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CLINICAL RESEARCH

Accuracy of an intraoral digital scanner in tooth color determination

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ABSTRACT

Statement of problem. Whether intraoral digital scanners with an integrated shade-taking function can substitute for colorimeters, spectrophotometers, or the visual method to reduce working time is unclear.

Purpose. The purpose of this clinical study was to evaluate the accuracy of the measurement of tooth shade obtained with an intraoral digital scanner in vivo.

Material and methods. Shades of 120 maxillary anterior teeth were evaluated by using a SpectroShade spectrophotometer (SS) and a TRIOS 3 intraoral digital scanner (T3) on 20 participants. The matching of shade readings between the T3 and SS was used to estimate the accuracy of the T3. The percentage of readings when a difference between the shades obtained by both devices was visually perceptible ($\Delta E>3.7$) was calculated. Each of the 120 teeth was measured 5 times to assess repeatability.

Results. The accuracy of the T3 was 53.3% when the color was recorded as a Vita 3D-Master (VM) shade and 27.5% for the Vita Classical (VC) shade guide when the SS was taken as a reference. A visually perceptible color difference was found in 25% (VM) and 50.8% (VC) of situations when the shade was determined with the SS and 48.3% (VM) and 78.3% (VC) with the T3. Repeatability was 92% (VM) and 93.5% (VC) for the SS, and 90.33% (VM) and 87.17% (VC) for the T3.

Conclusions. The findings of this study revealed that the tooth color determined by the T3 does not exactly match that obtained by the SS that additional methods of measuring tooth color are recommended. The accuracy of the T3 was higher when the color was recorded as VM values rather than VC values. (J Prosthet Dent 2020;123:322-9)

Dental restorations should restore both function and esthetics. The desire to reproduce natural optical features in dental restorations and to meet the esthetic requirements of patients and dentists has led to the development of new restorative materials and instruments to determine and reproduce color.[1]

To identify the color of a tooth and to reproduce it in a dental restoration, commercial shade guides have been used. As an alternative, custom shade guides, from the restorative material itself, can be used.[2,3] One of the most popular commercial shade guides, the Vita Classical (VC) (Vita Zahnfabrik), is based on the color frequency of natural teeth. Competing shade guides (Noritake; Kuraray Noritake Dental Inc, Chromascop; Ivoclar Vivadent AG, Bioform; Dentsply Sirona) are also based on the same principle.[4] Another shade guide (Vita 3D-Master [VM]; Vita Zahnfabrik) is systematically arranged on the CIELCh color scale and has been reported to be more reliable.[5-11]

The calculation and measurement of the color difference (ΔE) between the 2 objects can be achieved by using the CIELab color scale, where the L axis refers to lightness (0=pure black, 100=pure white), the a axis refers to red-green chromaticity (+a=redness, −a=greenness), and the b axis shows yellow-blue chromaticity (+b=yellowness, −b=blueness). Under experimental conditions, $\Delta E>1$ can be seen by the human eye,[12] but the clinically visible color difference for a tooth has been reported to be when $\Delta E>3.7$.[13] When the tooth color is determined with shade guides, several shade tabs could be visually acceptable, because ΔE between the tabs and the tooth could be less than 3.7. It is also possible that all shade tabs are visually

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Clinical Implications

Tooth color readings made with a TRIOS 3 intraoral digital scanner and a spectrophotometer can differ significantly. The accuracy of the intraoral digital scanner was 53.3% when the Vita 3D-Master shade guide values were used and 27.5% with the Vita Classical shade guide. When tooth shades are recorded with the Vita 3D-Master, fewer visually perceptible color differences ($\Delta E>3.7$) can be expected. Both devices have very high (>87%) repeatability. The Vita 3D-Master shade guide should be used with the TRIOS 3 intraoral digital scanner and supplemented with additional methods to determine color.

unacceptable because ΔE between the tabs and the tooth could be greater than 3.7.[14]

Digital cameras, spectrophotometers, and colorimeters have been used to assist in color determination and have been reported to be more reliable than the visual method.[1,15-20] They can also be used to determine the translucency of the tooth, which is the second leading factor, after color, for matching a restoration to adjacent teeth.[21]

