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Comparison of the Reproducibility of Various Tooth Color Measurement Techniques

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Abstract:

Objective(s): Accurate shade selection is the most challenging step in the natural reconstruction of teeth in most cases. The most commonly used method for adapting the color of tooth and restorative materials is the visual matching of the tooth color to shade guides. However, many factors affect color perception by the observer, making the visual evaluation of tooth color unreliable. Therefore, this study aimed to compare the reproducibility of tooth shade determination with two different types of spectrophotometers and two smartphone applications. **Methods:** The present in vitro study used four methods of colorimetry on 27 disk-shaped composite resin samples prepared from nine different shades of composite resin. Colorimetry tools included Easyshade (Vita, Germany) and SP60 (X-rite, USA) colorimetry devices, and two smartphone colorimetry applications: Color Grab and Dental Shade Navigator. Statistical analysis was performed using intraclass correlation coefficient (ICC) and repeated measures ANOVA at p<0.05. **Results:** The results indicated significant differences(P-value<0.05) among the four colorimetry methods, with the following reproducibility rates based on the ΔE parameter: SP60 spectrophotometer: 100%; Color Grab Software: 95.1%; Easyshade spectrophotometer: 40.7%; and Dental Shade Navigator Software: 34.4%. **Conclusion:** The SP60 spectrophotometer had the highest reproducibility in all the color parameters, followed by the Color Grab application. Easyshade device had a higher reproducibility rate than the Dental Shade Navigator Software.

Keywords: Tooth; Dental Materials; Spectrophotometry, Colorimetry

Introduction

An essential factor for the success of aesthetic restorative treatments is the accurate evaluation and determination of tooth color, along with an understanding of the unique optical properties of the tooth. This understanding enhances the consistency and reliability of tooth shade selection in dentistry.[1-4] Despite advancements in tooth shade selection methods, its accurate selection is still a challenge that affects esthetic outcomes. In addition, a precise color match between the restoration and the adjacent tooth is challenging in clinical dentistry. An esthetic restoration depends on its design, morphology, topography, translucency, and proper shade. However, from patients' viewpoints, the color match of the tooth with adjacent teeth has the most crucial role in smile esthetics.[5-8]

The most common method to match the tooth and restorative materials' shade is the visual comparing of tooth color with standard dental shade guides. One of the inherent features of tooth shade selection using this method is the variability in the selection made by an observer and between observers, which is affected by the human observer's ability to select the best and most harmonious shade due to the individual-oriented nature of the procedure.[9-12] The limitations of the visual tooth shade selection procedure have led to research on more accurate, compatible, and scientific methods for shade match, resulting in the use of automatic and objective tools for determining the tooth shade. Tooth shade selection using an instrument is superior to the visual method due to its objectivity. A growing number of computerized shade match tools have become available for clinical use, including colorimeters, spectrophotometers, digital color analyzers, or a combination of these tools.[13, 14]

Borse et al.[15] analyzed the shade selection process in dental prostheses. They reported that the VES spectrophotometer had the highest accuracy, reliability, and reproducibility, followed by colorimetry with the photography method. The Vita 3D Master Shade selection guide has shown consistent results in repeated shade selection. Knowledge and training protocols are necessary for shade selection to achieve a correct color match. Reyes et al. [16] evaluated the reproducibility of shade selection by the human eye compared to an intraoral scanner by comparing the conventional visual method with an intraoral scanner (3Shape TRIOS) to match tooth shade in patients, and concluded that the TRIOS intraoral scanner had better reproducibility than the visual method matching the tooth shade. Tabatabaian et al. studied the visual and digital shade selection processes and the factors and conditions affecting their accuracy. They reported that dental spectrophotometers were the most accurate among different tooth shade selection methods. However, they mentioned needing clinical adjustments to control the relevant factors and conditions to improve their performance.[13] On the other hand, Abu-Hossin et al. compared the visual shade selection method with digital methods, evaluated the reproducibility of intraoral scanners, and concluded that intraoral scanners could improve clinical performance as a supplementary method. However, they mentioned that the visual method should confirm the results. Digital tools are increasingly preferred to conventional methods; however, intraoral scanners should be continuously improved for the shade selection process.[14]

Hardan et al. [17] evaluated innovations in tooth shade selection procedures using different methods and concluded that digital photography and spectrophotometric measurements resulted in less color mismatch and incorrect shade match than conventional methods using shade selection tabs. Previous research indicates that color matching with different tools can lead to significantly different results, and each device or tool has specific limitations.[16]

Moreover, advancements in technology and the growing popularity of smartphones have led to healthcare providers' increased use of this tool. Considering their capabilities, including independent CPU calculation capacity, various applicability, diverse software programs, wireless connection, and high-quality imaging technology, tooth shade matching with software programs installed on smartphones has been more straightforward and cheaper than other methods.[17,18] Therefore, it is necessary to compare and evaluate the capability of shade match tools and software programs. The present study was designed to compare the reproducibility of Easyshade (Vita, Germany) and SP60 (X-rite, USA) colorimeters and two smartphone colorimetry applications; Color Grab and Dental Shade Navigator.

