



Illuminant-dependent color inconstancy and metameric behavior of anodized titanium through silicone-based gingival simulation layers of varying thickness

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Abstract

This in vitro study evaluated how gingival thickness and anodization color affect color perception of Grade V titanium discs under different light sources. Ninety-six titanium discs were anodized yellow, pink, or purple, or left non-anodized. Silicone gingival masks of 1 mm and 2 mm simulated soft tissue. A single spectral reflectance measurement was recorded for each specimen using a benchtop spectrophotometer, from which color coordinates under five standardized illuminants (D65, D50, A, F2, F11) were computationally derived. Color differences (ΔE_{00}) were calculated using the CIEDE2000 formula to evaluate color inconstancy, and metamerism was quantified using a CIEDE2000-based metamerism index (MI), the mean absolute difference between ΔE_{00} under the test illuminants (D50, A, F2, F11) and D65. Data were analyzed with one-way ANOVA, Tukey HSD post hoc tests, and independent t-tests ($\alpha=0.05$). All anodized colors at 1 mm exceeded the CIEDE2000 clinical acceptability threshold ($\Delta E_{00} > 1.8$), with purple showing the highest inconstancy, particularly under fluorescent lighting ($P < .05$). Increasing thickness to 2 mm significantly reduced ΔE_{00} across all groups ($P < .05$), although values remained above the acceptability threshold in every group, with purple showing the greatest relative stability under all illuminants. Metameric behavior remained imperceptible under most conditions, except for pink at 1 mm under F2. Thickness and lighting significantly affect color stability of anodized titanium, although the effect of illuminant type was color-dependent: fluorescent (F2) illumination increased color inconstancy for purple and, at 2 mm, yellow, whereas pink showed the opposite pattern, with its lowest ΔE_{00} values occurring under F2 rather than D65 at both thicknesses. Thinner tissue intensifies color shifts, while ≥ 2 mm thickness improves consistency. Pink performs better in thin tissue; purple shows greatest stability with thicker coverage. Metamerism was imperceptible under most conditions, except for pink at 1 mm under F2, which reached a perceptible but clinically acceptable level.

Keywords Anodized titanium · Gingival thickness · Color inconstancy · Esthetic implant dentistry · Spectrophotometry

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Introduction

Titanium and its alloys are widely used in dental implantology due to their biocompatibility, mechanical strength, and corrosion resistance. Among them, Grade V titanium (Ti-6Al-4V) is preferred for abutments because of its higher mechanical performance than commercially pure titanium [1]. However, its metallic gray color may cause esthetic challenges, especially through thin gingiva [2].

When titanium is exposed to oxygen, a thin TiO_2 layer forms, giving the surface its gray color; anodization thickens this layer to generate interference colors such as yellow, pink, and purple, improving soft tissue blending and reducing gray shine-through [3–7]. Beyond esthetics, anodization can also modify surface energy, wettability, and soft tissue integration [4, 7, 8], and standardized voltage-based color charts have been developed for reproducible clinical use [3]. The resulting colors are known to be sensitive to oxide thickness, refractive index, and illumination/viewing conditions [9–12].

Because implant abutments are often covered by soft tissue of varying thickness, gingival thickness below 2 mm may not sufficiently mask the underlying implant color, compromising esthetic outcomes, particularly in thin-biotype patients [13–24]. This has highlighted the need for controlled optical evaluation of anodized titanium under standardized conditions [25], making the interaction between abutment color and gingival thickness clinically relevant [13, 14].

Perceived color also depends on the illuminant: materials may appear different under daylight versus fluorescent light, a phenomenon termed color inconstancy, while metamerism describes materials that match under one illuminant but differ under another due to differences in spectral reflectance [26, 27]. These differences are quantified using CIE ΔE values, most commonly CIEDE2000 [26, 28–30], and clinical shade matching is conventionally standardized under D65 daylight [31–34], although indoor settings are frequently dominated by artificial illuminants [35]. However, most prior studies on anodized titanium and gingival thickness have assessed static color matching under a single illumination condition, without systematically addressing illuminant-dependent color inconstancy or the combined

influence of anodization color, gingival thickness, and multiple standardized illuminants [16, 17, 26, 28, 31, 36–38].

Given this background, the present in vitro study investigated the color perception and illuminant-dependent color behavior of anodized Grade V titanium discs simulating different soft tissue thicknesses (1 mm and 2 mm) under standardized lighting conditions. Three anodization colors—yellow, pink, and purple—were evaluated using spectrophotometric analysis in terms of ΔE_{00} color differences and metamerism index (MI). The findings may assist clinicians in improving esthetic predictability of implant-supported restorations under varying clinical lighting conditions. The research hypothesis was that gingival thickness, anodization color, and lighting conditions would not significantly influence ΔE_{00} values or metameric behavior of anodized titanium abutments.

Materials and methods

This in vitro study utilized ninety-six titanium Grade V discs ($\text{Ø}10 \times 2.5$ mm; Bilimplant). All specimens were sequentially polished with 400–1000 grit silicon carbide papers (Worth Industrial) on a polishing unit (Minitch 233, Presi) under water cooling at 250 rpm for 30 s per grit. A three-step ultrasonic cleaning (acetone, isopropanol, distilled water; 10 min each) was performed to remove surface contaminants, followed by air-drying at room temperature [39].

