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ORIGINAL ARTICLE

The accuracies of three intraoral scanners with regard to shade determination: An in vitro study

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Abstract

Purpose: To compare the accuracies of three intraoral scanners for shade determination function in vitro, and to preliminarily investigate the shade-matching characteristics of the three intraoral scanners.

Materials and Methods: The shade of the middle third region of each shade tab on the Vita Classical A1-D4 shade guide (VC) was measured with a spectrophotometer (Vita Easyshade V, VE) and three intraoral scanners, including CEREC Omnicam (OM), 3Shape TRIOS 3 (T3), and TRIOS 4 (T4). A conversion table between VC values and CIELAB values was established from the database of VE to analyze the trueness. The reproducibility of the instruments was then compared by repeating the measurements five times.

Results: The mean color difference for each instrument was highest in the OM, followed by the T4, and lowest in the T3 and VE, respectively. The L* and a* value for OM, and the b* value for T4, were significantly different from those for VE ($p < 0.05$). The reproducibility of the instrument was highest in the VE (Fleiss' kappa: 0.95), followed by the T3 (Fleiss' kappa: 0.89), T4 (Fleiss' kappa: 0.87), and OM (Fleiss' kappa: 0.78).

Conclusions: Of the three intraoral scanners, the trueness was best on the T3. The reproducibility of all the instruments was excellent.

KEYWORDS
intraoral scanner, shade guide, shade matching, spectrophotometer

Determining the colors, arrangements, positions, proportions, shapes, and morphologies of teeth are significant components of esthetic dentistry.[1] Nowadays, with the help of computer-aided technology, it is very easy to provide two-dimensional, three-dimensional (3D), and even four-dimensional simulations of restorative esthetic outcomes.[2,3] However, unmatched colors will still lead to dissatisfaction. Prior to fabricating a restoration, it is important to make an accurate shade determination.[4]

Visual and instrumental methods are commonly applied for tooth shade matching.[5] The visual method is used to select the best color match for a target tooth and is performed by comparing it to a commercial shade guide. The Vita classical A1-D4 shade guide (Vita Zahnfabrik, Bad Säckingen, Germany) and the Vita System 3D-Master shade guide are the most widespread systems used for the visual determination of tooth color.[6,7] Several instruments can be used, including spectrophotometers, colorimeters, spectroradiometers, digital cameras, and imaging systems.[5] Spectrophotometers are currently thought to be one of the most accurate, useful, and flexible instruments for the determination of color and are usually taken as the reference device in color research.[8,9] Furthermore, some intraoral scanners (IOSs) have been developed that feature modules to determine tooth color, including the 3Shape TRIOS (3Shape A/S, Copenhagen, Denmark), the CEREC Omnicam (Sirona Dental Systems, Bensheim, Germany), and the CEREC Primescan.[10,11] These powder-free IOS systems can obtain 3D intraoral information and create a photorealistic copy of tooth color, thus simplifying the workflow for color matching and providing a highly efficient and convenient tool for dentists and technicians.[12]

The color difference between two specimens can be calculated using the CIELAB color scale; this was proposed by the International Commission on Illumination (Commission Internationale de l'Eclairage, CIE).[13] This color system defines a specific color by three coordinates: L*, a*, and b*. The coordinate L* is related to lightness (0 = pure black, 100 = pure white), while the coordinates a* and b* are, respectively, related to chromatic characteristics on the red-green axis (+a = redness, −a = greenness) and the yellow-blue axis (+b = yellowness, −b = blueness).[12] ΔE^*_{ab} refers to the Euclidian color difference between the two specimens in the CIELAB system and is calculated by the CIE76 formula $\Delta E^*_{ab} = [\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}]^{1/2}$, which is frequently used in dentistry to quantify dental color, has been used in the majority of published dental research.[8,14–17] The larger the color difference, the more perceptible the difference to the human eye.[18] According to the previous research,[7,8,16,19–22] the clinically acceptable color difference for a tooth is $\Delta E<6.8$, and the perceptible color difference for a tooth is $\Delta E<3.7$.