Two types of spectrophotometers are available,[22] spot-measurement spectrophotometers (VITA Easyshade Advance 4.0; Vita Zahnfabrik, Shade-X; X-Rite), which determine the color of the tooth when the tip of the spectrophotometer is placed on the tooth surface, and complete-tooth-measurement spectrophotometers (SpectroShade; MHT Optic Research AG, Crystaleye; Olympus), which determine the color of the tooth through making and analyzing digital images. These spectrophotometers use illumination at 45 degrees and observation at 0 degrees (45/0). Spectrophotometers with 0-degree illumination and 45-degree observation (0/45) are not suitable for clinical use because of the limited space in the oral cavity.[23] Similarly, colorimeters are classified based on the same principles: spot-measurement (ShadeEye NCC; Shofu Dental, Digital Shade Guide DSG4; Rieth) and complete-tooth-measurement colorimeters (ShadeVision; X-Rite).[22] All color-measuring devices used in dentistry have an edge loss effect because some emitted photons are lost and are not detected by the device.[24] The influence of edge loss can be reduced by using a complete-tooth-measurement device instead of a spot-measurement device.[24]

Spectrophotometers are among the most accurate devices for determining tooth color.[1] Their operation is based on the transmission of white light being dispersed through a triangular prism from 1 to 25 nm wavelength intervals, reflected from the surface of the tooth, and returned to the device, where the total quantity of energy of the color spectrum is registered.[25,26] Colorimeters are less accurate because they do not register the entire returning spectrum of colors, but only 3 colors: red, green, and blue.[27,28] However, recent studies have reported that, in terms of accuracy, some complete-tooth measurement colorimeters produce results similar to those of spectrophotometers.[29]

Intraoral digital scanners (TRIOS 3; 3Shape, CEREC AC OmniCam; Dentsply Sirona, CS 3500; Carestream Dental, and others) have been increasingly used to make digital scans of dental arches. TRIOS 3 is an intraoral digital scanner with a shade-taking function. However, whether an intraoral digital scanner with an integrated shade-taking function can substitute for colorimeters or spectrophotometers is unclear. Two studies have evaluated the reliability of an intraoral digital scanner (TRIOS Color; 3Shape) in determining the tooth color. A subjective visual method[30] and the VITA Easyshade Advance 4.0[31] were used as references in these studies. More reliable reference devices such as complete-tooth-measurement spectrophotometers, however, should be used to better assess the accuracy of intraoral digital scanners for color determination. The influence of the shade guide system selected on these devices should also be investigated.

Therefore, the purpose of this clinical study was to evaluate the color determination accuracy of the TRIOS 3 intraoral digital scanner (T3) by comparing it with the SpectroShade spectrophotometer (SS); to estimate the percentage of situations when the determined shade difference with both devices was visually perceptible ($\Delta E>3.7$); and to evaluate the repeatability of both devices. The null hypothesis was that T3 measurements would not differ from SS measurements with regard to color determination.

MATERIAL AND METHODS

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This study was reviewed and approved by the Vilnius Regional Biomedical Research Ethics Committee, Lithuania (NR. 158.200-16-861-370). Twenty students aged 20 to 23 years (average 22 years) were recruited for the study from the third to the fifth year of the Institute of Odontology of the Faculty of Medicine of Vilnius University. All the participants received written information and signed an informed consent form. Participants with any restorative or bleaching procedures or with congenital or acquired tooth color

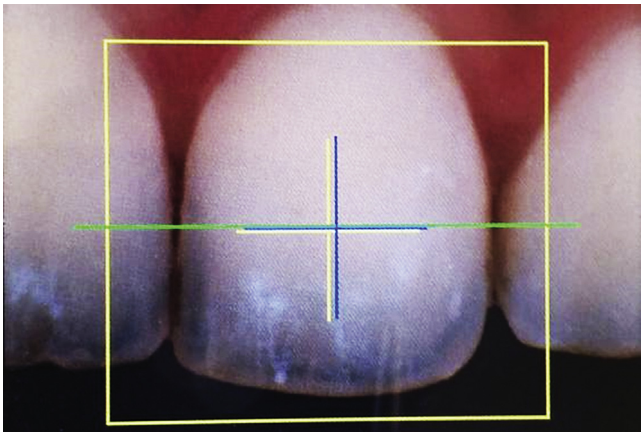

Figure 1. Positioning of SpectroShade spectrophotometer according to reference lines.

Figure 2. Division of teeth into 3 thirds.