The null hypothesis was that the Easyshade and SP60 colorimeters, as well as the Color Grab and Dental Shade Navigator smartphone applications, all have the same level of reproducibility.

Methods

The protocol for this study was approved by the Ethics Committee of Tehran University of Medical Sciences under the code IR.TUMS.DENTISTRY.REC.1401.023, and all requirements were met. Twenty-seven disk-shaped composite resin samples, 14 mm in diameter and 1 mm in thickness, were fabricated from different color shades of DenFil hybrid composite resin (Vericom, Korea) (Figure 1, Table 1).

Figure 1: A composite resin disk-shaped sample.

Table 1 - The characteristics of the composite resin used in the present study

	Material	Material type	Composition	Shade	Number of samples
1	DenFil hybrid	Composite resin	- Barium aluminosilicate - Fumed silica - Bis-GMA - Triethyleneglycol dimethacrylate	A1	3
2				A2	3
3				A3	3
4				A3.5	3
5				B1	3
6				B2	3
7				C2	3
8				C3	3
9				D3	3

A laser cutting instrument was used to create cylindrical holes measuring 14 mm in diameter in a Plexiglass mold plate with a thickness of 1 mm. Two glass slabs were placed under and over the mold containing composite resin, and each sample was placed under a 5-kg weight for 30 seconds to ensure sample uniformity and eliminate voids. All the samples were light-cured from both sides of the glass slabs with similar duration and light intensity by using an LED light curing unit (850mW/cm2, woodpecker, Guang Dong, China) in 20 seconds. Then, to complete dark polymerization, the disk samples were stored in distilled water for 24 hours and then polished to achieve a uniform, smooth surface.[19]

The samples were categorized into nine subgroups based on the composite resin shade used: A1, A2, A3, A3.5, B1, B2, C2, C3, and D3. In each group, three disk-shaped samples were prepared with a similar shade. Each sample underwent a colorimetry procedure three times using the four tools: Easyshade (Vita, Germany) and SP60 (X-rite, USA) colorimeters and Color Grab and Dental Shade Navigator smartphone software programs. A white piece of paper was placed under each composite resin sample to prevent the effect of background color during the colorimetry procedure. In addition, to prevent the impact of environmental light on the recorded numeric values, all measurements were performed under identical daylight conditions on the same day by a single operator, focusing on the central part of each composite resin sample.[20]

For colorimetry with the Easyshade spectrophotometer (Vita, Germany), the tip of the calibrated device was placed parallel but not in contact with the sample surface. Without any movement, the device's measuring button was pressed to carry out the colorimetry procedure at the center of the composite resin sample surface. Before each colorimetry procedure, the SP60 device was calibrated. Then, each sample was placed at the center of the device's target window, a white piece of paper was placed beneath the device, and the settings were ready for the colorimetry procedure of the samples. The results of these two devices were recorded using the CIELab color system.[21]

For smartphone colorimetry, a standard 8-cm distance was observed for standard smile capture, and the phone was adjusted parallel to each composite resin sample. Both software programs used in the present study could automatically use the smartphone's camera. Therefore, the photographs were taken automatically using the default conditions of each software. In addition, both software programs could register the results of colorimetry procedures based on the CIELab color system.

With the Color Grab software, the indicator's central circle at the center of the smartphone screen should be fixed on the object for 3 seconds until a blue tick mark, indicating the registration of the color, appears on the screen.[22]

The Dental Shade Navigator software has more specifically been designed for dental purposes. The relevant restoration type should be selected first to work with this software. In the present study, the 'veneer' option was selected. Then, the single shade option was selected in the clinical approach; then, for the 'estimated restoration thickness,' 1 mm was selected since the disk-shaped composite resin samples were 1 mm. After taking a picture of the composite resin sample on a white piece of paper, an indicator called 'grey pixel' was selected for the colorimetry of the sample so that the software could adjust the picture's luminescence automatically based on the color beneath this indicator. In the present study, the 'grey pixel' was adjusted at a distance of 5 cm from the composite resin disk border, its location was marked, and the disk location on the paper was determined for uniformity. After selecting the 'grey pixel,' the 'tooth pixel' was selected. This indicator determines a point on the sample for colorimetry, which was located at the center of the composite resin disk.

