Accuracy of CEREC Shade Analysis and Lightroom-Based Photographic Evaluation Compared with a Spectrophotometer: A Pilot In Vivo Study

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Abstract

Background: Accurate shade determination is essential for achieving esthetic success in fixed restorations. Digital devices have been increasingly adopted for objective color evaluation, yet their reliability compared with spectrophotometry remains uncertain. ***Materials and Methods:*** This pilot in vivo study compared two digital shade-matching techniques—CEREC Shade Analysis and Lightroom-based photographic evaluation—with a spectrophotometric reference (Vita Easyshade Compact). Four healthy volunteers (80 teeth) were evaluated at the cervical, middle, and incisal thirds using Vita Classical, Vita 3D-Master, and CIELAB systems. Statistical comparisons were performed using the Wilcoxon Signed-Rank Test and Welch's t-test ($\alpha = 0.05$). ***Results:*** Significant differences were observed between the CEREC scanner and the spectrophotometer in all regions except the middle third of the Vita Classical system ($p = 0.76$). The scanner tended to overestimate luminosity. Lightroom-based analysis showed significant discrepancies in L* and a* ($p < 0.001$), while b* values were comparable ($p = 0.24$). ***Conclusions:*** Both digital methods demonstrated lower agreement with spectrophotometric measurements. CEREC overestimated lightness, and Lightroom underperformed in chromatic precision. Spectrophotometric verification remains essential for accurate shade selection in restorative dentistry.

Keywords: dental shade matching; spectrophotometer; intraoral scanner; digital photography; CIELAB color system; restorative dentistry

INTRODUCTION

The accurate perception of dental color remains a fundamental requirement in restorative and esthetic dentistry, as the visual integration of a prosthetic restoration with surrounding dentition is critical to patient satisfaction. Color is a visual sensation resulting from the interaction between incident light, the optical properties of enamel and dentin, and the observer's visual system. Light energy within the visible spectrum (approximately 380–760 nm) is selectively absorbed, transmitted, or reflected by tooth tissues, and the combination of these processes determines the perceived shade. Because enamel is highly translucent and dentin provides chroma, tooth color is governed not only by surface reflection but also by internal light scattering.

Accurate shade perception is influenced by three key categories of factors: (1) the physical characteristics of the light source, (2) the optical properties of the tooth structure, and (3) the physiological and psychological aspects of the human visual system [1]. Warm or cool illumination can shift the apparent hue, while the spectral composition of the light source affects metamerism—the phenomenon whereby two-color samples match under one lighting condition but not under another. Tooth shade also changes when enamel is dehydrated or when surrounding colors bias the clinician's adaptation. Thus, visual shade matching is error-prone even under ideal conditions.

Traditional shade selection relies on manual comparison with commercial shade guides such as Vita Classical or Vita 3D-Master. The Classical guide organizes shades primarily by hue and chroma, while the 3D-Master system improves perceptual uniformity by structuring the sequence according to value (luminosity) [2]. However, manual shade selection remains limited by observer fatigue, color vision variability, and illumination instability. Several procedural recommendations—such as performing shade selection before tooth dehydration, using neutral backgrounds, limiting viewing time to 5–7 seconds, and periodically resting the eyes on a complementary color—can enhance consistency, but they do not eliminate subjectivity.

In response to these limitations, objective color determination methods have been introduced. These include spectrophotometers, colorimeters, and digital imaging–based systems capable of translating color into CIELAB coordinates, thereby reducing inter-operator variability [3]. The CIELAB color space, standardized by the Commission Internationale de l'Éclairage (CIE 15:2018), remains the reference model for quantitative color evaluation in dentistry, allowing reproducible measurement and comparison of lightness (L*), chroma (a*), and hue (b*) components [4]. Clinical perceptibility and acceptability thresholds for color differences (ΔE00) have been established, with $\Delta E00 \leq 1.8$ generally regarded as clinically acceptable [5].

