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Effect of cement type, luting protocol, and ceramic abutment material on the shade of cemented titanium-based lithium disilicate crowns and surrounding peri-implant soft tissue: a spectrophotometric analysis

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PURPOSE. The objective of the study was to analyze the impact of cement, bonding pretreatment, and ceramic abutment material on the overall color results of CAD-CAM ceramic crowns bonded to titanium-based hybrid abutments. **MATERIALS AND METHODS.** For single implant restoration of a maxillary lateral incisor a total of 51 CAD-CAM-fabricated monolithic lithium disilicate crowns were fabricated and subsequently bonded onto 24 lithium disilicate Ti-base abutments, 24 zirconia Ti-base abutments and 3 resin abutment replicas as a control group. The 48 copings were cemented with three definitive and one provisional cement on both grit-blasted and non-blasted Ti-bases. The color of each restoration and surrounding artificial gingiva was measured spectrophotometrically at predefined measuring points and the CIELAB (ΔE_{ab}) color scale values were recorded. **RESULTS.** The color outcome of ceramic crowns bonded to hybrid abutments and soft tissues was affected differently by cements of different brands. Grit-blasting of Ti-bases prior to cementing CAD-CAM copings affected the color results of all-ceramic crowns. There was a significant difference ($P = .038$) for the median ΔE value between blasted and non-blasted reconstructions at the cervical aspect of the crown. Full-ceramic crowns on zirconia Ti-base abutments exhibited significantly lower ΔE values below the threshold of visibility (ΔE 1.8). In all subcategories tested, the use of a highly opaque temporary cement demonstrated the lowest median ΔE for both the crown and the artificial gingiva. **CONCLUSION.** Various cements, core ceramic materials and airborne particle abrasion prior to bonding can adversely affect the color of Ti-base supported ceramic crowns and peri-implant soft tissue. However, zirconia CAD-CAM copings and an opaque cement can effectively mask this darkening. [J Adv Prosthodont 2024;16:231-43]

KEYWORDS
Ti-base abutment; Cement; Color; Soft tissue; Ceramic coping

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INTRODUCTION

High survival rates have been demonstrated for implant-supported single-tooth restorations.[1] Osseointegration of the implant, absence of biological and technical complications, and esthetic integration of the restoration with the adjacent teeth and surrounding soft tissue are key criteria for long-term implant success.[2] To achieve a harmonious and esthetic result, dental materials used in fixed implant prosthodontics should reproduce the color appearance of teeth. Given the above, the selection of the appropriate implant abutment becomes an essential determinant in ensuring a successful outcome. Abutments for the connection of implants and superstructures are available in a variety of designs and materials. Conventional prefabricated titanium abutments have shown high survival rates due to their mechanical strength and biocompatibility.[3] However, metallic abutments can cause a grayish discoloration of the peri-implant mucosa, which can compromise the overall esthetic result, particularly in thin soft tissue.[4,5] One-piece zirconia ceramic abutments have been introduced to address this esthetic limitation. Despite its excellent biocompatibility, zirconia has a lower flexural and fracture strength than titanium because it is a more brittle material. Technical complications were frequently observed with one-piece zirconia abutments supporting single crowns in the maxillary anterior region.[5] In the molar region, screw loosening and rotational misalignment were reported at 5-year follow-up.[6] Ongoing development and the increasing use of computer-aided design/computer-aided manufacturing (CAD-CAM) within a digital workflow have led to the expansion of abutment options that include titanium-base abutments. A prefabricated titanium-base assumes the function of a connector to the implant in this implant-supported hybrid restoration, and a customized ceramic coping (hybrid abutment) or a full-contour crown is cemented onto it. The hybrid design is intended to combine esthetic requirements with improved mechanical stability.[7-9]

Several studies have documented the impact of varying abutment materials on the color result of the peri-implant soft tissue and the crown.[4,5,10-12] In addition to the color of the abutment and the type and thickness of the ceramic, the color of the cement may also influence the shade of an all-ceramic crown.[13,14] A recent pilot study suggests that luting agents and different bonding regimes may contribute to the shade of CAD-CAM lithium disilicate crowns on titanium-base abutments and the surrounding soft tissue.[15] No consideration was given to the influence of different abutment core ceramics.

Despite the knowledge of individual limitations in color perception,[16] visual assessment is the most commonly used method of shade evaluation in clinical restorative dentistry. For the objective determination of color differences in teeth and restorative materials, shade difference formulas (ΔE) can be used in color science to quantitatively represent the perceived shade difference under specific test conditions. The CIELAB formula (ΔE_{ab}) and the more recent CIEDE2000 formula with corresponding color differences (ΔE_{00}) have been proposed.[17,18] Visual thresholds are of interest for quality control and guidance in the selection of dental materials, the assessment of clinical outcomes, and the interpretation of *in vivo* and *in vitro* experimental research. In the present study, the researchers opted to use the CIELAB color difference formula with 100% perceptibility thresholds (100% PT) established by Thoma *et al*.[19] for human teeth (ΔE_{ab} = 1.8), and Sailer *et al*.[20] for gingiva (ΔE_{ab} = 3.1), respectively, for comparability with the previous research.[15] These values serve as a reference for the detection of color differences perceptible to the human eye.

