Performance of Five Commercially Available Tooth Color-Measuring Devices

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Purpose: Visual tooth color assessment is neither accurate nor precise due to various subjective and objective factors. As newly developed tooth color-measuring devices for dental application provide the possibility of a more objective means of color determination, their performances in vitro and in vivo must be evaluated. The objective of this study was to evaluate the accuracy and precision of five commercially available tooth color-measuring devices in standardized and in clinical environments.

Materials and Methods: In an in vitro study, standards (A1, A2, A3, A3.5, and A4 shade tabs of Vita Lumin) were measured five times with five electronic devices (ShadeScan, Easyshade, Ikam, IdentaColor II, and ShadeEye) by two operators. In an in vivo study, the right upper central incisors of 25 dental students were measured with the same electronic devices by a single operator. Vita shade tab codes were expressed as CIE (International Commission on Illumination) $L^*a^*b^*$ values and in terms of the precision and accuracy of ΔE color differences. The Mann-Whitney statistical test was used to analyze the differences between the two operators in the in vitro study, and the Kruskal-Wallis one-way analysis of variance on ranks with the post-hoc Tukey test was used to analyze the accuracy and precision of electronic devices.

Results: No statistically significant difference was found between the different operators in the in vitro study. The obtained precision was Easyshade > ShadeScan ≅ Ikam > IdentaColor II > ShadeEye. The obtained accuracy was Easyshade > ShadeScan ≅ Ikam > ShadeEye > IdentaColor II. In the in vivo study, the Easyshade and the Ikam were the most precise, and the ShadeEye and the IdentaColor II were more precise than the ShadeScan. With respect to accuracy, there was no statistical difference between the ShadeScan, Ikam, and the Easyshade. The IdentaColor II was considered inaccurate ($\Delta E_a = 3.4$).

Conclusions: In the clinical setting, the Easyshade and Ikam systems were the most reliable. The other devices tested were more reliable in vitro than in vivo.

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THE ESTHETICS of a restoration depend on shape, surface form, translucency, and color. Esthetically acceptable restorations have become more achievable as a result of the improved material properties of composites and porcelains, and the use of layering techniques to mimic the color of natural teeth as closely as possible. Color assessment and reproduction remains one of the most challenging aspects of esthetic dentistry; however, matching of a restoration to existing tooth enamel is not predictable.

Color perception is the result of the interplay between the light source, an object, and the detector or perceiver. Human color observation depends on the color characteristics of the illuminant and the angles between the illuminant, the object, and

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the human eye. Because color registration via the eye is affected by previous eye exposure, aging of the eye, or color blindness, the color perception of an individual is not consistent. As a result of metamerism, the color match between two objects perceived under one illuminant can become a mismatch under a different illuminant. To avoid these inconsistencies, the electronic devices with integrated standardized illumination can be used to measure reproducible color parameters, which then will depend only on the angles formed between the illuminant, the object, and the detector.

Since the early 1970s several electronic devices for color assessment have been used for various purposes in dentistry. Spectrophotometers,[1-13] colorimeters,[14-18] spectroradiometers,[2,19,20] and digital cameras[13] have been used for color determination. Some studies have compared the electronic devices by visual observation or evaluated two electronic devices.[1-4,14,15] Other studies have evaluated color and translucency in relation to the physical properties of porcelains[5-8,16,17] and the color reproduction of porcelains.[9-11,18] In addition, these devices have been used to evaluate tooth color distribution in natural teeth,[12,13,21] and to monitor the color changes of teeth or restorative materials during bleaching.[22-25] Several studies have been performed in a clinical environment using vital teeth,[13,26-28] while only a few studies have evaluated the accuracy and precision of the devices in a clinical setting.[29-31]