Digital photography has gained popularity because it allows calibrated shade documentation, remote consultation, and improved communication with dental laboratories [6]. However, its accuracy depends heavily on camera optics, lighting geometry, and post-processing workflow [7]. Spectrophotometers, by contrast, remain the reference standard for shade matching due to their controlled illumination and stable optical geometry [1].

More recently, shade-matching functions have been integrated into intraoral scanners as part of digital CAD/CAM workflows. These tools are attractive to clinicians as they combine impression-taking and shade selection into a single step, potentially streamlining restorative planning. However, despite their convenience, the color-determination accuracy of intraoral scanners remains inconsistent when compared directly with spectrophotometers [8–10]. A recent systematic review and meta-analysis concluded that intraoral scanners show

high repeatability, but lower trueness compared with spectrophotometers, emphasizing the need for standardization in calibration and lighting control [11–13].

Parallel to these developments, calibrated photographic workflows have emerged as an intermediate solution between fully objective and subjective shade matching. Systems such as eLAB integrate gray-card calibration and standardized white balance to extract CIELAB values directly from intraoral images, improving reproducibility in laboratory communication [14]. Nevertheless, even under standardized conditions, DSLR-based methods exhibit residual deviations due to flash angulation, sensor characteristics, and lighting variability, preventing full concordance with spectrophotometric results [15,16]. A 2022 systematic review confirmed that device variability and inconsistent calibration remain key limitations of photographic and scanner-based color systems [17].

Aim and objectives

Despite the expanding adoption of digital shade-matching technologies, few in vivo studies have directly compared the accuracy of intraoral scanner–based shade determination and calibrated photographic analysis under standardized illumination using spectrophotometry as the reference. Therefore, this pilot in vivo study aimed to compare the accuracy of dental color determination using CEREC Shade Analysis and Lightroom-based photographic evaluation against the Vita Easyshade Compact spectrophotometer. The null hypothesis (H_0) was that no statistically significant differences would be found between the spectrophotometric values and those obtained using either digital method.

MATERIAL AND METHODS

1. Study design and participants

This prospective pilot in vivo study evaluated the accuracy of two digital shade-matching techniques compared with a spectrophotometric reference method. Ethical approval was obtained from the Research Ethics Committee of the "Carol Davila" University of Medicine and Pharmacy, Bucharest (approval no. 146/2024). Written informed consent was obtained from all participants prior to inclusion, in accordance with the Declaration of Helsinki.

Four healthy adult volunteers (mean age 24 years; two males and two females) were enrolled. For each participant, at least ten intact anterior and premolar teeth from both arches were evaluated, yielding a total of 80 teeth.

Inclusion criteria: (a) intact buccal enamel surfaces; (b) absence of discoloration; (c) no previous restorations in the evaluated area. **Exclusion criteria:** (a) presence of carious lesions or restorations; (b) orthodontic appliances on the buccal surface; (c) inability to obtain standardized photographs.

2. Overview of the three tested shade-matching methods

Three shade-matching techniques were evaluated in this study. The spectrophotometer (Vita Easyshade Compact, VITA Zahnfabrik, Bad Säckingen, Germany) served as the reference method due to its controlled illumination and proven reliability in CIELAB-based measurements [3,4]. The CEREC Primescan intraoral scanner (Dentsply Sirona, Bensheim, Germany) was assessed as a digital chairside solution integrating shade analysis into CAD/CAM workflows. The third method consisted of standardized digital photography with subsequent CIELAB extraction in Adobe Lightroom, representing a calibrated photographic color analysis workflow [3,6,7]. All three methods were applied to the same teeth, in the same regions (cervical, middle, and incisal thirds), under standardized clinical conditions.

a. Reference method: spectrophotometric color determination

Shade determination was performed using the Vita Easyshade Compact spectrophotometer. The device was calibrated before each session according to the manufacturer's protocol. For each tooth, measurements were recorded separately for the cervical, middle, and incisal thirds (figure 1). Two consecutive readings were taken per site, and mean values were registered. Results were expressed in Vita Classical, Vita 3D-Master, and CIELAB systems, according to the CIE 15:2018 standard [4].