Discs were randomly assigned to four groups: control (non-anodized), yellow (55 V), pink (75 V), and purple (90 V) based on previously established voltage-color correspondence for anodized Grade V titanium [3]. Electrochemical anodization was performed in a trisodium phosphate solution (2 g / 500 mL distilled water) at 23 ± 2 °C using an adjustable DC power supply (Smartgift 120 V). Each disc acted as the anode, with a stainless-steel cathode placed in the same bath without contact. Voltage was applied for 2 min to generate interference colors. After anodization, discs were rinsed with distilled water and stored in the dark for 24 h [3, 9, 39] (Fig. 1).

Silicone-based gingival masks were fabricated from medical-grade maxillofacial silicone (Silastic MDX-4-4210; Dow Corning, USA) and intrinsically pigmented to achieve a standardized pink gingival shade. The intrinsic pigment (Orbital Colors, Brazil) was prepared by combining yellow, red, and black pigments with a white opacifier, corresponding to 0.6% white, 0.122% yellow, 0.03% red, and 0.006% black relative to the silicone weight. The silicone and pigments were precisely weighed using a digital analytical balance (Adventurer, Ohaus Corporation, USA) and manipulated according to the manufacturer's instructions at 23 ± 2 °C. Pigment incorporation was initially performed



Fig. 1 Anodized (yellow, pink, purple) and non-anodized (control) Grade V titanium discs

by manual mixing for 15 s, followed by vacuum spatulation at 425 rpm using a mechanical spreader (Polidental Ind. e Com. Ltda, Brazil) until a homogeneous mixture was obtained. The pigmented silicone was then inserted into a custom metal mold to fabricate gingival masks with standardized thicknesses of 1 mm and 2 mm, ensuring optical uniformity and reproducibility. Final specimen thicknesses were verified using a digital caliper to confirm conformity with the nominal 1 mm and 2 mm mold dimensions. The mold was closed and subjected to a compressive load of 1 ton for 10 min, after which the specimens were allowed to polymerize under ambient conditions (29 °C) for 72 h to achieve complete curing (Fig. 2). The material was selected primarily for its documented color and optical stability over time, as well as its reproducible thickness and homogeneity, which enable standardized and reproducible spectrophotometric measurements across specimens [40–44]. This rationale is based on the reported stability of maxillofacial silicone itself rather than on direct evidence that its spectral transmittance, scattering, absorption, or translucency match those of natural peri-implant mucosa; such optical equivalence to soft tissue was not assessed in the present study. Accordingly, the silicone masks are best regarded as a standardized, reproducible optical medium for controlled comparative testing rather than a validated biomimetic simulator of gingival tissue. Eight experimental groups (4 anodization colors $\times$ 2 thicknesses) were created ($n = 12$ per group; total $N = 96$). A priori sample size was calculated based on an effect size derived from a comparable in vitro study evaluating the effect of titanium anodization on CIEDE2000 color difference (ΔE_{00}) [45]. This effect corresponds to Cohen's $f = 0.52$ ($\eta^2 = 0.21$) for a one-way ANOVA design. Using $\alpha = 0.05$ and power = 0.80, the minimum required sample size was calculated as $n = 12$ per group (G*Power v3.1.9.7); this sample size was therefore used (total $N = 96$) (Fig. 3).

Color was measured with a benchtop spectrophotometer (Konica Minolta CM-3600 A), calibrated before each session (Fig. 4), operating under diffuse illumination/ 8° viewing geometry ($d/8^\circ$). Both specular component included (SCI) and excluded (SCE) modes were recorded simultaneously; because SCI and SCE values were closely comparable, SCI data were used for all subsequent color-difference calculations. Measurements were performed using the



Fig. 2 Silicon-based gingival simulation masks fabricated in 1 mm and 2 mm thicknesses

small-area view (SAV) aperture (4 mm), with the UV setting maintained at 100% (full UV component, no UV cut filter applied). Prior to each measurement session, the instrument was calibrated using both black and white reference plates according to the manufacturer's instructions. A neutral gray background (Munsell) was placed behind each specimen, and each specimen was positioned with the aperture opening centered over the specimen surface. For each specimen, three consecutive readings were taken without repositioning the specimen between readings, and the mean of the three readings was used for analysis. A single spectral reflectance curve was thus obtained per specimen; this curve, rather than five separate physical light exposures, was used to computationally derive the CIE color coordinates under each of five standardized illuminants using a 10° standard observer setting and the illuminant weighting functions implemented in SpectraMagic NX software. The illuminants included D65 (daylight, 6500 K), D50 (horizon daylight, 5000 K), A (incandescent light, 2856 K), F2 (cool white fluorescent, 4230 K), and F11 (commercial fluorescent, 4000 K) [35, 46, 47], with color coordinates under each illuminant computed from the recorded spectral reflectance data using SpectraMagic NX software. Spectral reflectance data were used to compute color coordinates under each illuminant, and ΔE_{00} values were calculated using the CIEDE2000 formula (SpectraMagic NX software) by comparing the color differences between the control and anodized groups within the same gingival simulation thickness (1 mm and 2 mm), under each computationally derived illuminant condition:

$$\Delta E_{\infty} = \sqrt{\left[\left(\Delta L' / k_l SI \right)^2 + \left(\Delta C' / k_c Sc \right)^2 + \left(\Delta H' / k_h Sh \right)^2 + RT \left(\Delta C' / k_c Sc \right) \left(\Delta H' / k_h Sh \right) \right]}$$