Most published research on the performance of IOSs has focused on the digital scan accuracy based on the obtained standard tessellation language (STL) files. The scanning accuracy can be affected by the IOS selected, surface characteristics, scanning angle or protocols, the reconstruction and rendering methods used, and the operator's experience.[23–30] Previous evaluations of the shade-determination capability of different IOSs have varied widely,[7,8,10–12,16,31–33] and the lighting conditions at which the digital scans were performed were not reported, which have been recently identified as a significant factor that can influence the scanning accuracy. According to Revilla-León et al,[34–37] the light illuminance conditions can not only influence the mesh quality and accuracy of the digital impression, but also impact the shade-matching capability of the IOSs. Based on the recommendation of the European Committee for Standardization (EN 12464-1:2021), the ambient light for medical or examination rooms should be at least 1000 lx.[38] Consequently, the present study's lighting condition at which the scans were performed was set similar to clinical practice.

The aim of this study was to compare the trueness and reproducibility of three different IOS systems (CEREC Omnicam, 3Shape TRIOS 3, and 3Shape TRIOS 4) for the shade determination function in vitro, while a spectrophotometer (Vita Easyshade V) was taken as the comparison, and to preliminarily investigate the shade-matching characteristics of the three different IOSs. The null hypothesis was that no significant difference would be identified in terms of the trueness and reproducibility of color matching when compared between the instruments.

MATERIALS AND METHODS

All measurements in the study were conducted in the same enclosed room with no windows or natural light. The ceiling lighting in the room was standardized daylight lamps with a color temperature of 6500 K (TL-D Graphica 965 Philips, Amsterdam, Netherlands). The ambient light illuminance of the room was 1010 lux, which was measured by using a light meter (DLY-1802 Light Meter, Delixi, Zhejiang, China).[16,31,38] The 16 shade tabs of one Vita Classical A1-D4 shade guide were used as a specimen; the middle third region of each tab was measured.[8] All the measurements were recorded by the same trained dentist (H.M.M.) with 3 years of experience using IOSs and the dental spectrophotometer.

Instrumental shade matching

The 3Shape TRIOS 3 (T3) and the TRIOS 4 (T4)

Both of the TRIOS scanners were calibrated following the manufacturers' recommendations every time before the measurements were made. The TRIOS system can monitor the quality of the color data acquired real time by the built-in shade function, so that with its instructions, the target area can be scanned from different angles in-time to remove blue marks, thus avoiding stitching errors and completing the color information.[12,39,40] When scanning was completed, the color measurement mode in the software of the TRIOS system was applied to make the shade selection on the middle third of the digital impression of the shade tab. The T3 and T4 were used for scanning and color matching in the same procedure (Fig 1). Instrumental color determination by each IOS was repeated five times. The measurement results for the two IOSs in terms of VC values were recorded as the T3 group and T4 group, respectively.

CEREC Omnicam (Version 4.5.2, OM)

According to the manufacturer's instructions, the OM was previously calibrated every time. The specimen was scanned from different angles and the margin of it was scanned to avoid stitching errors and obtain complete color information.[40,41] After scanning, the Analyzing Tool in the software was applied to check whether the color information was obtained completely and to determine the shade for the middle third of the digital impression of the specimen (Fig 2). Measurements acquired from the OM were repeated

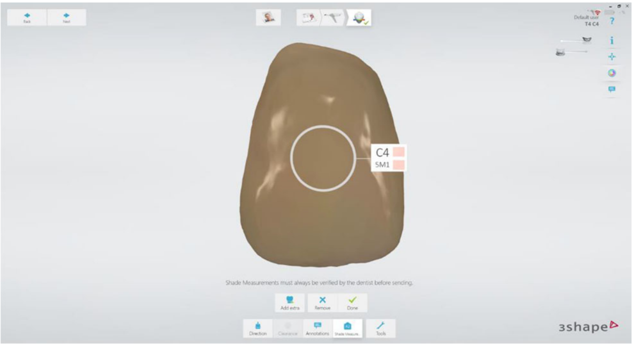

FIGURE 1 Screenshot of the digital scans completed by the 3Shape TRIOS 4 with color matching performed in the middle third of the C4 shade tab with reference to the Vita classical A1-D4 and Vita System 3D-Master shade guide values