Figure 1. a. - Study workflow and shade-matching protocol. b. Dental shade matching in Vita Classical

b. Test method 1: Intraoral scanning with CEREC Primescan

Digital scans were performed using the CEREC Primescan (Dentsply Sirona, Bensheim, Germany) under standardized illumination (5,500 K; color rendering index ≥ 93). The "Shade Analysis" function in CEREC Software (version 5.2) was used to determine shade values directly on the 3D model. The sampling circle diameter was set to 1.7 mm and positioned on the cervical, middle, and incisal thirds of each tooth (figure 1). Shade values were recorded using both Vita Classical and Vita 3D-Master systems.

c. Test method 2: Digital photography and Lightroom analysis

Standardized photographs were captured using a Canon EOS 6D DSLR with a 100 mm f/2.8 macro lens and twin macro flashes (Canon MT-24EX). Camera settings were ISO 100, f/22, and 1/125 s. A neutral 18% gray calibration card (X-Rite ColorChecker) was placed in each frame for white balance correction. Soft-tissue retractors were used to ensure unobstructed visualization. Six calibrated photographs were obtained per participant (three maxillary and three mandibular) (figure 2).

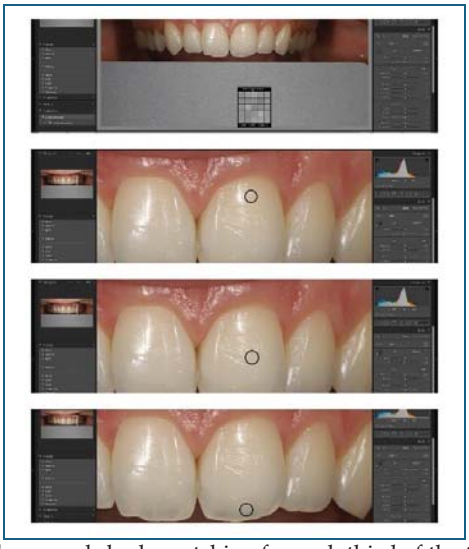

Figure 2. Setting the white balance and shade matching for each third of the tooth using Adobe Lightroom

Images were imported into Adobe Lightroom Classic (v.10). A custom white balance was set using the gray card, following standardized clinical photographic calibration protocols [6,7,14]. The color sampler tool was placed sequentially on the cervical, middle, and incisal thirds to extract CIELAB values for each region.

3. Data transformation and color difference calculation

The goal was to compare the results from the CEREC software (test method 2) and digital image analysis with Adobe Lightroom (test method 3) against those from the Vita Easyshade spectrophotometer (reference method).

For the comparison between the spectrophotometer (reference) and the CEREC system (test), the color values from both Vita Classical and Vita 3D Master shade guides were arranged in descending order based on their luminosity parameter. To ease statistical analysis and direct comparison, each dental color was then assigned a numerical value according to established literature methodologies [16] (tables 1 and 2), enabling a quantitative correlation between the spectrophotometer and CEREC software readings.

Table 1. Descending arrangement of the Vita Classical shade guide based on luminosity parameter [16]

B1	A1	B2	D2	A2	C1	C2	D4	A3	D3	B3	A3,5	B4	C3	A4	C4
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Table 2. Descending arrangement of the Vita 3D Master shade guide based on luminosity parameter [16]

0M1			2M1			3M1			4M1		5M1
0M2	1M1	2L1.5	2M2	2R1.5	3L1.5	3M2	3R1.5	4L1.5	4M2	4R1.5	5M2
0M3	1M2	2L2.5	2M3	2R2.5	3L2.5	3M3	3R2.5	4L2.5	4M3	4R2.5	5M3
1			6			13			20		27
2	4	7	8	9	14	15	16	21	22	23	28
3	5	10	11	12	17	18	19	24	25	26	29

For the comparison between the spectrophotometer and the Lightroom-based photographic method, all color readings were expressed in the CIELAB system, and color differences (ΔE_{00}) were calculated using the CIEDE2000 formula [17] for each tooth third. A threshold of $\Delta E_{00} \leq 1.8$ was used to indicate clinically acceptable agreement between the two methods, whereas ΔE_{00} values above this threshold were interpreted as lack of concordance [5].