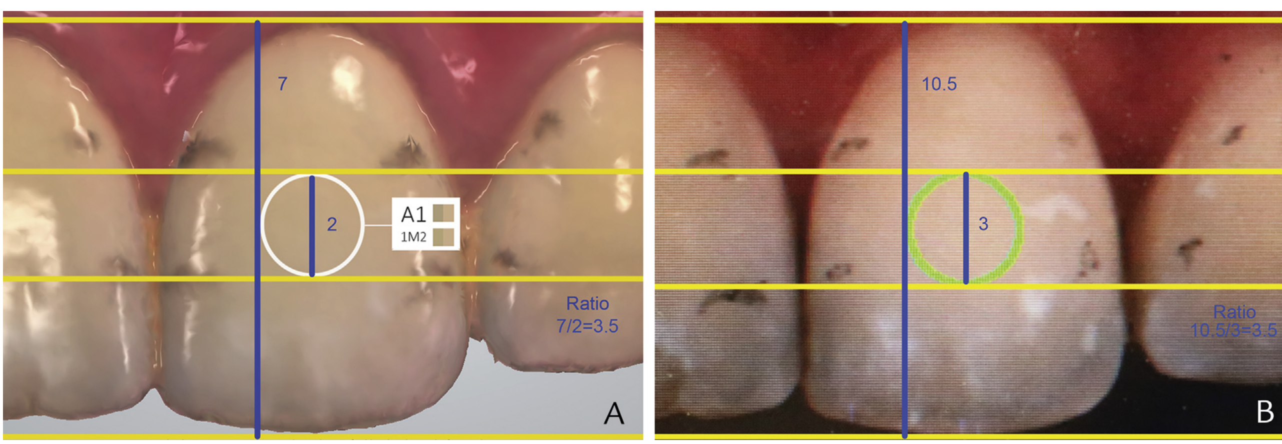

Figure 3. Unification of measurement areas with TRIOS 3 intraoral digital scanner (T3) and SpectroShade spectrophotometer (SS). A, Ratio of diameter of marked circle and vertical tooth height in T3 calculated. B, Circle of corresponding diameter selected on SS.

changes (demineralization, fluorosis, enamel hypoplasia) were excluded. Over the preceding 6 months, all the participants received professional oral hygiene procedures. The color of each participant's maxillary anterior teeth (2 canines, 2 lateral, and 2 central incisors) were measured. Overall, the color of 120 teeth was recorded in 20 participants.

The visual color parameters of each tooth were measured by using T3 and SS. The T3 is based on the principle of confocal microscopy. This optical imaging technique is used to increase optical resolution and contrast by blocking out-of-focus light while the image is being formed.[32] The intraoral digital scanner uses a light-emitting diode (LED) as a source of light and produces multiple images from different angles to reproduce a 3-dimensional (3D) view of the dental arch. Finally, software allowed a determination of the shade of a selected tooth area according to the VM and VC shade guides. The SS produces images when an intraoral adapter protecting against external light is positioned at a 90-degree angle to the targeted tooth center following the lines indicated on the screen (Fig. 1). One digital image is captured and processed by the software to determine tooth shade, which can be represented by 22 different shade guides. The spectrophotometer enables the overall shade average, the shades of the separate thirds of the tooth, a detailed shade map, or the levels of translucency to be displayed. The spectrophotometer can also read the shade of the selected tooth area recorded as L, a, b or L, C, h values.

On each tooth, marks dividing the tooth into thirds were made with a pencil (Fig. 2). After scanning with the T3, the standard shape (circle) for shade determination was placed in the middle third of the tooth according to the pencil marks. This area reflects tooth color most accurately, as the incisal third of the tooth is often too transparent and the gingiva in the cervical third disperses the reflected light, thus distorting the tooth color.[5,33] According to the ratio of the diameter of the marked circle and the vertical tooth height, a circle of the corresponding diameter was selected on the SS. In this way, the

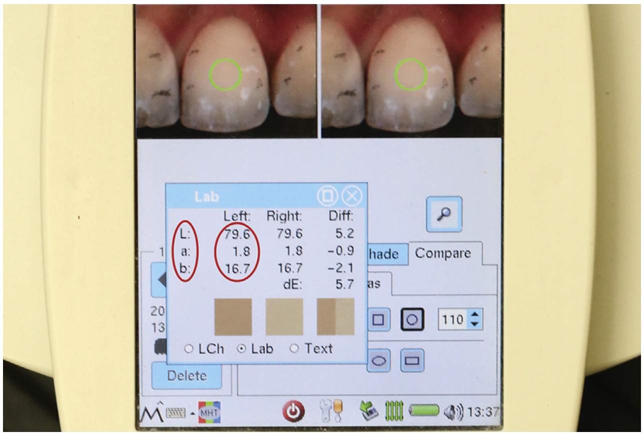

Figure 4. Determination of tooth color L, a, b/L, C, h value with SpectroShade spectrophotometer.

shades of the nearly identical tooth areas were determined by the SS and T3 (Fig. 3).