The basic principles of these mechanisms have been described elsewhere.[31-33] In general, the output of the color measurements can be classified and specified in several ways. The most common systems for describing color are Munsell's System and the International Commission on Illumination (CIE) $L^*a^*b^*$ color system. In the latter system, L^* represents the darkness–lightness coordinate, a^* the chromaticity between green (−) and red (+), and b^* the chromaticity between yellow (+) and blue (−). The CIE $L^*a^*b^*$ color system is commonly used in perceptual studies for dental color assessment because of its approximate visually uniform coverage of the color space. In this color space, color difference between two objects (L^*_1, a^*_1, b^*_1 and L^*_2, a^*_2, b^*_2) can be calculated according to Equation 1:

$$\Delta E = \left[\left(L_1^* - L_2^*\right)^2 + \left(a_1^* - a_2^*\right)^2 + \left(b_1^* - b_2^*\right)^2\right]^{1/2} \quad (1)$$

Among the color difference values expressed as ΔE, values greater than 1 unit were visually detectable by 50% of human observers in controlled conditions[34] and the color differences between 2.0 and 3.7 were visually detectable under clinical conditions.[35] Unfortunately, for historical reasons, colors in dentistry are almost always reported in shade tab codes of different shade guides, e.g., Vita Lumin, Vitapan 3D-Master, Chromascop, etc. The problem with these color tabs is that their colors are not distributed uniformly throughout the color space, and as a consequence, comparison between the shade tabs is incorrect.

A color-measuring device should be easy to handle, shockproof, and above all, accurate and precise. This study evaluated the accuracy and precision of five commercially available tooth color-measuring devices in laboratory circumstances and under clinical conditions. Two devices, the ShadeEye and the IdentaColor II, are based on colorimetric techniques. The ShadeScan and the Ikam both use CDD-digital camera techniques, and the Easyshade is a spectrophotometer. Most of the systems have multiple outputs, such as Vita Lumin, Vitapan 3D-Master, Chromascop, Hue, Chroma and Value, and CIE $L^*a^*b^*$, but the most commonly known output of the five selected devices is the Vita Lumin shade guide.

The measured shade codes were converted into the CIE $L^*a^*b^*$ color system to evaluate the accuracy and precision by means of ΔE. The aim of this study was to determine whether the investigated electronic devices have the same accuracy and precision under clinical conditions as they possess under laboratory conditions.

Materials and Methods

Five commercially available devices for tooth color-measurements were evaluated. Brand names, manufacturers, and configurations are summarized in Table 1. All devices were tested in two setups. Standard colors from artificial teeth in a phantom jaw of a phantom head were measured (i) in standardized in vitro conditions and (ii) in a clinical trial.

In Vitro Study

The shade tab A1, A2, A3, A3.5, or A4 of the Vita Lumin shade guide (Vita Zahnfabriek, Bad Sackingen, Germany) was placed in a phantom jaw of a phantom head in the location of the upper right central incisor

Table 1. Commercially Available Electronic Devices for Tooth Color-Measurement Tested

Device	*Manufacturer*	*Configuration*	*Calibration*	*Illumination*
ShadeScan	CYNOVAD®, Montreal, Canada	Digital camera	Nine colors	A-Illuminant
Ikam	DCM®, West Yorkshire, UK	Digital camera	Graycard	D-65 Illuminant
IdentaColor II	Identa®, Holbaek, Denmark	Colorimeter	Unknown	D-65 Illuminant
ShadeEye	Shofu®, Dental GMBH, Ratingen, Germany	Colorimeter	Zirconium oxide	D-65 Illuminant
Easyshade	Vident®, Brea, CA	Spectrophotometer	Unknown	D-65 Illuminant

and measured with one of the devices. The devices were calibrated according to the manufacturer's recommendations. The probes for determining the color were fixed in a standardized setup in such a way that the mesio-distal midline of the middle third of the labial surface of the shade tabs was selected for color determination. When translucent samples are measured, the background must be controlled so that reproducible results between devices can be obtained. For a consistent background a black backing was selected, because this mimics the clinical environment as closely as possible. This setup was used for all devices, except for the Ikam in which the original manufacturer's "crown holder" was used. Two operators measured each shade tab five times.

The colors determined by the ShadeEye, IdentaColor II, and the Easyshade were read out directly, while for the Ikam and the ShadeScan the acquired digital images were first analyzed with the manufacturer's software to obtain the color. All colors were determined as Vita Lumin shade guide colors.