All the achieved values were analyzed to evaluate the reproducibility of all the devices and software programs.[23]

The statistical analysis was conducted using IBM SPSS Statistics, version 24. The intraclass correlation coefficient (ICC) was calculated to evaluate the reproducibility of measurements. Additionally, repeated measures ANOVA was employed to compare the measurements obtained from different tools, accounting for within-subject correlations due to repeated measurements on the same samples. The level of significance was set at 0.05.

Results

The present study compared the reproducibility of four tooth colorimetry methods using the ICC test. Perceptibility threshold (PT) and Acceptability threshold (AT) of ΔE are shown in Table 2.

Table 2 - Perceptibility threshold (PT) and Acceptability threshold (AT) of ΔE

Perceptibility threshold (PT)	The minimum color change that an observer can perceive	ΔE=1.2
Acceptability threshold (AT)	Half of the observers can perceive the difference in color between the two samples, and the other half cannot perceive it	ΔE=2.7

Three color difference patterns are defined in the CIELab system based on ΔE between two tooth samples or tooth-colored materials:

a. Excellent match: two samples with ΔE≤PT (ΔE≤1.2)

b. Acceptable match: two samples with ΔE between the two values of PT and AT (1.2<ΔE≤2.7)

c. No match: two samples with ΔE>AT (ΔE>2.7).

According to Paravina et al., the CIEDE2000 formula (ΔE00) establishes key thresholds for color differences in dentistry under simulated clinical conditions. The 50:50% perceptibility threshold (PT), defined as the smallest color difference that 50% of observers can perceive, was determined to be 0.8, indicating minimal color differences detectable by the human eye. The 50:50% acceptability threshold (AT), representing the maximum color difference considered clinically acceptable by 50% of observers, was 1.8. These thresholds are critical for ensuring high standards in dental aesthetics, as PT helps gauge the sensitivity of human vision. At the same time, AT defines the limits of clinically acceptable variations in restorative materials. Together, these benchmarks support quality control, guiding clinicians in evaluating materials and ensuring aesthetic outcomes that meet professional and patient expectations.[24]

Tables 3 present the ΔE parameter for measurements first–second, second–third, and first–third with SP60 and Easyshade spectrophotometers, with ΔE values of these measurements at 100% (excellent) and 40% (acceptable), respectively (Table 3).

Table 3 - The color matches of the first, second, and third measurements of the samples using

		1, 2	2, 3	1, 3	Mean	Percentage
the SP60 spectrophotometer	ΔE>2.7	0	0	0	0	0
	1.2<ΔE≤2.7	0	0	0	0	0
	ΔE≤1.2	27	27	27	27	27
Easyshade spectrophotometer	ΔE>2.7	15	16	17	16	59.3
	1.2<ΔE≤2.7	6	7	5	6	22.2
	ΔE≤1.2	6	4	5	5	18.5
the Color Grab application	ΔE>2.7	2	0	2	1.3	4.8
	1.2<ΔE≤2.7	9	11	7	9	33.3
	ΔE≤1.2	16	16	18	16.7	61.8
the Dental Shade Navigator (D.S.N)	ΔE>2.7	18	17	18	17.7	65.6
	1.2<ΔE≤2.7	2	5	5	4	14.8
	ΔE≤1.2	7	5	4	5.3	19.6

Table 3 present the ΔE parameters for color measurements made by the Color Grab and Dental Shade Navigator Smartphone applications. The results ranged from 95.1% to 34.4%, from excellent to acceptable.

Intraclass correlation coefficient (ICC) was used to determine the intra-group reproducibility in shade selection procedures using the four shad selection tools evaluated in the present study at a 95% confidence interval.

A comparison of the measures of a, b, and L parameters between the first, second, and third shade selection procedures with each tool (Table 4) showed that the reproducibility of the two smartphone applications was almost similar to that of the Easyshade. The reproducibility of the SP60 was superior to the others.