The color was determined in natural daylight without direct illumination. The participants were sitting on the same chair with the same head position (the Frankfurt horizontal plane parallel to the floor). The teeth were moistened by saliva before each measurement as dry teeth can appear lighter.[34] The teeth were remoistened every minute. Both devices were used in an alternating order for each participant.

Before the study, the investigators standardized the measurement protocol. Each operator (J.D., V.B.) performed a pilot color determination of 24 teeth with the T3 and SS. Interoperator agreement was estimated by using Cohen kappa statistics.

The T3 and SS were calibrated before scanning each tooth. The scans were performed by 2 operators (J.D., V.B.). Each of the 120 teeth were scanned 5 times with both devices, resulting in 5 color readings in each shade guide: VM and VC. A total of 600 T3 and 600 SS color readings in each shade guide were obtained. The mode was calculated from 5 readings of each tooth for both shade guides, and the value obtained was considered the shade determined with the device. No bimodal data sets were recorded.

Because the spectrophotometer is able to record only the L, a, and b values of the selected area of a tooth, a separate step was needed to record shades as values of the VM and VC shade guides. For this purpose, ΔE values between L, a, and b (Fig. 4) were recorded with the SS, and L, a, and b values taken from the SS database representing the VM and VC shade guides (Table 1) were calculated to determine the closest shade tab (minimum ΔE). ΔE was calculated by using the following formula: $\Delta E=\sqrt{(\Delta L^2+\Delta a^2+\Delta b^2)}$.

The SS is one of the most accurate devices used to determine the color of teeth.[25,35-37] This study, therefore, used the tooth color determined by the SS as a reference.

Table 1. Conversion table: L, a, and b values of all VM and VC shade tabs taken from SS database

Shade Guide	L	a	b
VM			
0M1	81.6	0.7	6.3
0M2	81.3	0.8	7.9
0M3	80.9	0.6	9.1
1M1	76.9	0.7	11.5
1M2	77	0.9	16.7
2L1.5	73	1.2	16.5
2L2.5	72.4	1.3	20.9
2M1	72.3	1.3	12.5
2M2	72.7	1.6	17.3
2M3	72.2	1.5	21.1
2R1.5	71.8	2	13.9
2R2.5	73	2	20
3L1.5	68.4	2	18.9
3L2.5	68.9	2.2	22.8
3M1	68.2	2.3	14.2
3M2	69.5	2.5	19.5
3M3	69.4	3	25.6
3R1.5	68.2	3.3	16.7
3R2.5	68.5	3.7	23.5
4L1.5	63.9	3	19.4
4L2.5	65	3.6	25.6
4M1	64.3	3.1	16.4
4M2	65.9	3.7	21.4
4M3	65.1	4.2	27.6
4R1.5	64.5	4.2	19
4R2.5	64.9	4.8	24.3
5M1	60.2	4.1	17.8
5M2	61.1	5.4	25
5M3	62.1	6.1	30.1
VC			
A1	76.4	0.5	14
A2	73.7	1.3	18
A3	72	2.1	21.2
A3.5	68.8	2.8	23.6
A4	65.1	3.1	24.3
B1	75.1	-0.2	12.3
B2	74	0.5	17.9
B3	70.8	1.8	24.5
B4	69.8	1.8	25.4
C1	71.5	0.7	14.3
C2	68.5	1.2	19
C3	65.8	1.7	19.7
C4	61.8	2.9	22.8
D2	70.3	0.9	13.9
D3	68.5	2	17.6
D4	68.7	0.8	21.1

SS, SpectroShade spectrophotometer; VC, Vita Classical; VM, Vita 3D-Master.

The matches between the shades determined by the T3 and SS were used to estimate the accuracy of the intraoral digital scanner in determining the color (Fig. 5).