The metameric behavior of each specimen was quantified using a metamerism index (MI), calculated in accordance with ISO 18314-4:2020 and adapted to the CIEDE2000 color difference system:

$$MI(D65 \rightarrow \text{test}) = |\Delta E_{\infty}(\text{test light source}) - \Delta E_{\infty}(D65)|$$

Four MI values were determined for each specimen: MI(D65→D50), MI(D65→A), MI(D65→F2), and MI(D65→F11). Lower MI values indicate minimal color variation across different illuminants, whereas higher values reflect greater light-dependent color changes. MI values were interpreted as follows: <0.8 (imperceptible), 0.8–1.8 (perceptible but acceptable), and > 1.8 (clinically unacceptable) [26, 27].

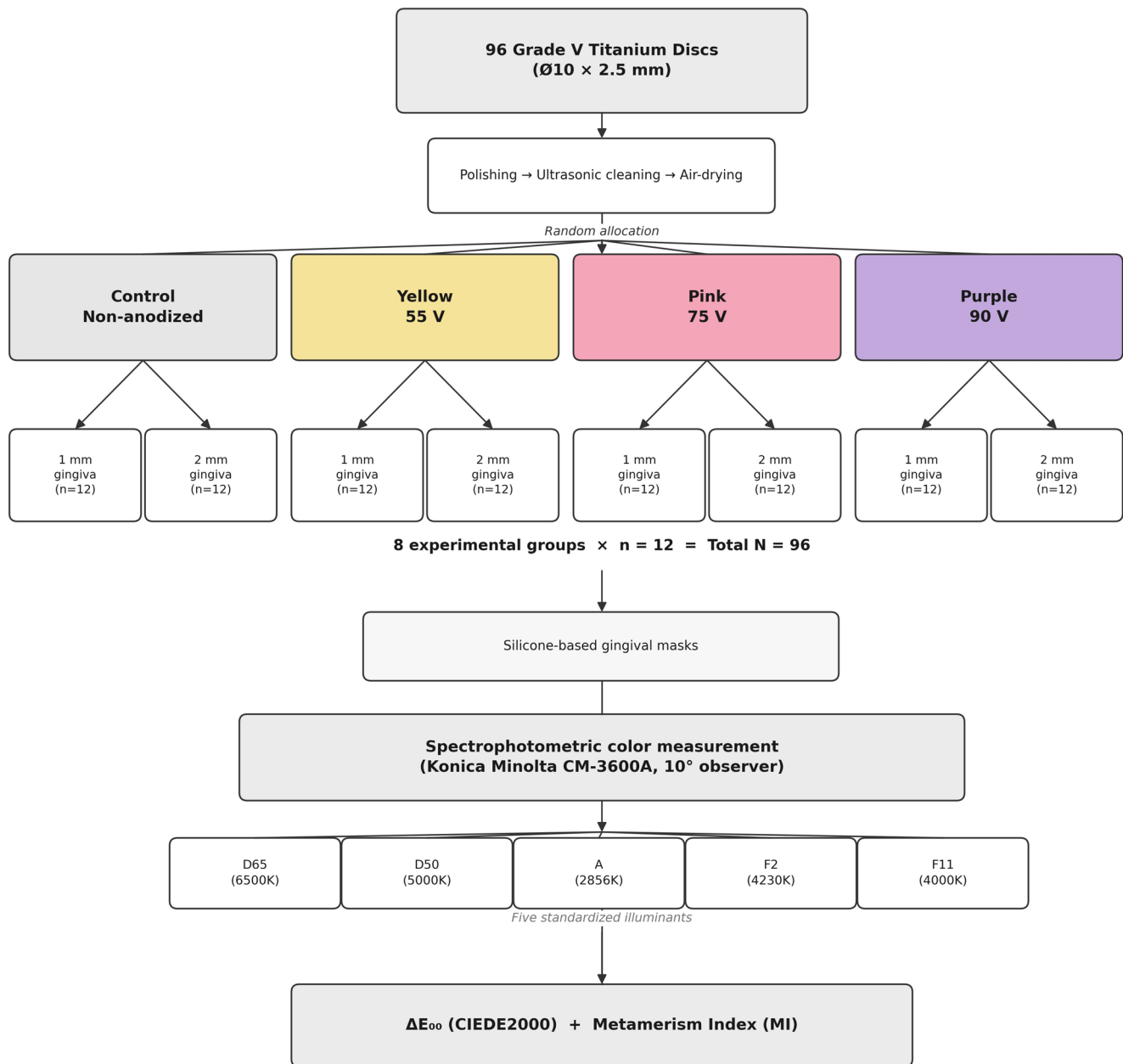


Fig. 3 Experimental grouping of titanium disc specimens according to anodization color and gingival thickness

Mean and SD values of ΔE_{00} were calculated for each group. One-way ANOVA with Tukey HSD was applied to compare illuminants and gingival thicknesses within anodization groups. Independent t-tests compared 1 mm and 2 mm thickness for each color. Significance was set at $P < .05$ (IBM SPSS v23).