4. **Statistical analysis**

Statistical analysis was carried out in two stages according to the nature of the comparison performed. First, the spectrophotometer (reference method) was compared with the intraoral scanner for both Vita Classical and Vita 3D-Master shade systems. Since the data consisted of paired ordinal values derived from shade tab ranking, the Wilcoxon Signed-Rank Test was used to assess whether paired measurements differed significantly [18]. The null hypothesis (H_0) stated that the spectrophotometer and the intraoral scanner would generate similar shade values, while the alternative hypothesis (H_1) stated that they would differ. Statistical significance was set at $\alpha = 0.05$.

In the second stage, the spectrophotometer was compared with the Lightroom-based photographic method. All color readings were expressed in the CIELAB system, and color differences (ΔE_{00}) were calculated as described above [17]. To determine whether the two methods produced statistically similar L*, a*, and b* values, an independent-samples t-test with unequal variance (Welch correction) was applied. The null hypothesis (H_0) stated that no difference would exist between the chromatic parameters obtained from the spectrophotometer and those derived from the photographic analysis; the alternative

hypothesis (H_1) stated that at least one parameter would differ. Statistical significance was set at $\alpha = 0.05$.

All statistical analyses were performed using IBM SPSS Statistics, version 27 (IBM Corp., Armonk, NY, USA).

RESULTS

3.1. Spectrophotometer versus CEREC shade analysis

Statistically significant differences were observed between the spectrophotometer and the CEREC scanner in most evaluated regions. For the Vita Classical system, significant discrepancies were found in the cervical and incisal thirds, while the middle third showed no statistically significant difference. For the Vita 3D-Master system, all three regions exhibited statistically significant deviations. In each case of significant difference, CEREC tended to report a higher value (lighter) shade compared with the reference method (table 3).

Table 3. Wilcoxon Signed-Rank Test results for Spectrophotometer vs CEREC (detailed per anatomical region and shade system)

Anatomical third	Vita Classical (p-value)	Direction of deviation	Vita 3D-Master (p-value)	Direction of deviation
Cervical	0.01	Higher value (lighter)	0.01	Higher value (lighter)
Middle	0.76	No significant shift	0.02	Higher value (lighter)
Incisal	0.00	Higher value (lighter)	0.00	Higher value (lighter)

Significance level $\alpha = 0.05$.

3.2. Spectrophotometer versus Lightroom (CIELAB comparison)

When comparing the spectrophotometer with Lightroom-based digital analysis, statistically significant differences were identified for L* and a* values across most regions, indicating deviations in lightness and chroma. The b* component demonstrated closer correspondence but did not fully compensate for the mismatch. These findings indicate that Lightroom under calibrated photographic conditions did not replicate the spectrophotometric color profile with sufficient precision. The detailed mean values and corresponding p-values are presented in table 4.

Table 4. Comparison of mean CIELAB values between spectrophotometer and lightroom (raw means ± sd, per anatomical region)

Anatomical Third	Parameter	Spectrophotometer (Mean ± SD)	Lightroom (Mean ± SD)	p-value
Cervical	L*	82.4 ± 2.1	80.1 ± 2.5	0.01
	a*	2.9 ± 0.6	1.8 ± 0.7	0.02
	b*	17.4 ± 1.3	17.0 ± 1.5	0.24
Middle	L*	84.1 ± 1.9	81.7 ± 2.3	0.00
	a*	2.4 ± 0.5	1.6 ± 0.6	0.01
	b*	15.9 ± 1.2	15.6 ± 1.4	0.28
Incisal	L*	86.8 ± 2.0	84.2 ± 2.3	0.00
	a*	1.8 ± 0.4	1.2 ± 0.5	0.01
	b*	13.1 ± 1.1	12.9 ± 1.3	0.30

Significance level $\alpha = 0.05$.

