Thus, using a commercially available material designed for dentistry, *e.g.* tooth-colored resin-based composite, as a substrate, may facilitate future research studies.

Further, it has been reported that CIEDE2000 metric is more effective on showing color differences similar to visual perception than CIELAB metric [39,40]. Previous studies on visual thresholds also showed that CIEDE2000 offered a better fit than CIELAB to evaluate color difference thresholds [31,41]. Yet, the present study did not find significant differences between these two metrics for the materials evaluated. In addition, the parametric factors ($K_L = 1$, $K_C = 1$, $K_H = 1$) for CIEDE2000 color difference metric were set to 1:1:1, since they are currently standardized by CIE [32]. Although, some studies [39,42,43] suggested the use of 2:1:1 instead of 1:1:1. As both versions, 2:1:1 and 1:1:1, showed statistically similar results, only the recommended version (1:1:1) is presented in this report.

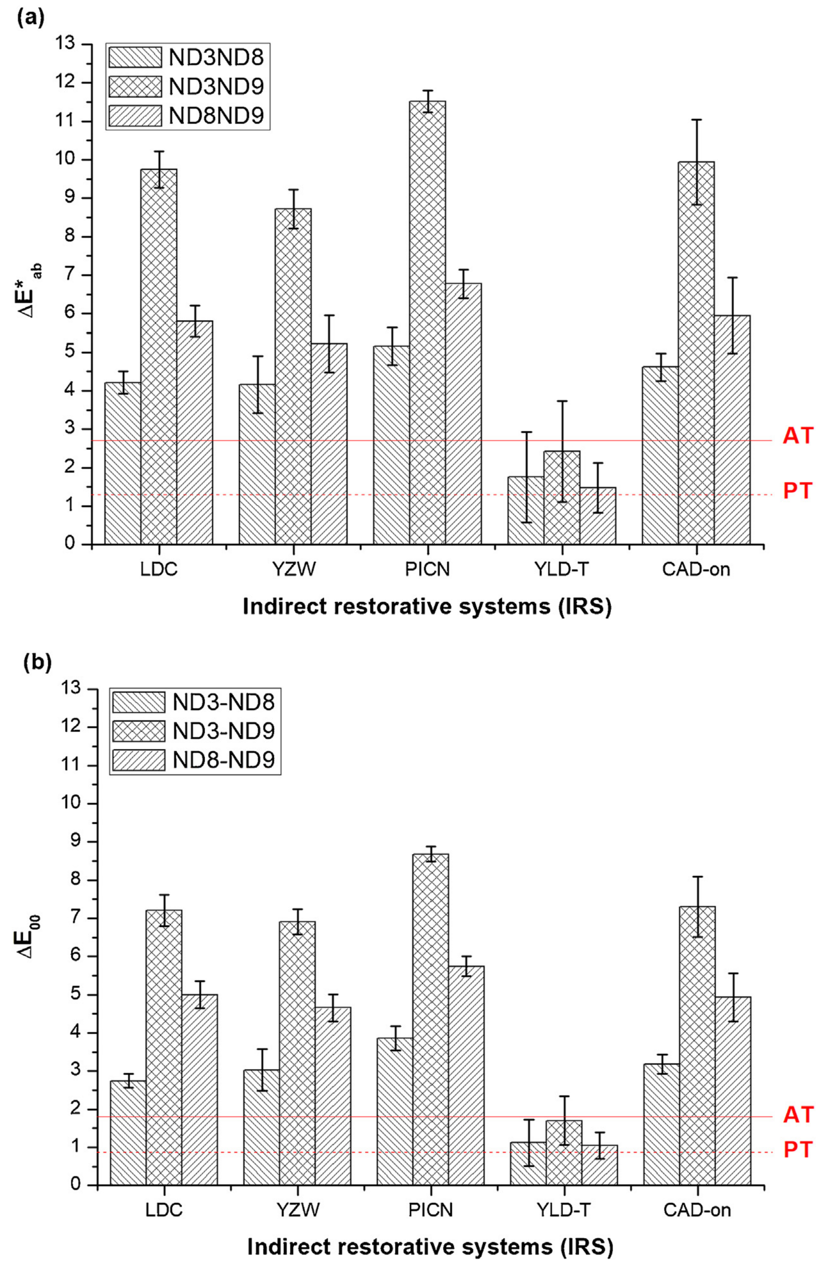

Fig. 3 – Histograms of (a) CIELAB (ΔE^*_{ab}) and (b) CIEDE2000 (ΔE_{00}) color differences between specimens of the same indirect restorative systems (IRS) cemented on different substrates (ND3, ND8 and ND9). The horizontal lines represent perceptibility (PT = 1.22 ΔE^*_{ab} units and 0.81 ΔE_{00} units) and acceptability (AT = 2.66 ΔE^*_{ab} units and 1.77 ΔE_{00} units) thresholds (Paravina et al. [31]).