Results

Statistically significant differences in color variation (ΔE_{00}) were observed across all test parameters, including anodization color, gingival thickness, and light source ($P < .05$).

At 1 mm gingival thickness, all anodized colors demonstrated notable color inconsistencies across different illuminants (Table 1). In the yellow group, ΔE_{00} values ranged from 6.93 ± 0.13 under incandescent light (A) to 8.20 ± 0.20 under F2. Pairwise comparisons showed significant differences among the other illuminants ($P < .05$) except between F2 and F11, which did not differ from each other statistically.



Fig. 4 Benchtop spectrophotometer (Konica Minolta CM-3600 A) used for standardized color measurement

and F2 yielded the highest ΔE_{00} value. In the pink group, ΔE_{00} values ranged from 6.37 ± 0.24 (F2) to 7.76 ± 0.31 (D65). There were significant differences among the illuminants ($P < .05$). The highest ΔE_{00} value was observed under D65, which did not differ significantly from D50. A and F11 yielded lower ΔE_{00} values compared to D65 and D50, but no significant difference was found between A and F11 themselves. F2 produced the lowest ΔE_{00} values, which were significantly lower than all other illuminants. The purple anodization group exhibited the highest ΔE_{00} values overall, ranging from 8.22 ± 0.16 (D65) to 9.09 ± 0.10 (F2). There were significant differences among the illuminants ($P < .05$). F2 showed the highest ΔE_{00} values, significantly higher than

all other light sources. F11 and A yielded significantly lower values than F2, with no significant difference between each other. The lowest values were recorded under D65 and D50, which did not differ significantly from one another. When comparing anodization colors under each illuminant, D65, D50, and A light sources showed the highest ΔE_{00} values for purple and the lowest for yellow ($P < .05$). Under F2 and F11 lighting, the highest ΔE_{00} values were also observed for purple anodization, whereas the lowest values were recorded for pink, with statistically significant differences among the three colors ($P < .05$). All ΔE_{00} values in the 1 mm groups exceeded the CIEDE2000 clinical acceptability threshold of 1.8 [29, 30], indicating visible and perceptible color differences across lighting conditions.

When gingival thickness was increased to 2 mm (Table 2), ΔE_{00} values were significantly reduced across all anodization colors ($P < .05$). For yellow anodization, values ranged from 2.77 ± 0.19 (D65) to 3.30 ± 0.18 (F2), remaining above the CIEDE2000 acceptability threshold [29, 30] despite the marked reduction relative to the 1 mm group. The highest ΔE_{00} values were observed under F2, followed by F11 and A, with no significant differences among these three illuminants. D65 and D50 showed significantly lower ΔE_{00} values compared to F2, F11, and A, but did not differ significantly from each other. In the pink group, ΔE_{00} values ranged from 2.68 ± 0.21 (F2) to 3.38 ± 0.38 (A). Statistically significant differences between light sources were again observed ($P < .05$). For purple anodization, ΔE_{00} values were generally the lowest among the tested colors, ranging from 2.60 ± 0.40 (D65) to 2.92 ± 0.23 (F2), with no significant differences between illuminants ($P > .05$). under

Table 1 Mean $\pm$ SD ΔE_{00} values of 1 mm gingival thickness materials evaluated

Anodized color	Light sources					+P
	D65	D50	A	F2	F11	
Yellow	$7.44 \pm 0.21^A, a$	$7.15 \pm 0.16^B, a$	$6.93 \pm 0.13^C, a$	$8.20 \pm 0.20^D, a$	$8.10 \pm 0.19^D, a$	*
Pink	$7.76 \pm 0.31^A, b$	$7.75 \pm 0.23^A, b$	$7.35 \pm 0.18^B, b$	$6.37 \pm 0.24^C, b$	$7.10 \pm 0.25^B, b$	*
Purple	$8.22 \pm 0.16^A, c$	$8.35 \pm 0.16^A, c$	$8.69 \pm 0.15^B, c$	$9.09 \pm 0.10^C, c$	$8.86 \pm 0.15^B, c$	*
+P	*	*	*	*	*	

+One-way ANOVA-Tukey HSD

Lowercase letters in-group (vertical), Capital letters (horizontal) indicate statistical difference between groups

* $P < .05$

Table 2 Mean $\pm$ SD ΔE_{00} values of 2 mm gingival thickness materials evaluated

Anodized color	Light sources					+P
	D65	D50	A	F2	F11	
Yellow	$2.77 \pm 0.19^A, a$	$2.89 \pm 0.20^A, a$	$3.17 \pm 0.23^B, a$	$3.30 \pm 0.18^B, a$	$3.20 \pm 0.19^B, a$	*
Pink	$3.12 \pm 0.28^A, B, b$	$3.26 \pm 0.28^A, B, b$	$3.38 \pm 0.38^A, a$	$2.68 \pm 0.21^C, b$	$3.03 \pm 0.25^B, a, b$	*
Purple	$2.60 \pm 0.40^A, a$	$2.62 \pm 0.43^A, a$	$2.71 \pm 0.48^A, b$	$2.92 \pm 0.23^A, c$	$2.81 \pm 0.42^A, b$	*
+P	*	*	*	*	*	