3.3. ΔE2000 (CIEDE2000) color difference analysis

ΔE00 analysis revealed that Lightroom-based measurements exceeded the 1.8 acceptability threshold in all three anatomical regions for both shade systems. The deviations were classified as perceptible or clearly perceptible, in accordance with color difference

interpretive conventions. The highest discrepancies occurred in the incisal third, reflecting scanner and photographic limitations in low-chroma and highly translucent enamel (table 5).

Table 5. ΔE2000 (CIEDE2000) values per anatomical region and shade guide system, with graded interpretive categories

Anatomical third	Vita Classical ΔE00 (range)	Interpretation	Vita 3D-Master ΔE00 (range)	Interpretation
Cervical	1.9 – 2.6	Perceptible	2.1 – 3.1	Clearly perceptible
Middle	1.8 – 2.4	Perceptible	2.0 – 2.8	Clearly perceptible
Incisal	2.3 – 3.4	Clearly perceptible	2.6 – 3.9	Clearly to highly perceptible

Threshold of clinical acceptability = ΔE00 ≤ 1.8.

DISCUSSIONS

The present pilot in vivo study compared three shade-matching approaches—spectrophotometry, intraoral scanner–based shade determination, and calibrated digital photography—and found substantial inconsistencies between the digital methods and the spectrophotometric reference standard. These findings reinforce the current understanding that, although digital workflows are increasingly integrated into restorative dentistry, objective shade measurement remains highly dependent on the optical reliability of the instrument and the standardization of acquisition protocols [1-3, 8-10].

The results showed that the CEREC Primescan consistently produced higher value (lighter) readings than the spectrophotometer, particularly in the cervical and incisal regions. This is consistent with several in vivo investigations reporting that intraoral scanners tend to overestimate luminosity due to reflective light scatter at the enamel surface and limitations in internal compensation algorithms [19,20]. The significant deviations in the 3D-Master system across all thirds further confirm that current integrated scanner-based shade estimation modules are not yet optimized for the full range of clinically relevant chromatic variation, particularly in high-translucency regions. Similar conclusions were drawn by Kim et al. (2022), who demonstrated that scanner-based shade capture differed significantly from spectrophotometry in anterior teeth due to inadequate correction for enamel translucency and ambient reflectivity [21].

The Lightroom-based workflow produced closer agreement than the scanner in terms of b* values but failed to achieve $\Delta E_{00} \leq 1.8$ in any anatomical region. This supports findings from recent digital photography studies showing that, even with standardized white balance calibration, image-based shade extraction remains susceptible to residual variability in light intensity, flash angulation, and sensor–lens characteristics [7]. A consecutive comparison by Lagouvardos et al. (2021) also confirmed that camera-based CIELAB estimation rarely replicates spectrophotometric output without advanced color compensation profiles [14]. The present findings therefore substantiate that calibrated photography may be a useful adjunctive documentation and communication tool but cannot yet replace spectrophotometric verification in shade determination [3,6,7].

The magnitude of ΔE_{00} deviation—ranging from perceptible to clearly perceptible—indicates that the observed mismatches are not only statistically significant but also clinically visible, especially in the incisal third, where translucency amplifies metameric behaviour. These findings echo the conclusions of Gómez-Polo et al. (2017), who reported that translucency gradients in enamel are the most frequent source of mismatch between instrumental methods [22]. Similarly, Dozić and colleagues highlighted that the cervical third is more dentin-dominant and therefore less prone to scanner error than the incisal zone, where enamel acts as an optical filter rather than a diffuser [23].

An additional consideration is the difference in measurement geometry across instruments. Spectrophotometers employ structured illumination and fixed detection geometry, whereas scanners and DSLR systems are influenced by ambient reflection and surface gloss. This geometric variation explains why objective digital methods cannot be assumed to be interchangeable without cross-validation. A 2023 systematic review by Prado-Ribeiro et al. concluded that optical geometry remains a fundamental limitation of integrated shade-matching modules in current-generation scanners [24].