Thus, the aim of the present study was to spectrophotometrically assess the combined effect of different cements, bonding protocols, and ceramic abutment core materials on the final shade of titanium-base supported lithium-disilicate crowns and the peri-implant soft tissue color. The hypothesis was that the color results of all-ceramic crowns bonded to titanium-based abutments and the surrounding soft tissues would be affected by either the cement (1), the core ceramic (2), or the airborne particle abrasion (3).

MATERIALS AND METHODS

The *in vitro* study was based on a master cast of a completed clinical case involving a single implant replacing the maxillary right lateral incisor. As clinical implant therapy had already been completed, the models could be used for the current *in vitro* study, and no ethics committee approval was required. The implant (ICX 3.75 × 10 mm, Medentis medical, Neuenahr-Ahrweiler, Germany) was inserted at bone level and digitally imprinted after the healing period using an intraoral scanner (iTero Element 5D, Align Technology, Rotkreuz, Switzerland) and the corresponding scanbody (ICX-Scanbasis/Scanbody narrow, Medentis medical, Neuenahr-Ahrweiler, Germany). The master cast was manufactured by Shera company (Shera, Lernförde, Germany) and supplied with the matching implant analog (ICX universal model analog for bone-level implants, Medentis medical, Neuenahr-Ahrweiler, Germany). The master cast was fabricated in acrylic and printed with a separate silicone gingival mask (Rosi, addition-cure silicone; Klasse 4 Dental GmbH, Augsburg, Germany), which was repeatedly printed to ensure consistent thickness over the course of each measurement. The implant analog was connected to the titanium base (ICX adhesive base, standard GH 0 mm, Medentis medical, Neuenahr-Ahrweiler, Germany) and digitized by means of a laboratory scanner (Ceramill Map 600, Amann Girrbach, Pforzheim, Germany). The resulting 3D model was uploaded and edited in a digital software (Exocad, Darmstadt, Germany). 24 lithium disilicate titanium based abutments with low translucency (IPS e.max CAD, LT A2, IvoclarVivadent, Lichtenstein), and 24 zirconia titanium based abutments with slight translucency (ceramill zi white, Amann Girrbach, Pforzheim, Germany) were fabricated. To ensure comparability of results with the reference pilot study of Liu *et al*.,[15] the same number of samples was selected for this study. The digital data from one of the test hybrid abutments was used to mill 3 acrylic abutment replicas for the control group (Ceramill A Temp A2, Amann Girrbach, Pforzheim, Germany). A total of 51 lithium disilicate (LS_2) crowns with low translucency (IPS e.max CAD, LT A2, Ivoclar Vivadent, Schaan, Lichtenstein) were produced (Fig. 1). The ceramic abutment

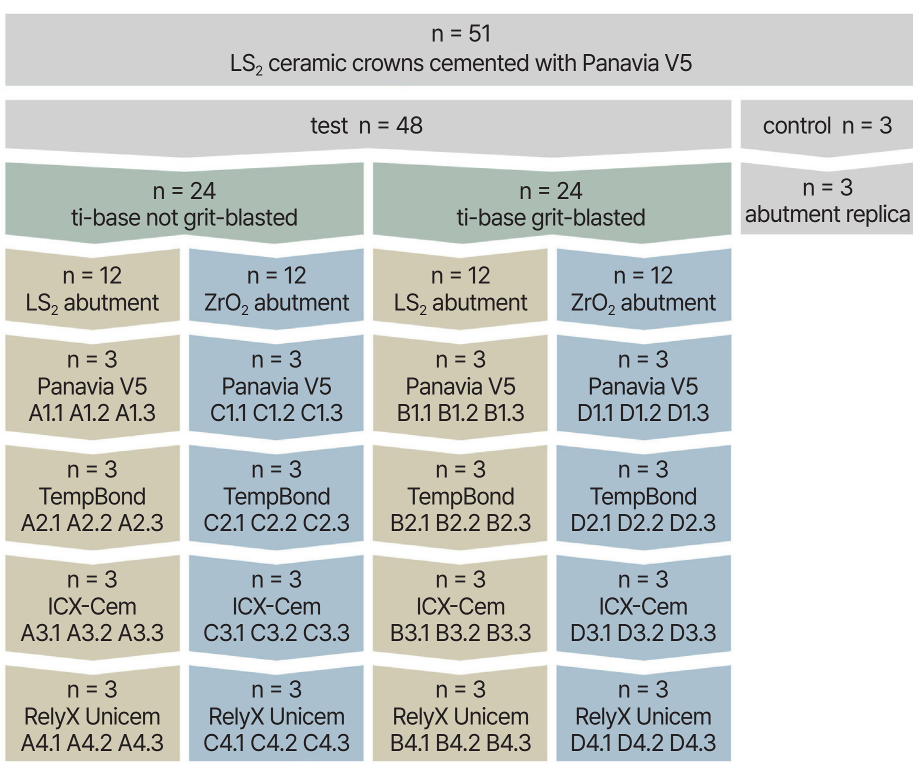

Fig. 1. Study design of test and control abutments according to coping material and cement type.