+One-way ANOVA- Tukey HSD

Lowercase letters in-group (vertical), Capital letters (horizontal) indicate statistical difference between groups

* $P < .05$

Table 3 Mean $\pm$ SD ΔE_{00} values of 1 mm/2 mm gingival thickness materials evaluated

Anodized color/gingiva thickness	Light sources				
	D65	D50	A	F2	F11
Yellow/1 mm	7.44 $\pm$ 0.21 ^a	7.15 $\pm$ 0.16 ^a	6.93 $\pm$ 0.13 ^a	8.20 $\pm$ 0.20 ^a	8.10 $\pm$ 0.19 ^a
Yellow/2 mm	2.77 $\pm$ 0.19 ^b	2.89 $\pm$ 0.20 ^b	3.17 $\pm$ 0.23 ^b	3.30 $\pm$ 0.18 ^b	3.20 $\pm$ 0.19 ^b
+P	*	*	*	*	*
Pink/1 mm	7.76 $\pm$ 0.31 ^a	7.75 $\pm$ 0.23 ^a	7.35 $\pm$ 0.18 ^a	6.37 $\pm$ 0.24 ^a	7.10 $\pm$ 0.25 ^a
Pink/2 mm	3.12 $\pm$ 0.28 ^b	3.26 $\pm$ 0.28 ^b	3.38 $\pm$ 0.38 ^b	2.68 $\pm$ 0.21 ^b	3.03 $\pm$ 0.25 ^b
+P	*	*	*	*	*
Purple/1 mm	8.22 $\pm$ 0.16 ^a	8.35 $\pm$ 0.16 ^a	8.69 $\pm$ 0.15 ^a	9.09 $\pm$ 0.10 ^a	8.86 $\pm$ 0.15 ^a
Purple/2 mm	2.60 $\pm$ 0.40 ^b	2.62 $\pm$ 0.43 ^b	2.71 $\pm$ 0.48 ^b	2.92 $\pm$ 0.23 ^b	2.81 $\pm$ 0.42 ^b
+P	*	*	*	*	*

+Independent sample t-test

Lowercase letters in-group (vertical), indicate statistical difference between groups. * $P < .05$ **Table 4** Metamerism index (MI) values of anodized titanium groups by illuminant and gingival thickness

Group	MI D50	MI Incandescent (A)	MI F2	MI F11	Interpretation
Yellow (1 mm)	0.294 $\pm$ 0.050 ^{aD}	0.516 $\pm$ 0.051 ^{aC}	0.763 $\pm$ 0.041 ^{cA}	0.662 $\pm$ 0.038 ^{aB}	Imperceptible
Pink (1 mm)	0.107 $\pm$ 0.025 ^{cD}	0.438 $\pm$ 0.036 ^{abC}	1.396 $\pm$ 0.116 ^{aA}	0.660 $\pm$ 0.060 ^{aB}	Imperceptible (except F2: perceptible but acceptable)
Purple (1 mm)	0.139 $\pm$ 0.036 ^{bcD}	0.478 $\pm$ 0.054 ^{aC}	0.871 $\pm$ 0.068 ^{bA}	0.648 $\pm$ 0.055 ^{aB}	Imperceptible
Yellow (2 mm)	0.120 $\pm$ 0.031 ^{bcC}	0.396 $\pm$ 0.042 ^{bbB}	0.528 $\pm$ 0.046 ^{dA}	0.424 $\pm$ 0.025 ^{bbB}	Imperceptible
Pink (2 mm)	0.146 $\pm$ 0.026 ^{bbB}	0.335 $\pm$ 0.038 ^{baA}	0.442 $\pm$ 0.035 ^{dA}	0.161 $\pm$ 0.077 ^{cbB}	Imperceptible
Purple (2 mm)	0.033 $\pm$ 0.009 ^{dC}	0.112 $\pm$ 0.025 ^{cbB}	0.340 $\pm$ 0.026 ^{caA}	0.211 $\pm$ 0.051 ^{caA}	Imperceptible

One-way ANOVA with Tukey HSD. Uppercase letters indicate significant differences between illuminants (horizontal); lowercase letters indicate significant differences between anodization colors (vertical). * $P < .05$. MI values interpreted as: < 0.8 imperceptible; 0.8 – 1.8 perceptible but acceptable; > 1.8 clinically unacceptable [29, 30].

D65 and D50 lighting, pink exhibited significantly higher ΔE_{00} values than yellow and purple, which did not differ significantly from each other ($P < .05$). Under A illumination, yellow and pink did not differ significantly from each other, while purple showed significantly lower values than both ($P < .05$). Under F2, all three anodization colors differed significantly from one another, with pink showing the numerically lowest ΔE_{00} value (2.68 ± 0.21), followed by purple (2.92 ± 0.23) and yellow (3.30 ± 0.18) ($P < .05$). Under F11, yellow showed significantly higher ΔE_{00} values than purple, while pink did not differ significantly from either yellow or purple ($P < .05$).