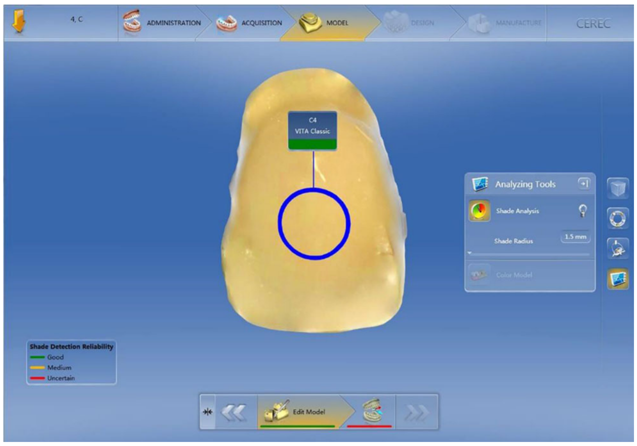

FIGURE 2 Screenshot of digital scans completed by the CEREC Omnicam with color matching performed in the middle third of the C4 shade tab with reference to the Vita classical A1-D4 shade guide value

five times to compare consistency. The measurement data were recorded as the OM group in terms of VC values.

Vita Easyshade V (VE)

According to the manufacturer's instructions, the VE was placed in its charging station so that the tip could lie flush on the calibration block to carry out white balance before using. When calibration was complete, the VE was set up to the base shade determination mode and the measuring tip was positioned in close contact with the shade tab surface to measure the middle site. The measurement results were displayed by VC values and recorded as the VE group.

Data processing

In the three IOS groups, the VC values were recorded and translated into CIELAB values by one-to-one mapping using a lookup table for further analysis.[8,12,42,43] This conversion table was established previously from the database of VE (Table 1).

Statistical analysis

The mean L*, a*, and b* values for each site measured by each instrument were calculated. The color difference (ΔE) between the mean L*, a*, and b* values of each group and the reference L*, a*, and b* values in the conversion table for each site was calculated by using the CIE76 formula $\Delta E^*_{ab} = [\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}]^{1/2}$. The Shapiro-Wilk test was used to assess the normality of the distribution of quantitative variables (L*, a*, b*, and ΔE values). Friedman's test and the Bonferroni test were also used for multiple comparisons since the L*, a*, b*, and ΔE values were not distributed normally. The calibration value of the shade guide itself and the measuring value given by the instruments was directly compared to calculate the overall accuracy rate of each group. Then, Pearson chi-square test followed by multiple comparisons using Bonferroni tests was used to assess the accuracy differences among the devices. The statistical significance level was 0.05. Fleiss' kappa statistical test for multiple measurements was used to assess the reproducibility of each method. Statistical analysis was performed using SPSS software (SPSS Statistics 26, IBM, New York, USA).

RESULTS

Mean L*, a*, and b* values for the 16 sites, as measured by the four devices, are provided graphically as box-and-whisker plots in Figure 3. The OM system produced lower L* values than the T3, T4, and VE ($p = 0.019$, $p = 0.037$, $p = 0.005$). With regard to a* values, the OM system yielded higher values than T3, T4, and VE ($p = 0.003$, $p < 0.001$, $p = 0.010$). The T4 system yielded lower b* values than the OM and VE ($p < 0.001$, $p = 0.019$). The T3 system also yielded lower b* values than the OM ($p = 0.030$). The median ΔE for each group (from low to high) was VE (0), T3 (0), T4 (3.4), and OM (5); the ΔE for the OM system was significantly higher than that for VE and T3 ($p = 0.001$, $p = 0.005$). There were no significant differences among VE, T3, and T4 with regard to ΔE. The overall accuracy rate of each group ranked in order from high to low was VE (75%), T3 (72.5%) > T4 (35%) > OM (15%) ($p < 0.001$). The reproducibility of the instruments (from high to low) was as follows: VE (Fleiss' kappa: 0.95), T3 (Fleiss' kappa value of 0.89), T4 (Fleiss' kappa value of 0.87), and OM (Fleiss' kappa value of 0.78).

DISCUSSION

In this research, it was found that the VE and T3 for color determination were better than the T4 and OM. Therefore, the null hypothesis for this study was rejected because significant differences were detected in terms of accuracy between the tested instruments.