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copings and LS_2 crowns were milled by computer-aided manufacturing (CAM)(Ceramill Motion 2, Amann Girrbach, Pforzheim, Germany), sintered and glazed according to the manufacturer's instructions (Fig. 2 and Fig. 3).

All 48 ceramic copings were divided into four groups and cemented to the titanium bases using four different luting materials (Panavia™ V5, Kuraray Noritake Dental, Tokyo, Japan; TempBond, Kerr Dental, Kloten, Switzerland; ICX-Flow Cem, Medentis medical, Neuenahr-Ahrweiler, Germany; RelyX Unicem 2 Automix, 3M ESPE, Neuss, Germany) (Table 1). For 24 of the 48 specimens, the bonding surfaces of the titanium inserts were subjected to grit-blasting (aluminum oxide particles 50 µm; 2 bar/0.25 MPa; 10 s; distance 10 mm) and cleaned with ethanol. The intaglio surfaces of the LS_2 ceramic copings were etched with 5% hydrofluoric acid for 20 seconds (IPS Ceramic Etching Gel, Ivoclar, Lichtenstein), and a primer (Monobond Plus, exposure time 60s; Ivoclar, Lichtenstein) was applied to the pretreated internal surfaces of the copings. In the group of specimens where resin cement was used for bonding, the excess cement was removed, and the adhesive joint was polished with silicone polishers and polishing paste according to a previously documented protocol.[21] Detailed information on the bonding protocol used in each group is given in Table 1 and Table 2. Each fabricated Ti-base hybrid test and control specimen was connected to the im-

Table 1. Classification of test groups

Group	Cement Type	Sandblasted
	Ti-base with LS_2 copings (IPS e.max CAD, LT A2)	
A1 (n = 3)	V5 Panavia A2	No
A2 (n = 3)	TempBond	No
A3 (n = 3)	ICX-Flow cem	No
A4 (n = 3)	RelyX Unicem A2	No
B1 (n = 3)	V5 Panavia A2	Yes
B2 (n = 3)	TempBond	Yes
B3 (n = 3)	ICX-Flow cem	Yes
B4 (n = 3)	RelyX Unicem A2	Yes
	Ti-base with ZrO_2 copings (Ceramill zi white)	
C1 (n = 3)	V5 Panavia A2	No
C2 (n = 3)	TempBond	No
C3 (n = 3)	ICX-Flow cem	No
C4 (n = 3)	RelyX Unicem A2	No
D1 (n = 3)	V5 Panavia A2	Yes
D2 (n = 3)	TempBond	Yes
D3 (n = 3)	ICX-Flow cem	Yes
D4 (n = 3)	RelyX Unicem A2	Yes

The test specimens of groups A-B consisted of lithium-disilicate (LS_2) ceramic copings and those of groups C-D of zirconia (ZrO_2) ceramic copings. All ceramic copings were cemented on Ti-bases GH 0 mm and provided with LS_2 crowns.

Fig. 2. Ti-base abutment with the ceramic coping.

Fig. 3. Ti-base hybrid specimen with cemented all-ceramic crown.