Table 4 - The results of the ICC for the L parameter

Material		Intraclass correlation		
		L1, L2	L2, L3	L1, L3
SP60	Single Measures	0.999ª	0.999ª	1.000ª
	Average Measures	0.999ª	1.000ᶜ	1.000ᶜ
Easyshade	Single Measures	1.000ᶜ	0.932ª	0.954ª
	Average Measures	0.932ª	0.965ᶜ	0.977ᶜ
Color Grab	Single Measures	0.965ᶜ	0.950ª	0.987ª
	Average Measures	0.950ª	0.974ᶜ	0.993ᶜ
D.S.N	Single Measures	0.974ᶜ	0.925ª	0.958ª
	Average Measures	0.925ª	0.961ᶜ	0.978ᶜ

The repeated measures ANOVA revealed significant differences in the mean ΔE between the first, second, and third colorimetry procedures and between each sample's first and third colorimetry procedures for each tool. The repeated measures analysis revealed a statistically significant effect of ΔE across measurement sessions, as evidenced by the multivariate tests: Pillai's Trace (0.978), Wilks' Lambda (0.022), Hotelling's Trace (45.109), and Roy's Largest Root (45.109), all with F (2, 106) = 177.3 and p < 0.001. These results indicate strong and consistent differences in ΔE between sessions (Table 5). However, Mauchly's Test of Sphericity (W = 0.776, p < 0.001) indicated a violation of the sphericity assumption, necessitating adjustments using Greenhouse-Geisser (ε = 0.817), Huynh-Feldt (ε = 0.817), and Lower-bound (ε = 0.5) corrections, which ensured the validity of the findings (Table 6).

Table 5 - Multivariate Tests for ΔE Across Repeated Measures

Effect	Value	F	Hypothesis df	Error df	p-value
ΔE					
Pillai's Trace	0.978	177.3	2	106	<0.001
Wilks' Lambda	0.022	177.3	2	106	<0.001
Hotelling's Trace	45.109	177.3	2	106	<0.001
Roy's Largest Root	45.109	177.3	2	106	<0.001

Table 6 - Mauchly's Test of Sphericity for ΔE

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	p-value	Epsilon (Greenhouse-Geisser)	Epsilon (Huynh-Feldt)	Epsilon (Lower-bound)
ΔE	0.776	199.312	2	<0.001	0.817	0.817	0.5

The tests of within-subjects effects confirmed significant mean differences in ΔE across sessions under all conditions: Sphericity Assumed, Greenhouse-Geisser, Huynh-Feldt, and Lower-bound, with F-values consistently at 255.069 and p < 0.001 (Table 7). Furthermore, within-subjects contrasts revealed a significant linear trend (F(1, 106) = 341.735, p < 0.001), indicating a progressive change in ΔE across measurements, alongside a significant quadratic trend (F(1, 106) = 127.369, p < 0.001), suggesting variability and a possible curvilinear relationship in ΔE patterns (Table 8).

The findings demonstrated statistically significant and interpretable differences in ΔE across measurement sessions. The observed linear and quadratic trends highlighted variability in reproducibility, which was probably influenced by the specific tools used. These results support the hypothesis that spectrophotometers and smartphone applications differ in reproducibility when comparing ΔE values across multiple sessions.

Table 7 - Tests of Within-Subjects Effects for ΔE

Source	Type III Sum of Squares	df	Mean Square	F	p-value
ΔE	71740.62	2	35870.31	255.069	<0.001
Greenhouse-Geisser	71740.62	1.634	43900.8	255.069	<0.001
Huynh-Feldt	71740.62	1.634	43892.93	255.069	<0.001
Lower-bound	71740.62	1	71740.62	255.069	<0.001
Error(ΔE)					
Sphericity Assumed	2211.256	106	20.867		
Greenhouse-Geisser	2211.256	86.832	25.47		
Huynh-Feldt	2211.256	86.92	25.426		
Lower-bound	2211.256	53	41.721		

Table 8 - Tests of Within-Subjects Contrasts for ΔE (Linear and Quadratic Trends)

Source	Type III Sum of Squares	df	Mean Square	F	p-value
ΔE Linear	70796.94	1	70796.94	341.735	0
Quadratic	943.684	1	943.684	127.369	0
Error(ΔE)					
Linear	1628.76	106	15.369		
Quadratic	582.496	106	5.494		

Discussion

The present study determined and compared the reproducibility of two colorimetry tools, Easyshade (Vita, Germany) and SP60 (X-rite, USA), and two smartphone colorimetry applications, Color Grab and Dental Shade Navigator. The results showed significant differences in the reproducibility of shade selection tools, indicating differences in their value. SP60 tool exhibited the highest reproducibility rate, followed by the Color Grab smartphone application. The Easyshade tool and the Dental Shade Navigator application had the lowest reproducibility. The results of the present study are comparable to similar previous studies; however, most previous studies have compared spectrophotometers, and only a limited number of them evaluated smartphone applications used for tooth shade selection procedures.