In Vivo Study

For the clinical trial, a group of 25 dental students whose anterior teeth had not received dental treatment or been affected by dental disease participated in the study. A written informed consent was obtained from every individual after a full explanation of the experiment. The group consisted of 15 males and 10 females, with ages ranging from 19 to 27 years (mean = 21.9, sd = 2.0). The color of the upper right central incisor of each subject was assessed thrice by a single operator using the same five devices as used in the in vitro study. The devices were calibrated according to the manufacturer's recommendations. The probes of the ShadeEye, IdentaColor II, and the Easyshade were held against the middle third of the tooth during the measurement. The tooth color measured by the Ikam and the ShadeScan was obtained by selecting and analyzing the middle third of the tooth in the digital image.

Data Evaluation

As noted earlier, the colors of the Vita Lumin shade guide are not uniformly distributed, and it is therefore inappropriate to evaluate the electronic devices based on these values. To overcome this problem, the Vita Lumin shade guide codes were expressed as CIE $L^*a^*b^*$ color parameters by using previously reported values,[36] which were also determined in the mesio-distal midline of the middle third of the labial surface of the shade tabs. The color difference (ΔE) between two colors of the Vita Lumin shade guide can be calculated by Equation 1 (above).

Table 2. Colorimetric Values of Each Vita Lumin Shade Tab, and Color Differences Between Them

	L*	a*	b*	*A1*	*A2*	*A3*	*A3.5*	*A4*
A1	79.6	−1.6	13.1	0.0	5.3	8.3	11.8	13.9
A2	76.0	−0.1	16.7	5.3	0.0	3.3	6.5	8.8
A3	75.4	1.4	19.6	8.3	3.3	0.0	3.8	6.9
A3.5	72.3	1.5	21.8	11.8	6.5	3.8	0.0	3.8
A4	68.6	1.6	21.0	13.9	8.8	6.9	3.8	0.0
B1	78.9	−1.8	12.3	1.0	5.5	8.7	12.0	13.9
B2	76.7	−1.6	16.6	4.6	1.7	4.4	7.4	9.7
B3	74.1	−0.5	22.3	11.0	6.0	3.1	2.1	5.8
B4	71.8	0.5	22.2	12.1	6.9	4.4	1.2	3.6
C1	74.2	−1.3	12.6	5.4	4.7	7.6	9.8	10.5
C2	71.0	−0.2	16.7	9.5	5.1	5.5	5.5	5.2
C3	68.8	0.0	16.7	11.4	7.2	7.3	6.4	4.6
C4	64.8	1.6	18.7	16.1	11.5	10.6	8.2	4.4
D2	75.3	−0.5	13.5	4.5	3.4	6.4	9.1	10.3
D3	72.6	0.6	16.1	8.0	3.6	4.5	5.7	6.4
D4	71.9	−1.0	17.8	9.1	4.4	4.6	4.8	5.3

The $L^*a^*b^*$ values for each Vita Lumin shade code and the calculated color differences (ΔE) between all colors of the Vita Lumin shade guide and the investigated color A1, A2, A3, A3.5, and A4 are summarized in Table 2. Vita Lumin shade guide codes like B3.5 (characteristic for the IdentaColor II device) were calculated based on a weighted average of the $L^*a^*b^*$ for the same color group (in this case B3 and B4), and ΔE was calculated according to the equation noted above. The latter values were omitted in Table 2 for practical reasons.

The different devices and the effect of operator influence were statistically analyzed. As the color difference, ΔE, is not normally distributed, analysis based on Gaussian functions was not justified. Therefore, a non-parametric method of evaluation, the Mann-Whitney test, was used to analyze the effect of the two operators in the in vitro study. In addition, the non-parametric Kruskal-Wallis one-way analysis of variance on ranks with post-hoc Tukey ($p = 0.05$) method of analysis was used to test the effect of the accuracy and precision of the devices. The latter method of analysis was used for both the in vitro study and the clinical trial. The software used was SigmaStat 3.1 (Systat Software Inc., Richmond, CA).

Results

The Vita Lumin shade guide tabs A1, A2, A3, A3.5, and A4 were measured five times by two operators under standardized laboratory conditions. The results for the devices are summarized in Table 3.