Table 2. Bonding protocol of test groups

	Cementation protocol (according to manufacturer's instructions)			
	Preparation of Ti-base	Preparation of CAD-CAM ceramic core	Bonding and light curing	Preparation of joint
V5 Panavia A2 (non grit-blasted)	Application of the primer (Clearfil Ceramic Primer Plus) with a brush and removal of the excess with a stream of air	Cleaning of the inner surface with alcohol	Application of PANAVIA V5 from the Automix syringe onto the titanium base, removal of the excess cement and light curing for 10 sec.	Polishing the bonding line with ceramic polishing set (Komet, SET 4313B)
V5 Panavia A2 (grit-blasted)	Blasting of the bonding area of titanium base with aluminum oxide; application of primer (Clearfil Ceramic Primer Plus) with brush and removal of excess with a stream of air	Cleaning of inner surface with alcohol	Application of PANAVIA V5 from Automix syringe onto the Ti-base, removal of excess cement and light curing for 10 sec.	Polishing of bonding line with ceramic polishing set (Komet, SET 4313B)
TempBond (non grit-blasted)	Degreasing with alcohol	Cleaning of inner surface with alcohol	Application of TempBond onto Ti-base, removal of excess cement.	-
TempBond (grit-blasted)	Degreasing with alcohol, blasting of bonding area of Ti-base with aluminum oxide	Cleaning of inner surface with alcohol	Application of TempBond onto the ti- base, removal of excess cement.	-
ICX-Flow cem (non grit-blasted)	Degreasing with alcohol	Cleaning of inner surface with alcohol	Application of ICX-Flow onto the Ti-base, removal of excess cement and light curing for 10 sec.	Polishing of bonding line with ceramic polishing set (Komet, SET 4313B)
ICX-Flow cem (grit-blasted)	Degreasing with alcohol, blasting of bonding area of Ti-base with aluminum oxide	Cleaning of inner surface with alcohol	Application of ICX-Flow onto the Ti-base, removal of excess cement and light curing for 10 sec.	Polishing of bonding line with ceramic polishing set (Komet, SET 4313B)
RelyX Unicem A2 (non grit-blasted)	Degreasing with alcohol	Cleaning of inner surface with alcohol	Application of RelyX Unicem A2 onto Ti-base, removal of excess cement and light curing for 10 sec.	Polishing of bonding line with ceramic polishing set (Komet, SET 4313B)
RelyX Unicem A2 (grit-blasted)	Degreasing with alcohol, blasting of bonding area of Ti-base with aluminum oxide	Cleaning of inner surface with alcohol	Application of RelyX Unicem A2 onto Ti-base, removal of excess cement and light curing for 10 sec.	Polishing of bonding line with ceramic polishing set (Komet, SET 4313B)

plant analog in the master cast. The intaglio surfaces of all LS_2 ceramic crowns were etched and primed prior to the bonding process as described above. The acrylic abutment replicas of the control group (n = 3) were bonded to the lithium disilicate crowns using the same dual-cure, resin cement as the test groups (Panavia^{TM} V5, Kuraray Noritake Dental, Tokyo, Japan) in order to evaluate and compare possible effects of titanium grit-blasting and cement type on the final shade outcome of LS_2 crowns. Any excess cement was carefully removed.

The artificial gingiva was marked 1 mm apical to the gingival margin. Two additional markings were placed on the adjacent incisor, one 1 mm incisal to the gingival margin and one in the center of the implant crown (Fig. 4). This procedure allowed reproducible color measurements of the individual implant crowns and artificial mucosa. Ceramic thickness was

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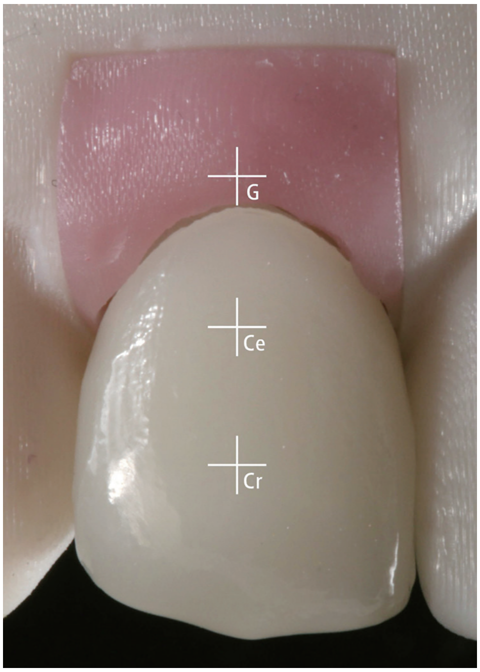

Fig. 4. Measuring points: G - gingival measuring point; Ce - cervical measuring point; Cr - measuring point in the middle of the ceramic crown.

digitally measured in the software as 1.2 mm at the 1 mm marker point apical to the gingival margin, 2.2 mm at the 1 mm mark incisal to the gingival margin, and 1.7 mm at the center of the implant crown. Artificial soft tissue thickness was manually measured with an ISO 20K file and determined to be 1.6 mm. The color of each inserted restoration was measured three times at the three defined measurement points using a spectrophotometer (ShadePilot Dentsply Degudent, Hanau, Germany & SpectroShade Micro, MHT Optic Research, Niederhasli, Switzerland)(Fig. 5). The cursor has been preset to a rectangle of size 30. For each specimen, the CIE L*a*b* color scale values were recorded. All measurements were taken in a room with closed door and dimmed light. The spectrophotometer was positioned at 45° and 30 cm from the sample. The following formula was used to calculate the color differences between the test groups and the control group: $\Delta E = ([\Delta L^*]^2 + [\Delta a^*]^2 + [\Delta b^*]^2)^{1/2}$.

The null hypothesis was that the Delta E values (ΔE_{ab}) of all-ceramic crowns bonded to titanium-base abutments and the surrounding soft tissues would not be affected by either the cement, the surface

Fig. 5. *In vitro* color measurement using the spectrophotometer.

preparation, or the core ceramic of the Ti-bases by airborne particle abrasion. Statistical analysis was calculated using the software BiAS für Windows (Version 11.12, Epsilon-Verlag, Frankfurt, Germany, 2021). The Kruskal-Wallis test and the Wilcoxon test for pair differences were used for dependent samples. For the case of independent samples, the Mann and Whitney U-test was performed. The level of statistical significance was set at $P < .05$.