The most common method to match the tooth color with dental materials is visually comparing tooth shades with standard dental shade guides. When selecting shades in the clinic, several factors come into play. These include the physiological and psychological states of the operator, the use of certain medications, eye fatigue, and environmental lighting. All of these elements are crucial in achieving optimal results.[19] Technological advances and digital tools have decreased operator-related limitations for visual shade-matching procedures. Some studies have indicated that using digital and computerized tools for shade selection may be precise; however, they are unreliable and may not reflect the patient's opinion.[25, 26]

Hampé-Kautz et al.[27] showed that, generally, irrespective of the background color, Easyshade achieved higher values for all the color parameters than SP60. This outcome differs from the present study and might be attributed to the light gray color used as the background color. In contrast, in the present study, white was the selected background color. Notably, the SP60 spectrophotometer has no specialized application in dentistry, and its use in the clinic will be challenging due to the device's large volume and heavy weight and the difficulty in adjusting the tooth surface to the target window. In addition, the spectrophotometer evaluates a relatively large surface area for colorimetry (a circle with a diameter of 10 mm) and reports one shade for this large surface. The color of teeth varies at different points on their surfaces, and the surfaces themselves are not perfectly smooth. As a result, even a slight change in the angle between the device and the tooth surface can lead to inaccuracies in the light rays reflected from the tooth that reach the device's sensors. Thus, ensuring the accuracy and reproducibility of this method poses challenges in clinical applications.[28, 29]

Sala et al. [30] reported a reproducibility rate of 0.928 for the L* color parameter using the Easyshade spectrophotometer based on the ICC test. These results are almost consistent with the present study's findings, which used the same test. The ICC test results for the color parameters of a and b in the present study were slightly higher than those reported by Panagiotis et al., which may be attributed to the comparisons of the Easyshade spectrophotometer with the ShadeEye NCC device in that study.[31] In a study by Sarafianou et al.[32], the reproducibility results for the Easyshade device were reported as moderate to high. This is questionable because the device was used under a daylight lightbulb in their study, and the achieved values showed that this device did not have high reproducibility. This is consistent with the present study.[33]

Some previous investigations with contrasting results to the present study include: Kim-Pusateri et al.[34] with a reproducibility rate of 96% for Easyshade, Hampé-Kautz et al.[35] who introduced Easyshade as the best tool for colorimetry in terms of reproducibility, Hampé-Kautz et al.[36] with a reproducibility rate of >87% for Easyshade, and Sirintawat et al. These contrasts may be attributed to differences in study methods. In addition, according to a study by Tsiliagkou et al. [37], one of the reasons for the low reproducibility of the Easyshade device is its manual mechanism and a lack of stability and fixation during the study. In the present study, this device was used manually. It should be noted that the manual use of this tool will more closely reproduce clinical conditions.[38, 39]

In a study by Navneet et al. [40], the smartphone application Chrommatcher exhibited less reliability than the Easyshade device for tooth colorimetry. In addition, Sirintawat et al. [41] reported almost similar reproducibility of colorimetry after analyzing images taken by a smartphone and the Easyshade device. Since reproducibility rates between the two smartphone applications were different in the present study, it may be concluded that a general statement cannot be made about all the smartphone colorimetry applications. However, it can be argued that smartphone applications such as Color Grab (as shown in the present study) can be superior to commonly used spectrophotometers such as Easyshade. However, further studies are necessary for more definitive conclusions in this respect.[42, 43]

Studies by Jarad et al.[44] and Tam et al.[45] showed that digital cameras could be reliable tools for tooth colorimetry, that could be justified considering the year these studies were done, when high-quality cameras were not available in smartphones, and the current significant advancements in smartphone cameras. Furthermore, studies by Jorquera et al.[46] reported no significant difference in tooth colorimetry values between new generations of smartphones and digital cameras, and Tam et al.[45] reported that smartphones could be used for shade selection if proper calculations are used, even without changing their default conditions. Therefore, the results of the present study about smartphone applications are consistent with the above studies regarding the reproducibility of the Color Grab software that can be used in smartphones.[47, 48]