ISO [30] suggests specimen thickness of 1 mm for composites and 0.3 mm for ceramics. As the present study was designed to simulate indirect dental restorations bonded to tooth-colored substrates, a 1.5 mm-thick structures were used.

It is worth mentioning that although all specimens were fabricated from shade A1, there was a wide distribution in CIELAB color coordinates (Fig. 1). This fact was previously studied with different dental ceramics [2]. There are important relationships between chemical composition, microstructure, atomic structure, fabrication process, and properties of dental materials [8]. Such relationships are even more critical for multilayer IRS, when a complete structural characterization, contemplating each material layer and interface, should be considered. Translucency is one of the main factors involved in dental esthetics and it is critical on selecting dental materials. The IRS evaluated in the present study have different composition, microstructure, crystalline content, phases and layers, which may influence the optical properties of these systems. Thus, significant differences for TP and TP_{00} values were found among the evaluated IRS (Fig. 2). However, when the translucency thresholds are used to compare IRS, there were ΔTP (0.83 for PICN/LDC; 1.24 for PICN/CAD-on; and 0.41 for LDC/CAD-on) and ΔTP_{00} (0.13 for LDC/CAD-on) values below the translucency perceptibility threshold ($TPT = 1.33$; and $TPT_{00} = 0.62$), and also ΔTP (2.93 for LDC/YZW; and 2.52 for YZW/CAD-on) and ΔTP_{00} (1.02 for PICN/LDC; 1.15 for PICN/CAD-on; 1.46 for LDC/YZW; and 1.33 for YZW/CAD-on) values below the translucency acceptability threshold ($TAT = 4.43$; and $TAT_{00} = 2.62$) [36]. As CIEDE2000 offers a better data fit than CIELAB metric for translucency thresholds [36], it can be assumed that for common human observers LDC and CAD-on show non-perceptible translucency differences and acceptable translucency differences when compared to PICN and YZW.

LDC, YZW and CAD-on showed acceptable translucency differences, which is probably due to CAD-on structural composition (LDC glass fused to YZW). The present study did not show differences for TP values between LDC and CAD-on, different from a previous study [25], which evaluated different specimen thicknesses and translucencies (LT and HT) of these systems and found that LDC showed greater TP values than CAD-on. Such differences between studies are probably due to the difference on optical properties of the zirconia frameworks (IPS e.max® ZirCAD vs Zenostar Zr Translucent). Previous studies showed greater TP values for lithium disilicate-based glass-ceramic than for PICN [44,45], disagreeing from the present study, which is probably due to the comparison between IPS e.max CAD LT and VITA Enamic® HT.

The bilayer structure (YLD-T) is composed of a zirconia framework (IPS e.max® ZirCAD) and a feldspathic veneer. Despite of the polycrystalline structure (IPS e.max® ZirCAD), considered an opaque material [12], has different optical properties (scattering, absorption and transmittance) than human dentin at same thickness (0.5 mm-thick specimens) [46], both of them showed similar TP values [47]. As the zirconia framework and the feldspathic veneer have different refractive indexes (2.1 and 1.55, respectively) [48], when light hits on the bilayer structure, the interaction of light flux through these structures is modified. Thus, the optical phenomena (reflection and scattering) in a multilayer structure could be different [9,49] and more opacity could be found in the restorative system. Additionally, the opaque effect of zirconia is attributed to the grain size, slightly larger than the wavelength of visible light [8,50]. These findings show that translucency varies with structural characteristics, accepting the second study hypothesis.

As a limitation of the present study, only instrumental color measurements were performed. Previous studies recommended [39,40,51] that instrumental shade determination should be accompanied by experienced human visual assessments, which could help to confront the visual thresholds and to have a better perceptive information about the masking ability of indirect restorative systems and clinical acceptability.

5. Conclusions

Within the above mentioned limitations of the present *in-vitro* study, it can be stated that resin-cemented YLD-T on different tooth-colored substrates showed less translucency and color differences below acceptability threshold, indicating the best masking ability among the evaluated systems.