Direct comparison of 1 mm and 2 mm gingival thicknesses within each color group (Table 3) revealed statistically significant reductions in ΔE_{00} values with increased tissue thickness ($P < .05$ for all light sources and colors). Yellow, pink, and purple groups each showed consistent decreases in color inconsistencies when covered with 2 mm gingival simulation. Across all lighting conditions, the 2 mm groups presented substantially lower color differences than the corresponding 1 mm groups; however, all 2 mm values remained above the CIEDE2000 acceptability threshold of 1.8 [29, 30], indicating that although gingival thickness

markedly improved color stability, clinically perceptible and unacceptable color differences persisted even at 2 mm.

Metamerism index values (Table 4) across all groups and illuminants remained below 0.8, indicating imperceptible metamerism behavior, with one exception: pink anodization at 1 mm under F2 illumination yielded an MI of 1.396 ± 0.116 , classified as perceptible but acceptable. Across all groups, F2 consistently produced the highest MI values, followed by F11 and incandescent (A), while D50 showed the lowest values ($P < .05$). Among the 1 mm groups, pink exhibited the highest MI under F2, significantly exceeding yellow and purple ($P < .05$). At 2 mm, MI values were reduced across most colors and illuminants, with one exception: pink under D50 increased slightly from 0.107 ± 0.025 at 1 mm to 0.146 ± 0.026 at 2 mm, with purple demonstrating the lowest metamerism variation overall ($P < .05$).

Discussion

The null hypothesis was rejected, as both gingival thickness and lighting conditions significantly affected the perceived color of anodized titanium abutments. Significant differences were found among anodization colors, between 1 mm

and 2 mm gingival thicknesses, and across all five illuminants ($P < .05$). These findings confirm that both the optical environment and the biological simulation layer critically impact the color stability of anodized implant components.

In the 1 mm groups, all anodized colors exceeded the clinical ΔE_{00} threshold (1.8) [29, 30], indicating insufficient masking by thin tissue. Purple showed the highest color inconstancy, especially under fluorescent illumination (F2, F11), followed by yellow and pink, with pink presenting the lowest ΔE_{00} values ($P < .05$). The elevated ΔE_{00} values across illuminants reflects the inability of 1-mm gingival simulation to mask the strong interference effects of anodized titanium, consistent with evidence that gingival thicknesses below 2 mm cannot adequately conceal the modified abutment colors [16, 17, 36]. The sharper spectral peaks of F2 and F11 lights intensify perceptual shifts in interference-based materials, explaining the peak values observed [26, 35, 48]. Overall, these findings emphasize the high risk of color inconstancy when anodized titanium is covered by only minimal soft tissue, particularly in esthetic zones with variable lighting.

Pink anodization showed the lowest ΔE_{00} magnitude among the 1 mm groups, with values ranging from 6.37 ± 0.24 (F2) to 7.76 ± 0.31 (D65), lower than yellow and purple. Although all colors exceeded the clinical acceptability threshold ($\Delta E_{00} > 1.8$), pink did not show the greatest illuminant-to-illuminant stability: its ΔE_{00} range (1.39) and average metamerism index ($MI = 0.650$) were greater than those of yellow (range 1.27; $MI = 0.559$) and, in particular, purple (range 0.87; $MI = 0.534$), which showed the most illuminant-stable behavior among the 1 mm groups. A possible explanation is pink's intermediate spectral reflectance between yellow and purple, which lowers its overall ΔE_{00} magnitude without necessarily reducing its sensitivity to spectral differences among illuminants [3, 9, 10]; however, as uncovered-surface reflectance was not directly measured in this study, this interpretation remains speculative and based on prior literature rather than empirical confirmation. Prior studies similarly found that pink and gold anodized abutments blend better with thin gingiva in terms of overall color magnitude, reducing gray shine-through [38, 49].

Increasing gingival thickness to 2 mm significantly reduced ΔE_{00} values for all colors and illuminants ($P < .05$); however, values remained above the CIEDE2000 acceptability threshold of 1.8 in every group, indicating that although color stability improved substantially, clinically perceptible and unacceptable differences persisted even at 2 mm. Yellow ranged from 2.77 ± 0.19 to 3.30 ± 0.18 , pink ranged 2.68 ± 0.21 – 3.38 ± 0.38 , and purple showed the lowest and most consistent values (2.60 ± 0.40 – 2.92 ± 0.23), with no illuminant-dependent differences; purple therefore represented the closest approach to the acceptability threshold