The present findings also align with recent AI-based analyses suggesting that future improvements in scanner accuracy will likely depend on spectral modelling algorithms rather than hardware miniaturization [25]. Likewise, refined photographic methods—such as cross-polarized illumination and multi-point calibration profiles—have been shown to enhance CIELAB stability and could represent a gateway to clinically acceptable camera-based shade analytics [26].

Taken together, our results highlight a persistent performance gap between reference-grade spectrophotometry and more accessible digital systems. While scanners and photographic workflows facilitate convenience and integration into digital dentistry, the accuracy required for final shade matching still necessitates spectrophotometric confirmation, particularly for esthetically critical anterior restorations. These outcomes should be interpreted in light of the study's pilot design and small sample size, but they nevertheless provide clinically relevant evidence supporting the continued role of spectrophotometry as the benchmark tool [1–3,8–10,24].

Limitations and clinical implications

This study has several limitations that should be considered when interpreting the findings. First, the sample size was small and limited to four participants, which restricts the generalizability of the results and does not account for population-level variability in enamel thickness, dentin hue, and age-related changes in optical properties. Second, only anterior and premolar teeth with intact buccal surfaces were included, which may not reflect shade-matching performance in posterior teeth or in clinically complex cases such as discolored substrates or restorations [22,23].

Third, although all photographic measurements were calibrated using an 18% gray reference, the digital photography method may still have been influenced by residual lighting geometry effects and sensor-based color compression, which are not fully standardized across camera systems [7,14–16,26]. In addition, the study evaluated a single intraoral scanner model and software version; therefore, the findings cannot be extrapolated to all scanner platforms [19–21,24,25].

Finally, this investigation was designed as a pilot study, and no power analysis was conducted to predetermine sample size. Further research with larger cohorts, multiple scanner systems, and enhanced photographic calibration protocols is required to confirm and extend these results [17,24-26].

From a practical standpoint, clinicians should interpret intraoral scanner and photographic shade readings as preliminary indicators rather than definitive measurements. Combining these technologies with spectrophotometric verification remains essential for achieving consistent color reproduction in esthetic zones.

Future perspectives

Future developments in digital shade matching are expected to focus on overcoming the limitations identified in this study by improving both hardware and computational modelling. Intraoral scanners will likely require enhanced spectral acquisition and machine-learning–based correction algorithms capable of compensating for enamel translucency and optical geometry, reducing the systematic luminosity bias observed in this and other studies. Moreover, the integration of cross-polarized illumination and standardized spectral light

sources directly into scanner optics may narrow the gap between chairside systems and spectrophotometry.

In digital photography, there is some really exciting work being done on color calibration, flash systems and AI-assisted tonal mapping. This work could help to get the color of a scene right using a digital camera, even in difficult lighting conditions. These innovations, combined with automated color checking, could allow photographers to quickly select photos and then check their color using a spectrophotometer.

Future research on this particular topic should include a larger number of patients of all ages, as well as posterior teeth and teeth that have become discolored over time. This would help to check how well the method works in real-world dental repair situations. It would also be a good idea to compare different scanner types and software versions, as well as to test how cross-polarization and camera sensor type affect the reproducibility of CIELAB results.

CONCLUSIONS

Within the limitations of this pilot in vivo study, both CEREC Shade Analysis and Lightroom-based photographic evaluation demonstrated significantly lower agreement with spectrophotometric measurements across multiple tooth regions and shade systems. The intraoral scanner exhibited a systematic tendency toward lighter value readings, while the photographic method failed to reach clinically acceptable ΔE00 thresholds, particularly in the incisal third where translucency is greatest. These findings confirm that current digital shade-matching technologies, although useful as supplementary tools, cannot yet replace spectrophotometric verification for definitive color selection in restorative dentistry. Spectrophotometry remains the most reliable method for accurate shade determination, especially in esthetically demanding anterior cases.

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Conflicts of Interest

The authors declare no conflict of interest.

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