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REFERENCES

[1] Raptis NV, Michalakis KX, Hirayama H. Optical behavior of current ceramic systems. Int J Periodontics Restor Dent 2006;26:31–41.
[2] Della Bona A, Pecho OE, Ghinea R, Cardona JC, Pérez MM. Colour parameters and shade correspondence of CAD/CAM ceramic systems. J Dent 2015;43:726–34.
[3] Suzuki A. Opacity control using pressed ceramic: part 1. Material selection. Quintessence Dent Technol 2014;37:149–56.
[4] Della Bona A, Nogueira AD, Pecho OE. Optical properties of CAD–CAM ceramic systems. J Dent 2014;42:1202–9.
[5] Suzuki A. Opacity control using pressed ceramic: part 2. Layering guidelines. Quintessence Dent Technol 2014;37:185–96.
[6] Kürklü D, Azer SS, Yilmaz B, Johnston WM. Porcelain thickness and cement shade effects on the colour and translucency of porcelain veneering materials. J Dent 2013;41:1043–50.
[7] Begum Z, Chheda P, Shruthi CS, Sonika R. Effect of ceramic thickness and luting agent shade on the color masking ability of laminate veneers. J Indian Prosthodont Soc 2014;14:46–50.
[8] Della Bona A. Bonding to ceramics: scientific evidences for clinical dentistry. São Paulo: Artes Médicas; 2009.
[9] Boscato N, Hauschild FG, Kaizer MR, Moraes RR. Effectiveness of combination of dentin and enamel layers on the masking ability of porcelain. Braz Dent J 2015;26:654–9.
[10] Oh SH, Kim SG. Effect of abutment shade, ceramic thickness, and coping type on the final shade of zirconia all-ceramic restorations: in vitro study of color masking ability. J Adv Prosthodont 2015;7:368–74.
[11] Della Bona A, Pecho OE, Alessandretti R. Zirconia as a dental biomaterial. Materials 2015;8:4978–91.
[12] Chen YM, Smales RJ, Yip KH, Sung WJ. Translucency and biaxial flexural strength of four ceramic core materials. Dent Mater 2008;24:1506–11.
[13] Della Bona A, Kelly JR. The clinical success of all-ceramic restorations. J Am Dent Assoc 2008;139:8S–13S.
[14] Beuer F, Stimmelmayr M, Gueth J-F, Edelhoff D, Naumann M. In vitro performance of full-contour zirconia single crowns. Dent Mater 2012;28:449–56.
[15] Taufer C, Della Bona A. Edge chipping resistance of ceramics bonded to a dentine analogue. J Mech Behav Biomed Mater 2019;90:587–90.
[16] Zhang Y. Making yttria-stabilized tetragonal zirconia translucent. Dent Mater 2014;30:1195–203.