TABLE 1 Conversion table: L*, a*, and b* values for all shade tabs in the Vita classical A1-D4 shade guide taken from the Vita Easyshade V database

	A1	A2	A3	A3.5	A4	B1	B2	B3	B4	C1	C2	C3	C4	D2	D3	D4
L*	82	77.7	75.5	73.2	69	86	78.5	74	72	73	72	69	61	73	72.5	65
a*	−0.7	0	0.8	1.9	2.5	−1	−0.3	1	1.6	−0.2	0	1	2.7	0.2	0.8	0.3
b*	13	18.5	22.5	26.9	23.9	12	16	22	26.5	13.5	17	19.5	22.3	14.3	19.3	20

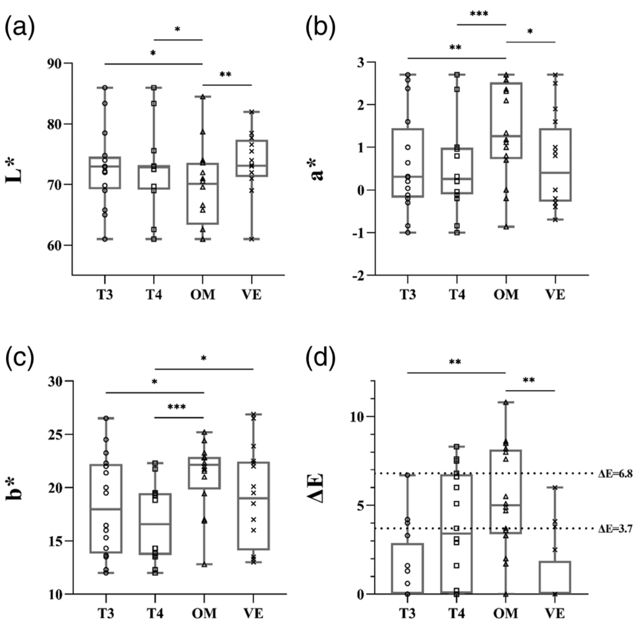

FIGURE 3 Box-and-whisker plots for the CIELAB values with the TRIOS 3 (T3), TRIOS 4 (T4), Omnicam (OM), and Vita Easyshade (VE) for the five repeated measurements (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). (a) L* values. (b) a* values. (c) b* values. (d) ΔE values

In the present study, all the VC values were translated to CIELAB values, which were numerical variables, by applying a conversion table. There was no significant difference between the L*, a*, and b* values for the T3 and VE systems; the b* value of the T4 was significantly lower than the VE, implying a more bluish hue. For the OM, the L* value was significantly lower than the T3, T4, and VE, implying a darker color; the a* value was significantly more positive than the T3, T4, and VE, implying a more reddish hue; and the b* value was significantly more positive than the T3 and T4, thus implying a more yellowish hue.[16] In addition, when analyzing the ΔE of each group, it was highest in the OM, followed by the T4, then the T3 and VE. The T3 indicated satisfying similarity to the VE. Besides the above statistical analysis based on the same lookup table to translate the specific VC shade number, the Pearson chi-square test was also used to facilitate the analysis of accuracy. And in this research, the best performance was detected for the trueness rate of VE (75%) and T3 (72.5%), followed by T4 (35%) and OM (15%). Therefore, the T3 system showed the best trueness among the three IOS systems.

With regard to reproducibility, Fleiss' kappa values ranged from 0.20 to 0.40 (fair), 0.40 to 0.75 (intermediate to good), and above 0.75 (excellent).[44] Therefore, the reproducibility of all the devices was excellent.

Spectrophotometers work by measuring the amount of light energy reflected from an object at 1-25 nm intervals along the visible spectrum and by converting the measured spectral reflectance to color coordinates and various dental shade guide values.[5,45] The 3Shape TRIOS works by employing photographic system and specialist technology referred to as ultrafast optical sectioning; this combines confocal microscopy with the projection of structured light. The CEREC Omnicam works by employing video-based raster scanning technology and active triangulation technology to calculate the position of the target object.[10,12,34,46–48]

When using the T3, T4, and OM, only shade guide values can be directly exported as the measuring outcome for clinical use; these systems cannot report color information via the color notation system of the International Commission on Illumination. In the present study, a one-to-one mapping table from the VE database was used to quantify the specific VC shade number to numerical variables (CIELAB values) for further analysis.[14,49,50] However, since this lookup table was created in a manner that was dependent on the VE's spectrophotometric system, it did not reflect the accuracy and data conversion of other colorimetric systems.[8,16] Although in the present study, to some extent, using the same table may help to compare the measurement differences of the three IOSs and VE within the same system.[12] Furthermore, the manufacturers of all three IOSs have not revealed the internal principles used for color scanning, acquisition, conversion, and display. And the manufacturers of the VC shade guide have not revealed the parameters used for each shade tab either; therefore, the full details involved in data conversion cannot be known. If the principles underlying how these IOSs work can be revealed, and more detail for certain key parameters can be provided, not only the shade guide values, this would be a significant asset for research focused on the shade-matching capabilities of IOS systems.