among the tested colors, although it too remained above it. These results are consistent with the general trend reported in the literature that greater soft tissue thickness improves masking of the saturated, reflective surfaces of anodized titanium [16, 18, 36]; however, as only two discrete thickness levels (1 mm and 2 mm) were tested, these findings cannot establish 2 mm as a specific critical or threshold thickness, nor characterize the continuous dose–response relationship between gingival thickness and color masking. Thicker tissue enhances optical diffusion and scattering, reducing visible discrepancies, consistent with clinical evidence that greater gingival thickness minimizes shine-through and improves esthetics in peri-implant zones [16, 19]. Purple's stability under D65 aligns with D65's established status as the reference illuminant for shade matching [31–33]; however, this pattern was not consistent across all anodization colors, as pink showed its lowest ΔE_{00} values under F2 rather than D65 at both thicknesses. Purple's superior constancy may plausibly be related to its thicker oxide layers (~80–100 nm), formed at higher voltages, which favor longer wavelengths less sensitive to lighting variations [11, 12]. It should be noted that this constancy reflects purple's stability across illuminants (no significant illuminant-dependent variation) rather than uniform statistical superiority over the other colors at every illuminant; purple did not differ significantly from yellow under D65/D50 or from pink under F11, and pink showed the numerically lowest value under F2. Its darker hue could also plausibly involve higher absorption, and reduced reflectance [9, 10, 26, 48]; as oxide thickness, absorption, and uncovered-surface reflectance were not directly measured in the present study, these explanations remain literature-based hypotheses rather than findings confirmed by our data. Overall, pink performs better in thin tissue, whereas purple is most stable in thicker soft tissue across illuminants.

Comparisons between 1 mm and 2 mm gingival thicknesses showed significant ΔE_{00} reductions with increased tissue thickness ($P < .05$). Pink decreased from 7.76 to 3.12 (D65), yellow from 8.20 to 3.30 (F2), and purple from 9.09 to 2.92 (F2), indicating that greater coverage markedly reduces color inconstancies across illuminants, although resulting ΔE_{00} values still exceeded the clinical acceptability threshold in all groups. These findings support previous evidence that gingival thickness is critical for masking abutment color, particularly in esthetic regions [16, 20–22]. Thicker tissue increases light absorption and scattering, filtering chromatic cues and producing a more uniform appearance, whereas thin tissue permits greater light transmission and enhances visibility of the anodized surface [23]. Clinically, our findings suggest that greater soft tissue thickness is associated with improved esthetic predictability; however, because only two discrete thickness levels were tested,

these results should not be interpreted as establishing 2 mm as a specific clinical cutoff. Insufficient tissue may lead to perceptible discrepancies and dynamic color shifts under common lighting, potentially affecting long-term patient satisfaction [24], but the precise thickness at which masking becomes clinically adequate remains to be determined using a continuous range of thicknesses.

Lighting type affected color perception in both thickness groups, but the pattern was not uniform across anodization colors. For purple, and to a lesser extent yellow at 2 mm, fluorescent illumination (F2) produced the highest ΔE_{00} values while D65 produced the lowest, consistent with F2's narrow, irregular spectral distribution amplifying color mismatches in interference-based materials [31, 35]. However, this pattern was not universal: in the pink group, F2 produced the lowest ΔE_{00} values at both thicknesses (6.37 at 1 mm; 2.68 at 2 mm), while D65 was among the highest, and in the yellow group at 1 mm the lowest ΔE_{00} value occurred under incandescent (A) illumination rather than D65. These group-specific exceptions indicate that the relationship between illuminant type and color inconstancy in anodized titanium is color-dependent rather than uniformly governed by D65's role as a daylight reference [34]. Clinicians should therefore assess shade under multiple lighting conditions, rather than assuming uniform stability under daylight illumination, especially when using anodized or color-modified abutments in esthetic zones.

Wang et al. [38] reported that anodized abutments, particularly pink and gold, enhanced soft-tissue esthetics in thin biotypes. Our findings align with this trend, showing higher ΔE_{00} at 1 mm and substantially reduced, though still clinically perceptible, color differences at 2 mm, supporting the importance of tissue thickness for esthetic outcomes. It should be noted that Wang et al. [38] reported color differences using the CIELAB (ΔE_{ab}) formula rather than CIEDE2000, so their absolute ΔE values are not directly numerically comparable to the ΔE_{00} values reported here; the comparison is therefore limited to the overall masking trend rather than absolute thresholds. This agreement reflects the overall masking behavior rather than absolute numerical equivalence, as vascularized gingiva and the silicone model differ optically. Wang et al. [38] did not specify the illuminant conditions, whereas the present study assessed color differences under multiple standardized light sources, offering a broader assessment of color inconstancy. These results represent an optical simulation and should not be directly extrapolated to biological tissue behavior.

Although absolute color values cannot be directly compared between gingiva and silicone, the trend observed here—limited masking at 1 mm thickness—conceptually aligns with Martínez-Rus et al. [37]. They reported perceptible color differences at 1 mm, particularly with purple

anodization. Likewise, in our 1-mm groups, purple showed the highest ΔE_{00} across all illuminants, exceeding 9.0 under F2, demonstrating the reduced masking capacity of thin mucosa over darker anodized surfaces. Both studies indicate that high-energy illuminants intensify chromatic shifts and that thin tissue remains a limitation when using darker anodized shades.

Unlike our findings, Farrag et al. [25] reported no clinically significant esthetic differences with pink anodized collars in a split-mouth study. Their *in vivo* observations differ with our *in vitro* results, where pink produced $\Delta E_{00} > 1.8$ across all illuminants at 1 mm. This discrepancy does not indicate a biological contradiction, as silicone simulations cannot reproduce hemoglobin absorption, vascular scattering, or hydration-dependent translucency. The differences likely stem from methodological factors, including clinical visual assessment versus controlled spectrophotometry, use of multiple standardized illuminants in our study, and the higher sensitivity of ΔE_{00} metrics. Additionally, Farrag et al. [25] evaluated only pink anodization, whereas our data showed larger discrepancies with purple, further explaining divergent conclusions. Thus, the present results reflect material-based optical patterns under standardized laboratory conditions rather than direct predictions of clinical perception.