Accuracy is a measure of how close the estimate is to the "true" value, which, in this case, is the color difference, ΔE_a, between Vita color and the value by the device. The Vita colors were converted into CIE $L^*a^*b^*$ parameters, and the color differences were calculated according to Equation 1 (see Table 2). The average color difference for each color, ΔE_a, and the average color difference for all the colors, $\Delta \bar{E}_a$, are summarized in Table 3.

Precision is usually a statistical measurement of repeatability expressed as a variance or standard deviation. Unfortunately, color is described by parameters, which do not permit calculation of a standard deviation. Instead, the obtained Vita colors were converted into CIE $L^*a^*b^*$ parameters and the average L^*, a^*, and b^* values were calculated. The precision is proportional to the average of the color difference between the obtained Vita colors and their averaged $L^*a^*b^*$ values. For example, $L^* = 77.0$, $a^* = -0.1$, $b^* = 16.5$ are the average values for the Vita colors, A1, A2, and A3. The color differences between the average $L^*a^*b^*$ values and A1, A2, and A3 are 4.5, 1.0, and 3.8, respectively, resulting in a mean color difference of 3.1. The latter values are summarized as ΔE_p in Table 3. The average values for all colors, $\Delta \bar{E}_p$, were also calculated and are summarized in the same table.

Accuracy and precision were calculated for the two operators, separately. The non-parametric Mann-Whitney test showed that there was no significant difference between the operators in either accuracy ($p = 0.727$) or precision ($p = 0.892$). The values in Table 3 represent therefore, the mean value for both the operators. The non-parametric Kruskal-Wallis one-way analysis of variance on ranks was used to evaluate the accuracy and precision of the devices. The accuracy of the ShadeScan, Ikam, and the Easyshade were not significantly different under standardized laboratory circumstances, while the ShadeEye and IdentaColor II were significantly less accurate. The precision of the Easyshade was significantly higher than the ShadeScan and the Ikam, followed by the IdentaColor II and the ShadeEye (see Table 3).

The clinical measurements were evaluated analogous to the laboratory study. An operator measured each anterior tooth thrice. The separate measurements of each anterior tooth per individual are summarized in Table 4. The precision of the three measurements was calculated as described above for the precision measured in the laboratory study. The observed shade tab color was converted into L^*, a^*, and b^* values and averaged.

Table 3. Accuracy and Precision of Color-Measuring Devices Tested

	A1	*A2*	*A3*	*A3.5*	*A4*	$\Delta\bar{E}_p/\Delta\bar{E}_a^*$
ShadeScan	10A1	6A2/2B2/2C1	9A3/A2.5	2A3.5/8B4	10A4	
$\Delta E_p/\Delta E_a$	0.0/0.0	1.6/1.3	0.3/0.2	0.3/1.0	0.0/0.0	$0.5^{abc}/0.5^a$
Ikam	5A1/5B2	10A2	10A3	A3/9A3.5	10A4	
$\Delta E_p/\Delta E_a$	2.3/2.3	0.0/0.0	0.0/0.0	0.7/0.4	0.0/0.0	$0.6^c/0.5^a$
IdentaColor II	5A1/5A1.5	8A1.5/2B2	3A2/5A2.5/C1.5/D3	6B3.5/B2/3B3	10A3.75	
$\Delta E_p/\Delta E_a$	1.3/1.4	0.7/2.5	1.6/2.9	1.4/2.2	0.0/2.2	$1.0^a/2.2$
ShadeEye	5A1/4A2/D1.5	8A2/D1.5/D2	10A3	10A3.5	5C4/5C3	
$\Delta E_p/\Delta E_a$	3.9/3.7	2.3/1.5	0.0/0.0	0.0/0.0	2.4/4.5	$1.7^{ab}/1.9$
Easyshade	10A1	10A2	10A3	10A3.5	10A4	
$\Delta E_p/\Delta E_a$	0.0/0.0	0.0/0.0	0.0/0.0	0.0/0.0	0.0/0.0	$0.0/0.0^a$

*No significant differences were observed if the mean color difference is quoted with the same superscript letter ($p = 0.05$).