RESULTS

The current *in vitro* investigation examined the effects of different bonding materials, adhesive pretreatment protocols by grit-blasting, and ceramic coping materials on the final color outcome of Ti-base-supported LS_2 crowns and the surrounding artificial peri-implant soft tissue. The influence of four bonding materials and two different abutment ceramics, as well as the pretreatment of the Ti-bases, i.e. blasted or not, was taken into account. In all subcategories tested (LS_2 and ZrO_2 on Ti-base blasted/non-blasted), the use of a highly opaque and thus non-translucent temporary cement (TempBond) demonstrated the lowest median Delta E values (ΔE_{ab}) for both the reconstruction (Fig. 6 and Fig. 7) and the artificial gingiva (Fig. 8 and Fig. 9) (Table 3).

The color differences measured in the crown center among all four cement materials were not statistically significant. However, in the cervical region of the crown, the differences reached statistical signifi-

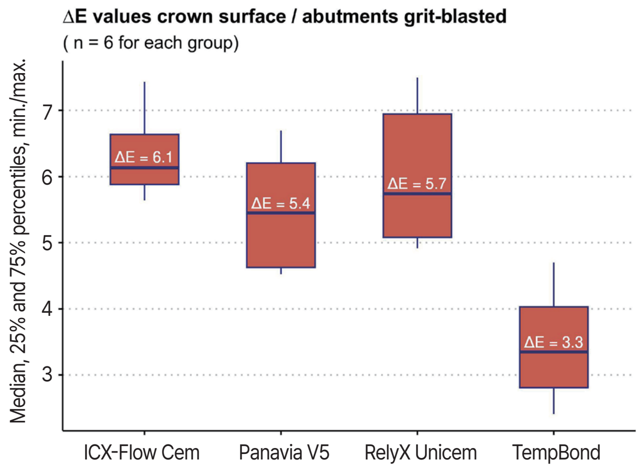

Fig. 6. Comparison of ΔE values for the crown surface between different cementation materials on grit-blasted Ti-bases.

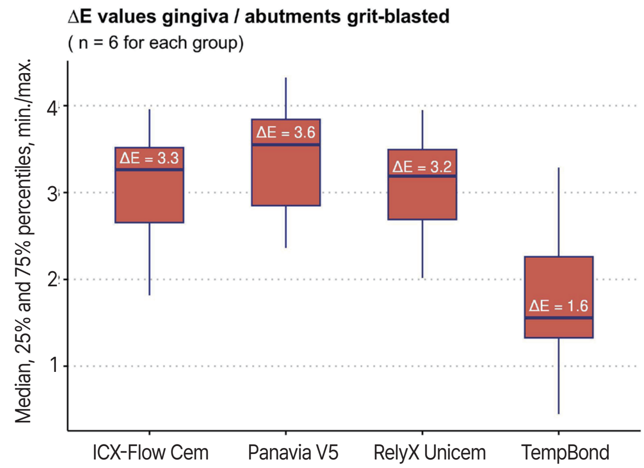

Fig. 8. Comparison of ΔE values for the artificial mucosa between different cementation materials on grit-blasted Ti-bases.

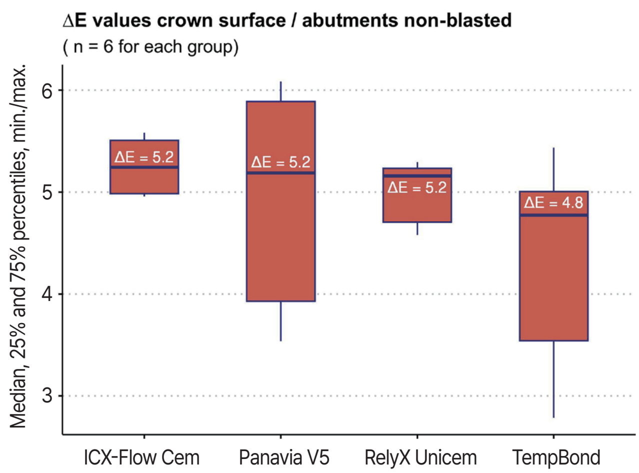

Fig. 7. Comparison of ΔE values for the crown surface between different cementation materials on non-grit-blasted Ti-bases.