[17] Basso GR, Moraes RR, Borba M, Duan Y, Griggs JA, Della Bona A. Reliability and failure behavior of CAD-on fixed partial dentures. Dent Mater 2016;32:624–30.
[18] Alessandretti R, Borba M, Benetti P, Corazza PH, Ribeiro R, Della Bona A. Reliability and mode of failure of bonded monolithic and multilayer ceramics. Dent Mater 2017;33:191–7.
[19] Della Bona A, Corazza PH, Zhang Y. Characterization of a polymer-infiltrated ceramic-network material. Dent Mater 2014;30:564–9.
[20] Facenda JC, Borba M, Corazza PH. A literature review on the new polymer-infiltrated ceramic-network material (PICN). J Esthet Restor Dent 2018;30:281–6.
[21] Chu FC, Sham AS, Luk HW, Andersson B, Chai J, Chow TW. Threshold contrast ratio and masking ability of porcelain veneers with high-density alumina cores. Int J Prosthodont 2004;17:24–8.
[22] Shono NN, Nahedh HN. Contrast ratio and masking ability of three ceramic veneering materials. Oper Dent 2012;37:406–16.
[23] Şoim A, Strîmbu M, Burde AV, Culic B, Dudea D, Gasparik C. Translucency and masking properties of two ceramic materials for heat-press technology. J Esthet Restor Dent 2018;30:E18–23.
[24] Kim HK, Kim SH, Lee JB, Han JS, Yeo IS, Ha SR. Effect of the amount of thickness reduction on color and translucency of dental monolithic zirconia ceramics. J Adv Prosthodont 2016;8:37–42.
[25] Basso GR, Kodama AB, Pimentel AH, Kaizer MR, Della Bona A, Moraes RR, et al. Masking colored substrates using monolithic and bilayer CAD–CAM ceramic structures. Oper Dent 2017;42:387–95.
[26] Chaiyabutr Y, Kois JC, LeBeau D, Nunokawa G. Effect of abutment tooth color, cement color, and ceramic thickness on the resulting optical color of a CAD/CAM glass-ceramic lithium disilicate-reinforced crown. J Prosthet Dent 2011;105:83–90.
[27] Farhan D, Sukumar S, von Stein-Lausnitz A, Aarabi G, Alawneh A, Reissmann DR. Masking ability of bi- and tri-laminate all-ceramic veneers on tooth-colored ceramic discs. J Esthet Restor Dent 2014;26:232–9.
[28] Tabatabaian F, Taghizade F, Namdari M. Effect of coping thickness and background type on the masking ability of a zirconia ceramic. J Prosthet Dent 2018;119:159–65.
[29] Choi YJ, Razzoog ME. Masking ability of zirconia with and without veneering porcelain. J Prosthodont 2013;22:98–104.
[30] International Organization for Standardization. ISO/TR 28642: Dentistry — guidance on colour measurement. Geneva: International Organization for Standardization; 2016.
[31] Paravina RD, Ghinea R, Herrera LJ, Della Bona A, Igiel C, Linninger M, et al. Color difference thresholds in dentistry. J Esthet Restor Dent 2015;27:S1–9.
[32] Commission Internationale de lÉclairage, CIE Pub No. 15.3 CIE technical report: colorimetry. Vienna: CIE Central Bureau; 2004.
[33] Luo MR, Cui G, Rigg B. The development of the CIE 2000 color difference formula: CIEDE2000. Color Res Appl 2001;26:340–50.
[34] Sharma G, Wu W, Dalal EN. The CIEDE2000 color-difference formula: implementation notes, supplementary test data, and mathematical observations. Color Res Appl 2005;30:21–30.
[35] Johnston WM, Ma T, Kienle BH. Translucency parameter of colorants for maxillofacial prostheses. Int J Prosthodont 1995;8:79–86.
[36] Salas M, Lucena C, Herrera LJ, Yebra A, Della Bona A, Pérez MM. Translucency thresholds for dental materials. Dent Mater 2018;34:1168–74.
[37] Paravina RD, Powers JH, editors. Esthetic color training in dentistry. Maryland: Elsevier Mosby; 2004.
[38] Johnston WM. Color measurement in dentistry. J Dent 2009;37:e2–6.
[39] Pecho OE, Ghinea R, Alessandretti R, Pérez MM, Della Bona A. Visual and instrumental shade matching using CIELAB and CIEDE2000 color difference formulas. Dent Mater 2016;32:82–92.
[40] Pecho OE, Ghinea R, Pérez MM, Della Bona A. Influence of gender on visual shade matching in dentistry. J Esthet Restor Dent 2017;29:15–23.
[41] Ghinea R, Perez MM, Herrera LJ, Rivas MJ, Yebra A, Paravina RD. Color difference thresholds in dental ceramics. J Dent 2010;38:e57–64.
[42] Pérez MM, Ghinea R, Herrera LJ, Ionescu AM, Pomares H, Pulgar R, et al. Dental ceramics: a CIEDE2000 acceptability thresholds for lightness, chroma and hue differences. J Dent 2011;39:e37–44.
[43] Pecho OE, Pérez MM, Ghinea R, Della Bona A. Lightness, chroma and hue differences on visual shade matching. Dent Mater 2016;32:1362–73.
[44] Kurtulmus-Yilmaz S, Cengiz E, Ongun S, Karakaya I. The effect of surface treatments on the mechanical and optical behaviors of CAD/CAM restorative materials. J Prosthodont 2018;28:e496–503.
[45] Gunal B, Ulusoy MM. Optical properties of contemporary monolithic CAD–CAM restorative materials at different thicknesses. J Esthet Restor Dent 2018;30:434–41.
[46] Pecho OE, Ghinea R, Ionescu AM, Cardona JC, Della Bona A, Pérez Mdel M. Optical behavior of dental zirconia and dentin analyzed by Kubelka-Munk theory. Dent Mater 2015;31: 60–7.
[47] Pecho OE, Ghinea R, Ionescu AM, Cardona JL, Paravina RD, Pérez MM. Color and translucency of zirconia ceramics, human dentine and bovine dentine. J Dent 2012;40:e34–40.
[48] Heffernan MJ, Aquilino SA, Diaz-Arnold AM, Haselton DR, Stanford CM, Vargas MA. Relative translucency of six all-ceramic systems. Part I: core materials. J Prosthet Dent 2002;88:4–9.
[49] Ragain JC, Johnston WM. Accuracy of Kubelka-Munk reflectance theory applied to human dentin and enamel. J Dent Res 2001;80:449–52.
[50] Vagkopoulou T, Koutayas SO, Koidis P, Strub JR. Zirconia in dentistry. Part 1. Discovering the nature of an upcoming bioceramic. Eur J Esthet Dent 2009;4:130–51.
[51] Della Bona A, Barrett AA, Rosa V, Pinzetta C. Visual and instrumental agreement in dental shade selection: three distinct observer populations and shade matching protocols. Dent Mater 2009;25:276–81.