To evaluate the visually perceptible color difference of the VM and VC shades registered with both devices, L, a,

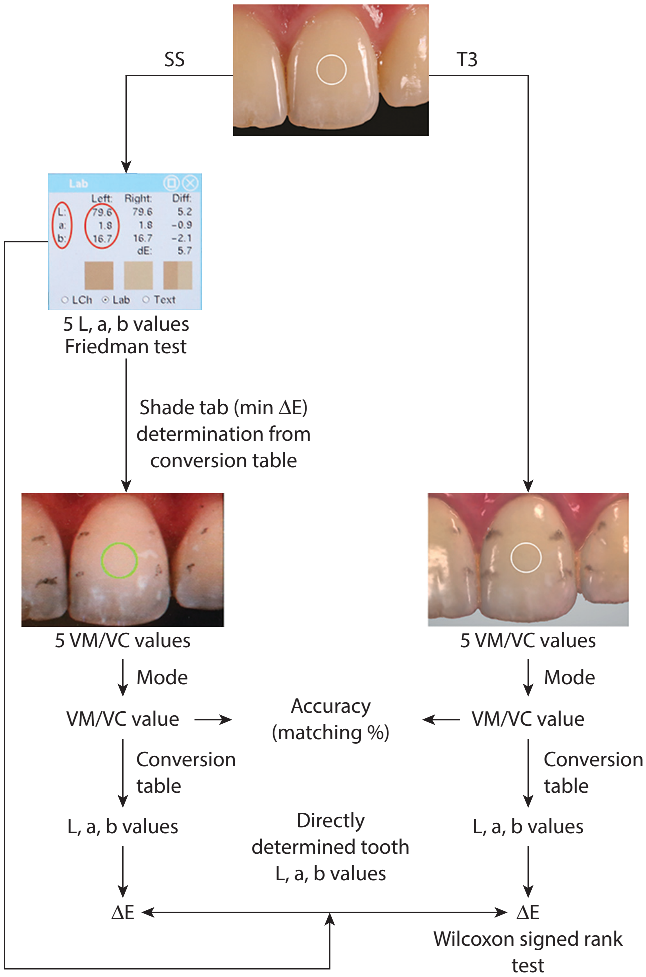

Figure 5. Scheme of measurements. SS, SpectroShade spectrophotometer; T3, TRIOS 3 intraoral digital scanner; VC, Vita Classical; VM, Vita 3D-Master.

and b values from the SS database were used. For this purpose, shades recorded by the T3 and SS according to the VM/VC guides were converted to L, a, and b values by using a conversion table. ΔE was calculated between the L, a, and b values obtained from the conversion of the VM/VC shades and the L, a, and b values which were initially directly determined with the SS. The purpose of calculating ΔE was to identify the instances when the shade determined with the T3 and SS had a visually perceptible color difference ($\Delta E>3.7$) (Fig. 5).

Because each tooth was scanned 5 times with the SS and the T3, it was possible to evaluate and compare the repeatability of both devices. The repeatability of the T3 and SS was evaluated by calculating the average percentage of the shades most often registered from the 5 measurements of the same tooth (n=120) according to the VM and VC guides.

Assuming that the T3 and SS measurements would not be normally distributed, the sample size was calculated based on Wilcoxon signed-rank test assumptions, 5% type I error, 80% power, and effect size not higher than 0.3. The sample size was estimated to be at least 94 teeth. Descriptive statistics were used to describe the percentage of color match (accuracy) of the T3 and SS readings, situations when the shade determined by both devices was visually perceptible ($\Delta E>3.7$), and the repeatability of both devices. The Shapiro-Wilk test was used to assess the normality of the distribution of quantitative variables (L, a, and b values). Nonparametric tests were further used because the L, a, and b values were not distributed normally. The Wilcoxon signed-rank test was used to evaluate the differences between the L, a, and b values obtained from the conversion of the VM/VC shades registered with T3 and the L, a, and b values that were directly determined with the SS. The Friedman test was used to evaluate the repeated measurements of variables L, a, and b from the SS (α=.05). Statistical analysis was performed with statistical software (IBM SPSS Statistics, v21; IBM Corp). The sample size calculation was done using software (G*Power 3.1; Heinrich Heine University of Dusseldorf).