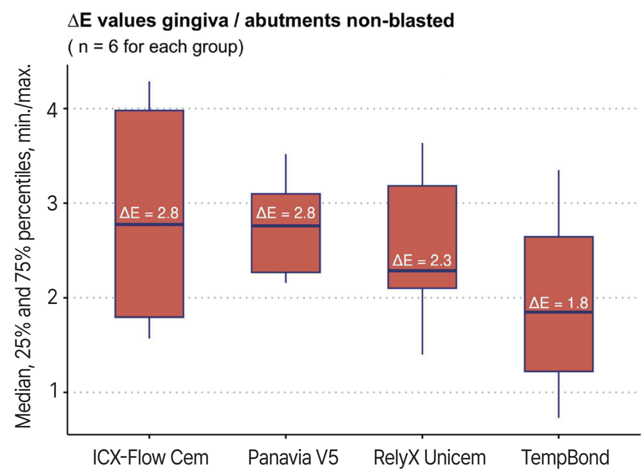

Fig. 9. Comparison of ΔE values for the artificial mucosa between different cementation materials on non-grit-blasted Ti-bases.

cance of $P < .001$ with the lowest median Delta E value for TempBond (ΔE 4.3), followed by RelyX Unicem A2 (ΔE 5.87), V5 Panavia A2 (ΔE 6.29) and ICX-Flow cem (ΔE 7.06). Measurements in the gingival region also revealed the lowest median delta E value for single crowns cemented with TempBond (ΔE 1.69), while this gingival value was the highest for crowns cemented with ICX-Flow cem (ΔE 3.26). RelyX Unicem A2 reached the value of 2.76 and V5 Panavia A2 3.04 with statistical significance of 0.02. The comparison of the three measuring points for each test specimen showed a clear statistically significant difference ($P < .001$) (Table 3). There was a significant difference ($P = .04$) for the median Delta E value between the grit-blasted (ΔE 6.62) and non-grit-blasted (ΔE 5.49) reconstructions at the cervical aspect of the crown

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Table 3. ΔE values depending on the adhesive material

Variable	N	Mean	Median	Standard Deviation
		ICX-Flow cem		
ΔE crown center	12	4.45	4.36	0.8
ΔE cervical	12	6.91	7.06* ($P < .001$)	1.33
ΔE gingival	12	2.97	3.26* ($P < .02$)	1.01
		RelyX Unicem A2		
ΔE crown center	12	4.48	4.45	0.72
ΔE cervical	12	6.39	5.87* ($P < .001$)	1.46
ΔE gingival	12	2.8	2.76* ($P < .02$)	0.8
		TempBond		
ΔE crown center	12	3.58	3.61	1.04
ΔE cervical	12	4.2	4.3* ($P < .001$)	1.13
ΔE gingival	12	1.86	1.69* ($P < .02$)	0.96
		V5 Panavia A2		
ΔE crown center	12	4.07	4.16	0.87
ΔE cervical	12	6.36	6.29* ($P < .001$)	1.42
ΔE gingival	12	2.98	3.04* ($P < .02$)	0.9

Values marked with * achieved statistical significance in the Kruskal-Wallis H test.

Table 4. Differences in L*a*b and ΔE values between the non grit-blasted (N1) and the grit-blasted (N2) groups (Wilcoxon-Mann-Whitney U test)

			Group 1: non grit-blasted. Group 2: grit-blasted		
Variable	N1	N2	non grit-blasted	grit-blasted	*P*-value
L crown center	24	24	72.3	70.47	.00
a crown center	24	24	0.32	0.28	.27
b crown center	24	24	11.98	11.68	.13
L cervical	24	24	72.08	70.73	.02
a cervical	24	24	1.58	1.18	.05
b cervical	24	24	12.85	11.75	.03
L gingival	24	24	64.18	63.93	1.0
a gingival	24	24	21.73	21.50	.33
b gingival	24	24	11.93	11.58	.44
ΔE crown center	24	24	4.38	4.17	.93
ΔE cervical	24	24	5.49	6.62	.04
ΔE gingival	24	24	2.29	2.97	.21

(Table 4).

With respect to the different ceramic abutment coping materials, the measurements showed a statistically significant difference ($P < .001$) in median ΔE in the gingival region (Table 5 and Fig. 10).

At the gingival measurement point, ΔE was 1.92 for the ZrO_2 and ΔE 3.48 for the LS_2 abutment. While the readings for LS_2 exceeded the selected critical threshold for perceptible changes in mucosa color of ΔE 3.1, the non-translucent ZrO_2 exhibited a significantly lower ΔE and therefore resulted in less visible mucosa color shift.[20]

Table 5. Differences in L*a*b and ΔE values between LS_2 (N1) and ZrO_2 (N2) groups

		Group 1: LS_2. Group 2: ZrO_2			
Variable	N1	N2	LS_2	ZrO_2	*P*-value
L crown center	24	24	70.9	70.98	.56
a crown center	24	24	0.23	0.37	.05
b crown center	24	24	11.63	12.02	.09
L cervical	24	24	70.42	72.13	.06
a cervical	24	24	1.4	1.53	.32
b cervical	24	24	12.03	12.47	.15
L gingival	24	24	64.25	63.98	.31
a gingival	24	24	21.47	21.83	.09
b gingival	24	24	10.92	12.32	< .001*
ΔE crown center	24	24	4.41	4.03	.03
ΔE cervical	24	24	6.27	5.6	.05
ΔE gingival	24	24	3.48	1.92	< .001*

Values marked with * achieved statistical significance in the Wilcoxon-Mann-Whitney U test.