Revilla-León et al[34–37] reported a higher scanning accuracy and mesh quality under room lighting conditions (about 1000 lx) using the TRIOS 3. The lighting conditions at which the digital scans were performed were not detailed and emphasized in most published research on the shade-determination capability of the IOSs. Another clinical investigation by Revilla-León et al[33] focused on the shade-matching ability of TRIOS 3 and Vita Easyshade V under different ambient light illuminance conditions, and the results showed that ambient light illuminance conditions can significantly influence the shade-matching capability of TRIOS 3, with a high variability and low consistency, while the spectrophotometer demonstrated high consistency among the different lighting conditions. Admittedly, there is no common optimal lighting condition for different IOSs. And it seems that recommended lighting conditions may vary depending on the purpose of the digital scan performed.[33–37] Furthermore, different illuminance conditions have been recommended for a private practice environment. Recommendations are 500 lx for general illumination, 1000 lx for medical or examination rooms, and 10,000 lx for operating within the intraoral cavity.[33,38,51] Considering the clinical use of the IOS, and in order to better incorporate the IOS in restorative workflows,[12,52] it is hoped that the color-determination function can be applied with excellent scanning accuracy and mesh quality, thus providing a new and reliable digital tool to assess tooth color. For the above reasons, the ambient illumination of this study was set as 1010 lx.

The specimen used for this research was the middle region of the shade tabs for the VC shade guide; this resource is very popular in clinical use and can represent part of common tooth-color. However, according to previous research, the range of colors provided by the VC shade guide is associated with certain drawbacks.[6,45,53,54] Therefore, there are certain limitations associated with the specimen used in this research; consequently, the color measured by the instruments in this research study may not cover all forms of color. Future research should use more common clinical tooth colors to investigate the color determination accuracy and characteristics of each instrument.

In the present study, there was no significant difference between the L*, a*, and b* values for the T3 and VE systems; the ΔE for the T4 was higher than the T3, and the overall accuracy rate of T4 was lower than that of T3. This may have been due to improvements in the hardware and software for T4 and its detailed design. The specific characteristics of T3 and T4 should be investigated further. Furthermore, since there are no standard guidelines for the evaluation of accuracy, and there is no guidance from the manufacturers on how to balance the acquisition of color information and the requirements of accuracy and mesh quality during scanning, dentists should be careful when considering shade determination data provided by these instruments and apply the appropriate method in clinical practice.

This in vitro study was conducted in the same laboratory with fewer influential factors than in the in vivo environment. Furthermore, laboratories are relatively stable, variables are easy to control, and error sources are relatively less. Future research should be carried out in vivo and consider more complex factors, such as saliva and light, as these are all known to influence the shade-matching capabilities of IOS systems.[8,16,33] Meanwhile, since the human eye and spectrophotometer are the most used methods for shade determination, the in vivo comparison between the IOS and them should also be done. The in vivo study will be more representative of the true performance of these methods in the clinic and can better demonstrate the IOS's possibility in clinical application.

In this study, the trueness and reproducibility of the shade determination function for three IOSs (T3, T4, and OM) and the spectrophotometer VE were evaluated to provide instructions for subsequent therapy and support for accurate personalized digital esthetic dentistry. Previous research found that visual color matching was quick and economical, but objective.[9,31,55] Although the human eye can discriminate very small differences in color, doctors, technicians, and patients are unable to communicate efficiently with regard to their perception and requests for color information.[45,56] For this reason, the development of instrumental tooth-color matching will facilitate color determination more accurately and make communication more convenient and effective.[4,12,57,58] Dentists and technicians can consider applying IOSs to assist with visual shade matching in esthetic dentistry but should be cautious.[8] These powder-free systems enable the acquisition of 3D information from tooth surfaces and allow clinicians to create a photorealistic copy of tooth color that can simplify traditional workflow practices.

CONCLUSIONS

Within the limitations of this study, a few conclusions were drawn. The VE and T3 system showed the best trueness, followed by the T4 and OM, respectively. The instruments all revealed excellent reproducibility. Analyzing the L*, a*, and b* values, respectively, the differences between T3 and VE were negligible. T4 tended to calculate a more bluish hue than VE and OM; OM tended to calculate a more yellowish hue than T3, and to calculate darker colors and a more reddish hue than T3, T4, and VE.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

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