Table 2. Tooth color frequency by percentage

Shade Guide	T3 (%)	SS (%)
Vita 3D-Master		
0M3	2.5	2.5
1M1	0.8	3.3
1M2	47.5	38.3
2L1.5	0.0	0.8
2L2.5	0.8	0.0
2M2	1.7	4.2
2M3	22.5	1.7
2R2.5	2.5	16.7
3M2	0.0	3.3
3M3	19.2	16.7
3R2.5	0.8	9.2
4M3	1.7	3.3
Total	100.0	100.0
Vita Classical		
A1	12.5	25.8
A2	1.7	28.4
A3	1.7	15.8
A3.5	0.8	8.3
A4	0.0	1.7
B2	39.2	1.7
B3	25.8	15.0
B4	18.3	3.3
Total	100.0	100.0

SS, SpectroShade spectrophotometer; T3, TRIOS 3 intraoral digital scanner.

RESULTS

A slight difference was observed in the distributions of tooth color recorded as the VM/VC values by using the

Table 3. Interoperator agreement for measurements with different devices and shade guides

Device/Shade Guide	Number of Teeth	Cohen Kappa
SpectroShade/Vita 3D-Master	24	0.95
SpectroShade/Vita Classical	24	0.88
TRIOS 3/Vita 3D-Master	24	0.76
TRIOS 3/Vita Classical	24	0.77

Table 4. Matching of measurements between T3 and SS

	Vita 3D-Master		Vita Classical	
Measurement Comparison	Frequency	%	Frequency	%
Matching	64	53.3	33	27.5
Not matching	56	46.7	87	72.5
Total	120	100	120	100

SS, SpectroShade spectrophotometer; T3, TRIOS 3 intraoral digital scanner.

Table 5. Visually perceptible color difference ($\Delta E>3.7$) when teeth shades recorded as VM and VC values with both devices

Vita 3D-Master						Vita Classical					
Device/ΔE Threshold	Rate	%	Device/ΔE Threshold	Rate	%	Device/ΔE Threshold	Rate	%	Device/ΔE Threshold	Rate	%
SS $\Delta E<3.7$	90	75	T3 $\Delta E<3.7$	62	51.7	SS $\Delta E<3.7$	59	49.2	T3 $\Delta E<3.7$	26	21.7
SS $\Delta E>3.7$	30	25	T3 $\Delta E>3.7$	58	48.3	SS $\Delta E>3.7$	61	50.8	T3 $\Delta E>3.7$	94	78.3
Total	120	100	Total	120	100	Total	120	100	Total	120	100

SS, SpectroShade spectrophotometer; T3, TRIOS 3 intraoral digital scanner; VC, Vita Classical; VM, Vita 3D-Master.

T3 and SS (Table 2). The interoperator agreement using the SS and T3 was good ($\kappa>0.75$), but agreement among the researchers using the SS was better than those using the T3 (Table 3).

The percentage of color match (accuracy) of T3 readings compared with that of the SS was 53.3% when the color was recorded as VM shade guide values and 27.5% for the VC shade guide values. The percentage of color match with the T3 was almost twice as high when the color of the tooth was recorded using the VM shade guide than it was with the VC shade guide (Table 4).

Statistical analysis of the detailed comparison of both devices (Wilcoxon signed-rank test) revealed a significant difference between L ($P<.001$) and a ($P<.001$) values when the T3 shades were recorded as VM values. The b (yellow-blue) values remained equally distributed ($P=.082$). When the shades were recorded as VC values, significant differences in all 3 coordinates were found ($P<.012$).

The visually perceptible color difference was found to be at least 25% when color was recorded as a VM/VC value with both devices (Table 5). The repeatability of the T3 and SS was similar. The highest repeatability was observed with the SS when shades were recorded as VC values (93.5%) and slightly lower (92.0%) when using VM values. The repeatability of the T3 was 90.3% with VM and 87.2% with VC. No significant differences (Friedman test) were found between the 5 repeated measurements of L ($P=.088$), a ($P=.714$), and b ($P=.131$) values obtained with the SS. This comparison could not be applied to the T3 because this device does not record L, a, and b values directly.