Mohammadi et al.[8] reported reproducibility rates of 98.88%, 100%, and 63.3% for Adobe Photoshop, Chrommatcher, and DTSR software programs, respectively, at a moderate to high level. The reproducibility of Color Grab software and Adobe Photoshop software, that are not designed for tooth colorimetry, were at an excellent level. In addition, the tooth colorimetry software Dental Shade Navigator exhibited lower reproducibility, indicating that colorimetry in dentistry is not as developed as digital photography and design, and the specialized software programs for tooth colorimetry have lower accuracy and efficacy than other colorimetry software programs. On the other hand, despite the advantages of general colorimetry software programs in terms of accuracy and accurate expression of color parameters in commonly used color systems, these pieces of software do not have the potential to show color in the commonly used color system in dentistry (such as the Vita Classic color system). This leads to difficulty for dental practitioners in using these programs. Therefore, there is still a software deficiency for accurate and efficient tooth colorimetry with smartphones.[8]

Conclusion

Shade determination is of utmost importance in tooth restorations to achieve esthetic outcomes. In the present study, comparisons of the samples' ΔE, a*, b*, and L* variables with four colorimetry tools showed that the SP60 spectrophotometer exhibited significantly higher reproducibility for all these variables. Evaluation of ΔE showed that the smartphone Color Grab application had higher reproducibility among the three other tools, and the Easyshade device had better reproducibility than the Dental Shade Navigator. Considering the limitations of the PS60 device in clinical applications, the smartphone Color Grab application is a better tool for tooth colorimetry reproducibility. The current study's findings indicated significant differences in the reproducibility of colorimetry devices, highlighting varying values and importance.

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Author Contributions:
M.R: Conceptualization, Methodology, Investigation, Writing – Original Draft and H.B.M: Methodology, Investigation, Writing – Original Draft and N.D.S: Methodology, Investigation, Writing – Original Draft and S.A: Methodology, Investigation.

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Informed Consent Statement: Our study was in-vitro and did not involve any human participants.

Data Availability Statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of Interest: No conflicts of interest to declare.

References

1. Ebeid K, Sabet A, Della Bona A. Accuracy and repeatability of different intraoral scanners on shade determination. J Esthet Restor Dent. doi: 10.1111/jerd.12687

2. Ragain J. A review of color science in dentistry: shade matching in the contemporary dental practice. J Dent Oral Disord Ther. 2016;4(2):1-5. doi: 10.15226/jdodt.2016.00156

3. Yuan K, Sun X, Wang F, Wang H, Chen J-h. In vitro and in vivo evaluations of three computer-aided shade matching instruments. Oper Dent. 2012;37(3):219-27. doi: 10.2341/11-230-c

4. Olms C, Setz JM. The repeatability of digital shade measurement—a clinical study. Clin Oral Investig. 2013 May;17(4):1161-6. doi: 10.1007/s00784-012-0796-z

5. Igiel C, Lehmann KM, Ghinea R, Weyhrauch M, Hangx Y, Scheller H, et al. Reliability of visual and instrumental color matching. J Esthet Restor Dent. 2017 Sep;29(5):303-308. doi: 10.1111/jerd.12321

6. Kalantari MH, Ghoraishian SA, Mohaghegh M. Evaluation of accuracy of shade selection using two spectrophotometer systems: Vita Easyshade and Degudent Shadepilot. Eur J Dent. 2017;11(2):196-200. doi: 10.4103/ejd.ejd_195_16

7. Chang J-Y, Chen W-C, Huang T-K, Wang J-C, Fu P-S, Chen J-H, et al. Evaluation of the accuracy and limitations of three tooth-color measuring machines. Journal of Dental Sciences. 2015;10(1):16-20. doi: 10.1016/j.jds.2013.04.004

8. Mohammadi A, Bakhtiari Z, Mighani F, Bakhtiari F. Validity and reliability of tooth color selection by smartphone photography and software applications. J Indian Prosthodont Soc. 2021 Jul-Sep;21(3):281-6. doi: 10.4103/jips.jips_193_21.

9. Tam W-K, Lee H-J. Accurate shade image matching by using a smartphone camera. J Prosthodont Res. 2017 Apr;61(2):168-76. doi: 10.1016/j.jpor.2016.07.004

10. Bergen SF, Paravina RD. Color Education and Training in Dentistry: A First-Hand Perspective. J Esthet Restor Dent. 2017;29(2):E3-5. doi: 10.1111/jerd.12294

11. Brewer JD, Wee A, Seghi R. Advances in color matching. Dent Clin North Am. 2004;48(2):v, 341-58. doi: 10.1016/j.cden.2004.01.004