The color difference between this average value and the separate measurements were expressed as ΔE values, and reported in Table 4 as ΔE_p.

As there is no objective way to assess the "true" color of teeth, the average $L^*a^*b^*$ values of the ShadeScan, Ikam, and the Easyshade were used as "true" colors (see "Discussion"). The nine shade tab color measurements from the ShadeScan, Ikam, and the Easyshade were converted into L^*, a^*, and b^* values and averaged. This was considered the "true" color. The color difference, expressed as ΔE, of each individual measurement and this "true" color were averaged, and reported in Table 4 as ΔE_a.

The non-parametric Kruskal-Wallis one-way analysis of variance on ranks was used to evaluate the accuracy and precision of the devices for the averaged accuracy and precision, $\Delta\bar{E}_a$ and $\Delta\bar{E}_p$, for all patients. In a clinical setting, only the accuracy of the ShadeScan was significantly better than the accuracy of the IdentaColor II. On the other hand, the ShadeScan was significantly less precise than the Ikam and the Easyshade, which were the two devices with highest precision.

Discussion

Tooth color is a complex phenomenon, in which the overall perception is influenced by various factors such as the lighting conditions, translucency, opacity, gloss, and the limitations of the human eye and brain. Besides visual assessment with a shade guide, tooth color can be measured with colorimetry, spectrophotometry, and digital cameras. Only a few reported studies have evaluated the precision of these devices in a clinical setting.[4,21,31] Visual assessment with a shade guide has been compared with color measurement of spectrophotometer.[4] Recently, Tung et al found that the ShadeEye system agreed with itself 82% of the time, whereas clinicians agreed with each other on 73% of the selected shades.[30] Remarkably, selections made by the colorimeter and the clinicians matched only 55% to 64% of the time. Although most previous studies have been designed to test the precision of the equipment on different measuring times and with different persons, accuracy is not often investigated. To test the accuracy of any electronic device intended for use in the oral environment, an intraoral standard must be developed; currently such a standard is not available. Despite this lack in standardization, the shade guides are the "de-facto standard" for color determination in dentistry. For this reason, the Vita Lumin shade guide was used to evaluate the precision and accuracy in standardized laboratory conditions.

The Vita Lumin shade guide is divided into four series with the letters A, B, C, and D. These shades have brown, yellow, gray, and red characters, respectively. Within a group (e.g., A1, A2, A3, A3.5, and A4) chroma increases and value decreases. This group was measured with the five instruments. The obtained precision was in the order Easyshade > ShadeScan ≅ Ikam > IdentaColor II > ShadeEye. The IdentaColor II and the ShadeEye had precisions with $\Delta E_p > 1.0$. Since differences greater than 1 ΔE unit are visually detectable by 50% of human observers, measuring color with the latter devices will give visually observable color differences, confirming the findings of Tung et al.[30] The common output of all the devices was the Vita Lumin shade guide code, and by measuring

Table 4. Color Measurements of the Anterior Teeth in Vita Lumin Shade Tab Colors of 25 Dental Students, and the Color Difference for the Precision (ΔE_p) and Accuracy (ΔE_a) Between the Measurements and the Average from the ShadeScan, Ikam, and Easyshade Measurements