DISCUSSION

The research hypothesis was rejected because T3 measurements differed from SS measurements with regard to color determination. The results of the present study differed from a study that concluded that an intraoral digital scanner, a spectrophotometer, and the visual method are equally reliable methods of determining tooth color.[30] In the present study, the SS was used as a reference ("true" color), while Gotfredsen et al[30] used a subjective visual method as a reference, that is to say, if the colors determined by the T3 and SS did not match, the "true" color of the tooth was considered to be the one determined by the visual method using a shade guide. Based on results obtained from earlier studies, spectrophotometers are more accurate and reliable than the visual method in determining the tooth color.[16,17] These findings can be explained by many factors affecting human color perception.[1] Therefore, in the present study, the use of the visual method was excluded, and the mode calculated from 5 SS color readings was considered the "true" color of the tooth. Another study investigated the reliability of an intraoral digital scanner in vivo, but the "true" color of teeth was determined by a VITA Easyshade Advance 4.0.[31] Because an SS is considered to be one of the best in terms of precision and reliability in vitro and in vivo settings, it was chosen as a reference.[25,35,36] An earlier study revealed that an SS under clinical conditions is more reliable than the Easyshade.[25] Under freehand conditions, the repeatability and accuracy of the Easyshade was negatively influenced, but that was not the case with the SS.[36] Nevertheless, both devices are reliable and can be used as a reference instrument.[35] The present study found that the accuracy of the T3 (percentage color match) was 53.3% compared with that of the SS when color was recorded as VM values, while the other study indicated 43.9% when compared with the Easyshade spectrophotometer. The differences may be explained by the fact that the "true" color of the tooth was defined from only 1 reading of the Easyshade spectrophotometer. This single measurement may have been inaccurate because the repeatability of the Easyshade was 76.6% in vivo. That study did not assess the accuracy of an intraoral digital scanner with VC values, while the present study revealed that T3 accuracy was

27.5%. This study evaluated T3 accuracy by comparing it with the SS and estimating the match between the T3 and the SS shades recorded as VM/VC values. A statistically significant difference between the T3 and SS L and a values may not represent the accuracy of the T3 accuracy as conversion from VM/VC values to L, a, and b values was needed. Therefore, if it were possible to record the shades with an intraoral digital scanner as L, a, and b values and not just as VM/VC values, the accuracy of the device could be estimated in a better way.

Shade determination using VM and VC values was also assessed. The VM shade guide is better than the VC shade guide because it has a broader range of coverage and an equidistant distribution of color samples in the color space of natural teeth.[5,6] However, the VC shade guide is still widely used to determine color. Based on the findings of this study, the T3 and the SS were more reliable when the shades of teeth were recorded as VM values rather than VC values. The results are consistent with the findings of previous studies, which indicate that using the VM shade guide to determine color is more reliable than using the VC.[7,8]

Reports have indicated that commercially available shade guides do not provide sufficient spectral coverage of the colors present in teeth, which means that when shades are measured, coverage error (CE) is possible. CE is the index that shows the mean value of the minimal color differences between each tooth and the shade tabs. Bayindir et al[5] reported that the CE was 3.93 for the VM shade guide and 5.39 for the VC. Other studies also reported that the VM shade guide had the lowest CE compared with other shade guides used.[9-11] Johnston and Kao[13] reported that color differences (ΔE values) above 3.7 can be perceived by the human eye. Because the mean value of CE is higher than the mean perceptibility threshold, the determined shade can differ perceptibly from the adjacent teeth. Studies have evaluated clinically acceptable color difference,[13,31] but in the present study, the visually perceptible difference was not evaluated, and therefore, the threshold value was chosen as 3.7.[13]

This study shows that the repeatability of the T3 is similar to that of the SS and that the repeatability of both devices is good (>87%). Also, it confirms the repeatability of the SS determined by previous in vitro studies to be from 82.7% to 96.9%.[29,37] The repeatability of the T3 was found to be 90.33%, while the other study reported 78.3%.[31] This moderate difference could have occurred for several reasons. First, the measurements in the present study could have been carried out more accurately because the teeth were divided into 3 thirds. Second, each tooth was measured 5 times instead of 3. Nevertheless, intraoral digital scanner repeatability could be determined more accurately if the shades were recorded as L, a, and b values.

This study has several limitations. The software of the intraoral digital scanner does not provide actual L, a, and b values, and a conversion table was used to calculate ΔE. Potential colorimetric data could, therefore, have been lost. True reference was not available in the study, and only 1 color-measuring instrument was used as a reference. An attempt should be made to use more accurate color-measuring devices as reference instruments in future studies.

CONCLUSIONS

Based on the findings of this clinical study, the following conclusions were drawn:

1. The T3 does not exactly match the SS in determining tooth color, and therefore, additional methods are recommended.
2. The accuracy of the T3 is higher when the color is recorded as VM values rather than as VC values.
3. The repeatability of both devices with the VM and VC was very high (>87%).

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