12. Sorensen JA, Torres TJ. Improved color matching of metal-ceramic restorations. Part I: A systematic method for shade determination. J Prosthet Dent. 1987;58(2):133-9.doi: 10.1016/0022-3913(87)90163-6

13. Abu-Hossin S, Onbasi Y, Berger L, Troll F, Adler W, Wichmann M, Matta RE. Comparison of digital and visual tooth shade selection. Clin Exp Dent Res. 2023;9(2):368-374. doi: 10.1002/cre2.721

14. Tabatabaian F, Beyabanaki E, Alirezaei P, Epakchi S. Visual and digital tooth shade selection methods, related effective factors and conditions, and their accuracy and precision: A literature review. J Esthet Restor Dent. 2021;33(8):1084-104. doi: 10.1111/jerd.12816

15. Borse S, Chaware SH. Tooth shade analysis and selection in prosthodontics: A systematic review and meta-analysis. J Indian Prosthodont Soc. 2020;20(2):131-140. doi: 10.4103/jips.jips_399_19

16. Reyes J, Acosta P, Ventura D. Repeatability of the human eye compared to an intraoral scanner in dental shade matching. Heliyon. 2019 ;5(7):e02100. doi: 10.1016/j.heliyon.2019.e02100

17. Hardan L, Bourgi R, Cuevas-Suárez CE, Lukomska-Szymanska M, Monjarás-Ávila AJ, Zarow M, et al. Novel trends in dental color match using different shade selection methods: a systematic review and meta-analysis. Materials (Basel). 2022;15(2):468. doi: 10.3390/ma15020468

18. Pavlidis G. Chapter 3: A brief history of colour theory. In: A brief history of colour theory: Foundations of colour science. Cham (CH): Springer Nature; 2021. p. 60–72.

19. Chu SJ, Paravina RD, Sailer I, Mieleszko AJ. Chapter 6: Technology-based shade matching. In: Color in dentistry: A clinical guide to predictable esthetics. Hanover Park (IL): Quintessence Publishing; 2017. p. 54–70.

20. Magdy NM, Kola MZ, Alqahtani HH, Alqahtani MD, Alghmlas AS. Evaluation of surface roughness of different direct resin-based composites. J Int Soc Prev Community Dent. 2017 ;7(3):104-9. doi: 10.4103/jispcd.JISPCD_72_17

21. Gupta S, Sayed ME, Gupta B, Patel A, Mattoo K, Alotaibi NT, et al. Comparison of composite resin (Duo-Shade) shade guide with vita ceramic shades before and after chemical and autoclave sterilization. Medical Science Monitor: Med Sci Monit. 2023 30:29:e940949. doi: 10.12659/MSM.940949

22. Stawarczyk B, Schmid P, Roos M, Eichberger M, Schmidlin PR. Spectrophotometric evaluation of polyetheretherketone (PEEK)

as a core material and a comparison with gold standard core materials. Materials (Basel). 2016 ;9(6):491. doi: 10.3390/ma9060491

23. Nafea I, Alharbi A, Abduh A, Alharbi A, Moussa RM. Color shade matching by mobile applications in dental practice: An experimental comparative in-vitro double-blind study. The Saudi Dental Journal. 2019;31:S13. doi: 10.1016/j.sdentj.2019.02.006

24. Paravina RD, Ghinea R, Herrera LJ, Bona AD, Igiel C, Linninger M, Sakai M, Takahashi H, Tashkandi E, Mar Perez MD. Color difference thresholds in dentistry. J Esthet Restor Dent. 2015 :27 Suppl 1:S1-9. doi: 10.1111/jerd.12149

25. Berns RS. Chapter 6: Technology-based shade matching. In: Billmeyer and Saltzman's principles of color technology. 4th ed. Hoboken (NJ): John Wiley & Sons; 2019. p. 136-148.

26. Hilton TJ, Ferracane JL, Broome JC, Santos JD, Summitt JB. Chapter 4: Color and shade matching. In: Summitt's fundamentals of operative dentistry: A contemporary approach. 4th ed. Chicago (IL): Quintessence Publishing; 2013. p. 79–92.

27. Hampé-Kautz V, Salehi A, Senger B, Etienne O. A comparative in vivo study of new shade matching procedures. Int J Comput Dent. 2020 Jan 1;23(4):317-23.