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
ShadeScan	D2/C1/A2	A2/2A3	2A2/C1	3C1	3B2	2D2/D3	2A2/A3	B1/2D2	A2/2A3	2A2/B2	D2/2D3	2A3/C1	2D2/D3	B1/2B2
$\Delta E_p/\Delta E_a$	1.8/2.1	1.5/1.0	2.1/1.7	0.0/2.8	0.0/1.0	1.8/1.3	1.5/2.0	1.8/1.9	1.5/4.3	0.7/2.7	1.8/3.4	3.4/3.0	1.8/2.2	2.2/2.0
Ikam	3A1	2A1/B2	2A1/B2	3B2	2A1/A2	3C1	3B2	3A1	3A1	3A1	3A1	3A1	3A1	3A1
$\Delta E_p/\Delta E_a$	0.0/2.9	2.0/5.5	2.0/2.1	0.0/3.1	2.4/2.0	0.0/2.4	0.0/1.8	0.0/1.3	0.0/3.7	0.0/3.1	0.0/3.6	0.0/3.7	0.0/3.6	0.0/1.0
IdentaColor	3A1	3A2	2A1/A2	3A1	3B1	3D1.5	A1/2C1	3B1	3A1	3B1	2A1/B1.5	3A1.5	A1/2B1	3B1
$\Delta E_p/\Delta E_a$	0.0/2.9	0.0/1.8	2.4/1.9	0.0/6.1	0.0/3.9	0.0/9.6	5.4/3.5	0.0/0.8	0.0/3.7	0.0/2.9	0.4/3.6	0.0/1.1	0.4/3.2	0.0/1.4
ShadeEye	3A2	A2/2A3	3A1	3D2	3C1	2C1/D2	3C2	3C1	2A1/A2	3A1	3A2	3A2	3A1	3A1
$\Delta E_p/\Delta E_a$	0.0/2.6	1.5/1.0	0.0/3.6	0.0/2.3	0.0/4.5	0.7/2.2	0.0/4.3	0.0/4.1	2.4/2.0	0.0/3.1	0.0/2.1	0.0/1.7	0.0/3.6	0.0/1.0
Easyshade	3B2	4B4	3B2	3C2	3B2	2C2/D2	2C1/C2	3B1	3C1	3C1	3B2	3B2	3C1	3A1
$\Delta E_p/\Delta E_a$	0.0/2.1	0.0/5.2	0.0/1.3	0.0/3.4	0.0/1.0	0.0/3.1	2.4/3.0	0.0/0.8	0.0/3.2	0.0/2.9	0.0/1.8	0.0/1.3	0.0/2.0	0.0/1.0
	15	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*		$\Delta\bar{E}_p^*$	$\Delta\bar{E}_a^*$
ShadeScan	A2/2B2	2A2/B1	3B1	A2/2B2	3B2/C1	A1/2B1	C1/2D3	2A3/C1	3B2	A2/2C1	B2/2D2			
$\Delta E_p/\Delta E_a$	0.7/1.6	2.4/1.6	0.0/0.5	0.7/1.7	2.1/0.6	0.4/0.1	1.9/1.0	3.4/1.3	0.0/2.3	2.1/2.1	1.6/1.7		1.5^a	1.8^b
Ikam	3A2	3A1	A1/B1/C1	3A1	3A1	3A1	3A1	A1/A2/B2	3A1	2A2	3A1			
$\Delta E_p/\Delta E_a$	0.0/1.7	0.0/4.8	2.3/0.9	0.0/3.1	0.0/4.6	0.0/0.6	0.0/5.9	2.3/3.6	0.0/2.8	0.0/1.3	0.0/2.8		0.4^b	2.9^{ab}
IdentaColor	2C3.5/C4	3B2	3A1	2A2/B2	2A1/B1.5	3B1	3B1	C1/D3/D3.5	2B1/D1.5	3B1	2A1/B1			
$\Delta E_p/\Delta E_a$	2.1/8.4	0.0/1.1	0.0/1.3	0.7/2.0	0.4/4.5	0.0/0.4	0.0/5.6	1.6/4.3	7.0/3.0	0.0/4.7	0.4/2.8		0.7^{ab}	3.4^a
ShadeEye	2D2/D3	A1/2A2	2A1/C1	2A1/A2	2A2/D2	3A1	3C1	A1/C1/D1	3B1	3A2	2A1/C1			
$\Delta E_p/\Delta E_a$	1.8/1.7	2.4/1.4	2.4/0.8	2.4/1.5	1.5/1.1	0.0/0.6	0.0/2.5	2.3/5.5	0.0/2.7	0.0/1.3	2.4/1.9		0.7^{ab}	2.4^{ab}
Easyshade	3C1	3B3	3B1	3B2	3C2	3B1	B1/2D1	3B3	3D2	3B2	3B2			
$\Delta E_p/\Delta E_a$	0.0/3.1	0.0/6.2	0.0/0.5	0.0/1.5	0.0/4.9	0.0/0.4	7.0/4.9	0.0/4.2	0.0/2.2	0.0/1.4	0.0/2.0		0.4^b	2.5^{ab}