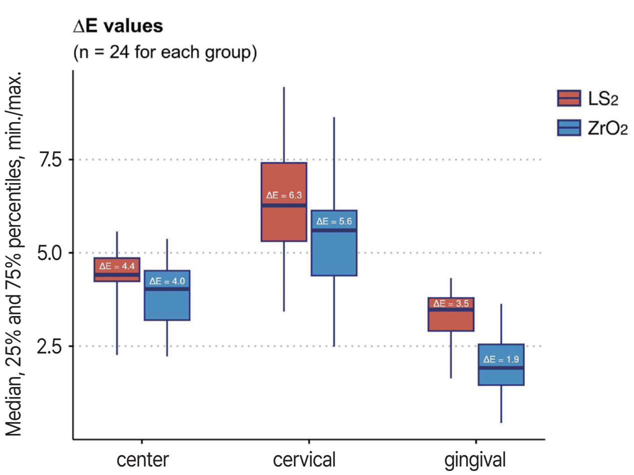

Fig. 10. Comparison of ΔE values between the groups of crowns cemented on LS_2 or ZrO_2 abutments.

DISCUSSION

Implant restorations on Ti-base abutments have become a popular choice in clinical treatment due to their ease of use and low complication rate.[22,23] Despite their biocompatibility, low inflammatory response and no negative effect on the surrounding hard and soft tissues,[24] discoloration of ceramic restorations or of the mucosa due to the metallic Ti-base has been reported.[5,25] The present study examined additional factors such as the influence of the ceramic coping material, cement type, and bonding pretreatment that may negatively affect the color of Ti-base supported ceramic crowns and peri-implant soft tissue. With respect to the ceramic coping material, the results showed less color shift in all-ceramic crowns on zirconia (ZrO_2) Ti-bases compared to lithium disilicate (LS_2). These results are consistent with the findings of Dede *et al.*,[10] suggesting that ZrO_2 may be a better esthetic choice for Ti-base abutments supporting ceramic restorations. While LS_2 is commonly employed for superior adhesion,[26] it can be difficult to achieve an appropriate shade of the final crown due to its high translucency. In this regard, it should be noted that recent data show that 2 mm ceramic alone and 1.5 mm ceramic with resin cement can mask crown discoloration.[12] It was reported that the minimum thickness of zirconia restorations being able to neutralize the color change was 1.5 mm.[12]

The color of the soft tissue around implants can also affected by the abutment and crown material as well as the luting material.[4] According to a systematic review, zirconia abutments are not superior to titanium abutments in this regard.[27] In an *in vitro* study, gold-hue titanium nitride-coated CAD-CAM abutments showed better esthetic results than titanium and zir-

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conia abutments, emphasizing that the thickness of the mucosa has a decisive influence on the color change.[28] Lops *et al*. showed that mucosal thickness of ≤ 2 mm is sufficient to minimize discolorations when using gold or zirconia abutments and suggested that they can be an acceptable choice for restorations in the anterior region. Titanium abutments presented much higher ΔE values. Despite the better performance of zirconia and gold abutments, it was evident that the measurements of all implant restorations tested were above the selected critical threshold of ΔE_{ab} = 8.74 for intraoral color distinction by the naked eye.[29] Reduced soft tissue color difference has also been achieved with the use of anodized pinkneck implants and abutments.[30] In the current study, the ΔE values for ZrO_2 at the gingival measurement site were significantly lower than those for LS_2, placing the non-translucent zirconia below the threshold for visible discoloration. Furthermore, a greyish color shift at the gingival and cervical measuring points could be neutralized by cementing the all-ceramic crowns on both blasted and non-blasted Ti-bases with a temporary opaque cement (TempBond). For all other resin cements tested, the masking effect was lower due to their reduced opacity. They exhibited higher ΔE values when compared to the temporary cement. The optical advantage of opaque cements for bonding all-ceramic crowns to Ti-based abutments has also been demonstrated by Liu *et al*.[15] They also showed that a temporary cement showed the highest masking effect. It has been shown that additional treatment of restorations with airborne particle abrasion prior to cementation significantly increases bond strength.[31] The present study demonstrated that grit-blasting of the Ti-bases performed to improve the adhesive bond to the ceramic coping resulted in increased ΔE values above the threshold of color difference perceptible to the human eye. This underscores the clinical need for an opaque permanent luting material to mask any darkening caused by blasting the Ti-base. Ceken *et al*. confirmed the positive effect of using an opaque luting agent to cement restorations on Ti-base abutments. In addition, the study showed that the combination of zirconia or hybrid abutments with yellow luting materials produced the best esthetic results.[32]