Metamerism index values across all groups remained below the imperceptible threshold (< 0.8) under most illuminants, suggesting that anodized titanium surfaces covered by gingival simulation do not produce clinically significant metameric shifts under the tested conditions. The sole exception was pink anodization at 1 mm thickness under F2 illumination (MI = 1.396), which reached the perceptible but acceptable range. These findings are consistent with those reported by Davut et al., [27] who similarly observed minimal metameric behavior across illuminants in an anodized titanium-based spectrophotometric study. The relatively low MI values suggest that, despite notable ΔE_{00} color inconstancy, the illuminant-dependent spectral mismatch relative to D65 remains limited in most clinical lighting scenarios.

Across all groups, F2 illumination consistently produced the highest MI values, particularly in the 1 mm specimens, reflecting its narrow and irregular spectral power distribution, as previously demonstrated by Lee and Powers [48]. The elevated MI under F2 for pink anodization at 1 mm may be attributed to its intermediate spectral reflectance, which interacts differently with narrow-band fluorescent emission compared to broader daylight spectra. Increasing gingival thickness to 2 mm reduced MI values across most colors and illuminants, with one exception: pink under D50, where MI increased slightly (0.107 to 0.146), indicating that the protective effect of increased thickness on metameric behavior,

while generally consistent, was not entirely uniform across all color–illuminant combinations. Purple demonstrated the lowest metameric variation overall. These findings further support the clinical recommendation that adequate peri-implant soft tissue thickness not only reduces absolute color differences but also buffers illuminant-dependent metameric shifts, improving esthetic predictability across diverse lighting environments.

This study has some limitations. Silicone gingival masks, though standardized, cannot reproduce the vascularity or full optical complexity of human gingiva. Their use was intended to provide optical standardization and reproducibility appropriate for ΔE -based spectrophotometric analysis. Direct evidence of the spectral transmittance, scattering, absorption, and translucency of the silicone relative to natural peri-implant mucosa was not obtained in this study; the cited literature on maxillofacial silicone primarily addresses its own color and mechanical stability rather than its optical equivalence to soft tissue, and this should be considered a limitation of the present optical simulation model. Future in vivo research using natural gingival tissues is necessary to validate clinical correlations. Spectrophotometric analysis may also differ from human visual perception, especially under variable intraoral conditions. Dynamic clinical factors such as saliva, movement, and pigmentation were not simulated. Only three anodization colors were tested, limiting generalizability, and long-term effects such as aging or discoloration were not evaluated. Additionally, the anodized colors were assigned based on established voltage-color relationships rather than on direct pre-placement measurement of the uncovered discs; color coordinates, reflectance spectra, and oxide-thickness measurements of the bare specimens were not obtained. Future in vivo studies with broader color ranges, incorporation of the verification of the fabricated colors and follow-up are needed to confirm these results. Similarly, mechanistic explanations proposed for color behavior differences among anodization colors (e.g., oxide thickness, absorption, uncovered-surface reflectance) were not directly measured and should be empirically verified in future work. Additionally, no CIEDE2000-specific acceptability threshold has yet been established for peri-implant or gingival soft tissue in the literature; the present study therefore applied the CIEDE2000 threshold established for dental hard tissues ($\Delta E_{00} \leq 1.8$) [29, 30], and this extrapolation to soft-tissue esthetics should be interpreted with appropriate caution.

Conclusion

Based on the study findings, the following conclusions were drawn:

1. Gingival thickness significantly influenced color perception. Specimens covered with 1 mm gingival simulation exhibited significantly higher color differences than those covered with 2 mm, regardless of anodization color and illumination condition.
2. Illumination conditions significantly affected color stability, although this effect was color-dependent rather than uniform across all groups. Fluorescent light sources (F2) produced significantly higher color differences than daylight for purple and, at 2 mm, yellow; however, pink showed the opposite pattern, with F2 producing the lowest ΔE_{00} values at both thicknesses, and yellow at 1 mm showed its lowest value under incandescent (A) rather than daylight.
3. Anodization color significantly influenced color inconsistency. At 1 mm gingival thickness, pink anodization demonstrated lower color differences than yellow and purple, whereas at 2 mm thickness, purple anodization generally exhibited the lowest and most illuminant-stable color differences, although it did not differ significantly from yellow under D65 and D50, or from pink under F11, and pink showed the numerically lowest value under F2.
4. Increasing gingival thickness from 1 mm to 2 mm significantly reduced color differences for all anodization colors and illumination conditions, although ΔE_{00} values remained above the CIEDE2000 clinical acceptability threshold (1.8) even at 2 mm thickness, indicating that complete color masking was not achieved within the tested thickness range.
5. Metameric behavior remained imperceptible under most conditions; however, pink anodization at 1 mm thickness under F2 illumination reached a perceptible but acceptable level.

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval and consent to participate Not applicable. This study was conducted entirely in vitro and did not involve human participants, animal subjects, or identifiable human data.

Consent for publication Not applicable.

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