28. Kim-Pusateri S, Brewer JD, Davis EL, Wee AG. Reliability and accuracy of four dental shade-matching devices. J Prosthet Dent. 2009;101(3):193-9. doi: 10.1016/S0022-3913(09)60028-7

29. Van der Burgt T, Ten Bosch J, Borsboom P, Kortsmit W. A comparison of new and conventional methods for quantification of tooth color. J Prosthet Dent. 1990;63(2):155-62. doi: 10.1016/0022-3913(90)90099-x

30. Sala L, Carrillo-de-Albornoz A, Martín C, Bascones-Martínez A. Factors involved in the spectrophotometric measurement of soft tissue: A clinical study of interrater and intrarater reliability. J Prosthet Dent. 2015;113(6):558-64. doi: 10.1016/j.prosdent.2014.11.003

31. Rosenstiel SF, Land MF, Walter R, editors. Chapter 23: Color, the color-replication process, and esthetics. In: Contemporary fixed prosthodontics. 6th ed. St. Louis (MO): Elsevier; 2022. p. 703–730.

32. Sarafianou A, Kamposiora P, Papavasiliou G, Goula H. Matching repeatability and interdevice agreement of 2 intraoral spectrophotometers. J Prosthet Dent. 2012;107(3):178-85. doi: 10.1016/S0022-3913(12)60053-5

33. Green P. Colorimetry and colour difference. Fundamentals and Applications of Colour Engineering. 2023 Oct 11:27-52. doi: 10.1002/9781119827214.ch2

34. Kim-Pusateri S, Brewer JD, Davis EL, Wee AG. Reliability and accuracy of four dental shade-matching devices. J Prosthet Dent. 2009;101(3):193-9. doi: 10.1016/S0022-3913(09)60028-7

35. Hampé-Kautz V, Roman T, Schwob T, Cournault B, Etienne O. In-vivo repeatability of three intra-oral spectrophotometers. J Esthet Restor Dent. 2024;36(3):520-6. doi: 10.1111/jerd.13182

36. Hampé-Kautz V, Salehi A, Senger B, Etienne O. A comparative in vivo study of new shade matching procedures. Int J Comput Dent. 2020;23(4):317-23.

37. Tsiliagkou A, Diamantopoulou S, Papazoglou E, Kakaboura A. Evaluation of reliability and validity of three dental color-matching devices. Int J Esthet Dent. 2016; 11 (1): 110-24.

38. Durmus D. CIELAB color space boundaries under theoretical spectra and 99 test color samples. Color Research & Application. 2020;45(5):796-802. doi: 10.1002/col.22521

39. Hunter RS, Harold RW. Chapter 13: Instruments for the geometric attributes of object appearance. In: The measurement of appearance. 2nd ed. New York (NY): John Wiley & Sons; 1987. p. 273–289.

40. Navneet PN, Sethi A, Garg N, Makkar S, Goel P. To Compare Different Methods of Shade Matching of Anterior Teeth for Color Evaluation. Ann Rom Soc Cell Biol. 2021;25(6):2674-9.

41. Sirintawat N, Leelaratrungruang T, Poovarodom P, Kiattavorncharoen S, Amornsettachai P. The accuracy and reliability of tooth shade selection using different instrumental techniques: An in vitro study. Sensors. 2021 Nov 11;21(22):7490. doi: 10.3390/s21227490

42. Tung FF, Goldstein GR, Jang S, Hittelman E. The repeatability of an intraoral dental colorimeter. J Prosthet Dent. 2002;88(6):585-90. doi: 10.1067/mpr.2002.129803

43. 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(1):82-92. doi: 10.1016/j.dental.2015.10.015

44. Jarad F, Russell M, Moss B. The use of digital imaging for colour matching and communication in restorative dentistry. Br Dent J . 2005;199(1):43-9; discussion 33. doi: 10.1038/sj.bdj.4812559

45. Tam W, Lee H. Dental shade matching using a digital camera. J Dent. 2012:40 Suppl 2:e3-10.doi: 10.1016/j.jdent.2012.06.004

46. Jorquera GJ, Atria PJ, Galán M, Feureisen J, Imbarak M, Kernitsky J, Cacciuttolo F, Hirata R, Sampaio CS. A comparison of ceramic crown color difference between different shade selection methods: visual, digital camera, and smartphone. J Prosthet Dent. 2022;128(4):784-792.doi: 10.1016/j.prosdent.2020.07.029

47. Paravina RD, Pérez MM, Ghinea R. Acceptability and perceptibility thresholds in dentistry: A comprehensive review of clinical and research applications. J Esthet Restor Dent. 2019;31(2):103-12. doi: 10.1111/jerd.12465

48. Sikri VK. Color: Implications in dentistry. J Conserv Dent. 2010;13(4):249-55. doi: 10.4103/0972-0707.73381