*No significant differences were observed if the mean color difference is quoted with the same superscript letter ($p = 0.05$).

the Vita tabs the accuracy was evaluated. The obtained order was Easyshade > ShadeScan ≅ Ikam > ShadeEye > IdentaColor II. Based on both the accuracy and precision, the ShadeScan, Ikam, and the Easyshade perform better than the IdentaColor II and the ShadeEye. Apparently, there is no difference in performance of measuring tooth color under standardized conditions with a spectrometer or a digital camera.

Evaluation of a color-measuring device in the oral environment is much more complicated than under standardized laboratory circumstances. Because there is no "gold standard" for the oral environment, the evaluation is not straightforward. In this study, 25 teeth were measured with the five color-measuring devices. Tooth color was determined thrice with each device by a single operator. These circumstances were chosen, because they represent a typical clinical setting in a dental laboratory or practice and because, from the results of the in vitro study, it could be concluded that there was no statistically significant difference between the two operators. The precision was evaluated as in the laboratory study, showing that the ShadeScan was less precise, compared with the IdentaColor II and the ShadeEye. In the clinical study, the Ikam and the Easyshade were also the most precise. The in vitro study showed that there were no significant differences between the accuracy of the ShadeScan, Ikam, and the Easyshade. Moreover, the average accuracy of the Easyshade was so high ($\Delta\bar{E}_a < 0.5$) that the visual perceptibility of color difference is not expected. For each patient, the average $L^*a^*b^*$ values of tooth color were calculated by averaging the obtained colors for the ShadeScan, Ikam, and the Easyshade. The color difference between this "gold standard" and each measurement was then calculated. The ShadeScan was the most accurate device, followed by the ShadeEye, Easyshade, and the Ikam. The IdentaColor II was rather inaccurate with $\Delta\bar{E}_a = 3.4$. On the other hand, it must be realized that the color of the tooth and the restoration can also be determined at the dental laboratory with a single device, ensuring that accuracy does not play a role, and the success of the restoration is only dependent on the precision of the device used. The ShadeScan, Ikam, and the Easyshade were the most reliable devices in the in vitro setting, but only the Ikam and the Easyshade performed equally well with respect to precision in the clinical setting.

In contrast to the in vitro study, it is clear that accuracy of the devices (see Table 4) is not high enough to make predicable restorations using different electronic devices. Apparently, the devices are still too sensitive to patient or equipment movement. Furthermore, factors such as the pressure, the angle and position of the probe, and the anatomic shape of the tooth surface may play a role in color determination. Moreover, the accuracy of the light source in the device can change over the time, influencing the observed color.

In this study, the shade tabs of Vita Lumin shade guide were used as a standard, and their $L^*a^*b^*$ values, estimated in one earlier study,[36] were used as the gold standard. The problem with different shade guides is that their shade tabs do not always match each other, although they represent the same color. This is due to the lack of standardization during the manufacturing of shade guides, which is visual instead of instrumental. As a result, the gold standard used in this study may not exactly represent the output colors of different electronic devices; however, this fact is not of importance for the comparison of the accuracy of the different systems.

Within the limits of this study, it can be concluded that different commercial electronic devices have different accuracy and precision in vitro and in vivo. Colorimeters are significantly less reliable than spectrophotometers and digital cameras. The precision of the ShadeScan decreased in clinical circumstances. Most of the devices are more reliable in vitro than in vivo, whereas the Easyshade and the Ikam show the same results in both standardized and clinical conditions.

Conclusions

Commercially available electronic systems for tooth color measurements show different levels of accuracy and precision. Within the limits of this study, the following conclusions can be drawn:

1. Generally, the colorimeter (ShadeEye, IdentaColor II) was less reliable than the spectrophotometer (Easyshade) and the digital camera (Ikam).
2. The spectrophotometer (Easyshade) was the most reliable instrument in both in vitro and in vivo circumstances.
3. The digital camera (ShadeScan) was less precise in the clinical environment.

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