A further aspect to consider is the mechanical stability of the restoration. LS_2 crowns are reported to be more fracture resistant than ZrO_2 under dynamic loading.[33,34] However, the ability to maintain a stable shade over time varies among ceramic materials. In contrast to the studies mentioned above, Fouda *et al*.[35] reported that zirconia showed slightly higher fracture resistance and color stability after aging compared to lithium disilicate restorations. It is important to note that in the above study, the number of aging cycles did not have a significant effect on fracture resistance in either group but did have a significant effect on color stability. A limitation of the current investigation is that the results were obtained under laboratory conditions. *In vitro* results have limited applicability to complex clinical situations. The thickness of the artificial mucosa in the present experimental setup was 1.6 mm. This differs from clinical experiences where the thickness of the peri-implant soft tissue was measured to be 1.8 ± 0.4 mm.[36] Such difference can be critical when measuring color differences. Despite the considerable number of test specimens, the relatively small number of samples in the resulting subgroups may be considered another limiting factor of the study. Since the sample size was selected to allow comparison with the reference study of Liu *et al*.,[15] sufficiently meaningful conclusions and comparisons could still be drawn.

A variety of visual threshold values have been reported in numerous studies related to teeth, ceramic restorations, gingiva, and gingiva-colored restorative materials.[19,20,37-40] A just noticeable difference or perceptibility threshold (PT) refers to the smallest color difference that can be detected by an observer. A 50:50% perceptibility threshold refers to a situation in which 50% of observers notice a difference in color between two objects while the other 50% notice no difference. Analogously, the difference in color that is acceptable for 50% of observers corresponds to a 50:50% acceptability threshold (AT).[41] Evaluations of the applicability of the CIELAB (ΔE_{ab}) and CIEDE2000 (ΔE_{00}) color difference formulas differ in terms of their ability to accurately reflect color differences perceived by the human eye and to establish standardized perceptual thresholds for different dental materials and tissues. The CIELAB color difference formula with 100% perceptibility thresholds (100%

PT), as proposed by Thoma *et al*.[19] for human teeth (ΔE_{ab} = 1.8), and Sailer *et al*.[20] for gingiva (ΔE_{ab} = 3.1), was chosen for the present study. In contrast, more recent studies have reported 50:50 PT/AT values of ΔE_{ab} = 1.2/2.7 for tooth colored white ceramic using the CIELAB and values of ΔE_{00} = 0.8/1.8 applying the CIEDE2000.[41] In addition, the PT and AT for human gingiva using the CIEDE2000 were reported as 50:50% PT/AT: ΔE_{00} = 1.1/2.8, with corresponding CIELAB values of 50:50% PT/AT: ΔE_{ab} = 1.7/3.7.[37] While some studies suggest that the CIEDE2000 color difference formula provides better agreement than the CIELAB formula in assessing visual tolerances,[39,42] other researches indicate that both formulas similarly reflect the gingival color differences perceived by the human eye.[43] This discrepancy highlights the ongoing debate about which color difference formula is more accurate and reliable for determining perceptual thresholds in dental applications.

In addition to the study design being limited to a single abutment/crown configuration and excluding other restorative options such as implant-supported bridges, another potential limitation was the restricted field of view of the spectrophotometer used. It was not possible to cover a larger area due to the short range of the device, and therefore many factors that could potentially affect the measurements may not have been taken into account. However, it is reasonable to assume that the results of the present trial can be considered relevant until appropriate experience under clinical conditions is available. Since the shade of ceramic crowns cemented to Ti-base abutments was affected by the cement (1), the airborne particle abrasion (2), and the core ceramic (3), the hypothesis can be accepted. Further clinical studies with larger test groups and long-term follow-up may be beneficial in evaluating the esthetic performance of Ti-base abutments and all-ceramic single crowns.

While the present *in vitro* study has identified the Ti-base abutment options that provide superior esthetic results due to their processing, it is imperative that future research be conducted that includes comprehensive mechanical retention and strength testing. Such research is critical to determine whether these esthetically favorable Ti-Base abutment options can also provide the mechanical reliability required for long-term clinical success that combines both esthetics and mechanical predictability, ultimately improving clinical outcomes.

CONCLUSION

Within the limitations of the current *in vitro* study, the following results can be drawn: The color of all-ceramic crowns bonded to Ti-base hybrid abutments and the color of the surrounding artificial peri-implant soft tissue were affected by all measured factors, including different bonding materials, luting protocols prior to cementation, and abutment ceramics. Zirconia core copings on Ti-bases cause less mucosal discoloration compared to lithium disilicate ceramic and therefore have better masking properties. Airborne particle abrasion prior to cementation can adversely affect the color of Ti-base supported ceramic crowns and peri-implant soft tissue. An opaque luting material displayed the highest masking ability to cover the darkening caused by grit-blasting Ti-base.

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