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Smartphone-Based Color Measurement of Tooth Shade Guide in Clinical Lighting Conditions

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***Abstract*—Caries is a common disease of hard tissues of teeth which results in dental cavities, which are usually replaced by dental fillings. Matching the color of a dental filling is usually a subjective assessment. In this study, we conducted a color analysis of GC Gradia Direct shade guide in the lighting conditions of the dental office. Color measurement was performed using Color Grab mobile app and the results were acquired as values of RGB (red, green, blue) and HSV (hue, saturation, color value) values. The results indicate the possibility of identifying each shade of tooth by the most prominent changes in RGB and/or HSV components.**

I. Introduction

CARIES is a common disease of hard tissues of the teeth caused by bacteria, which leads to the demineralization and proteolytic decay [1], [2]. The damage of tooth hard tissue associated with caries is defined as cavity [3]. Due to the fact that the damaged structure of the tooth does not regenerate, it must be replaced by a filling. Restorative materials include gold, dental amalgam, composite, and porcelain resins [4].

One of the composite materials used for fillings to match the color to the patient's teeth is GC Gradia Direct dental composite material (GC Europe NV, Leuven, Belgium), which recreates the optical properties of natural teeth and is available in several versions that differ in color scale [5].

Color as an optical value significantly affects the appearance of the tooth [6], [7]. The color depends not only on the shade, but also on the saturation, brightness, and tooth morphology [7]. The perception of tooth color depends on the way it reflects the light [6], [8].

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In most cases, a dentist matches the filling color by the subjective assessment based on comparison of the shade of tooth with the shade guide [6], [7]. To reduce the effects of metamerism, a standardized light source should be used [6]. Three most common light sources in dentistry are natural, fluorescent, and incandescent [9]. Measurement of color of a wide range of materials and substrates has been performed by spectrophotometers and colorimeters for several years [10], also in dentistry [11], [12].

Spectrophotometers measure the amount of light absorbed by the sample using the Lambert Beer law. They consist of their own light source, monochromator, a sample, and photodetector [10]. Due to the technological progress and the decreasing price of devices, the use of spectrophotometers in dentistry has become a viable alternative to visual matching [13], [14]. Another method for tooth color analysis is using dental microscopes [2].

Due to the increasing capabilities of smartphones, there have been proposed several applications, including color measurements [15], [16]. For instance, Kim et al. [15] applied smartphones to perform colorimetric pH measurement. Hasan et al. proposed a method for measuring hemoglobin level with smartphones [16].

The purpose of the study was to perform the color analysis of a commercially available shade guide (GC Gradia Direct) with mobile apps in the lighting conditions of the dental office and analyze the influence of light intensity and energy (visible light or ultraviolet light) on the color components of available shades in RGB and HSV color spaces, which may be useful in distinguishing the available shades.

II. Material and Methods

A. Material

Our study involved only a commercially available tooth shade guide (GC Gradia Direct produced by GC Europe NV, Leuven, Belgium) which contains the shades of teeth in the form of a palette with wedge-shaped color samples (see Fig. 1). The order of the colors in the shade guide is as follows: BW, A1, A2, A3, A3.5, A4, B2, B3, C3, CV, CVD, WT, DT, CT, NT and GT [5, pp. 6–7].

Fig. 1. GC Gradia Direct shade guide (own source).

B. Experiments

The study was conducted on a commercially available tooth shade guide (GC Gradia Direct) in typical lighting conditions of a dental office (visible light and ultraviolet (UV) light additionally lit by daylight through the windows). We used a smartphone with a camera, its own light source, and two mobile apps for Android: Lux Light Meter (Marcel Waldau Webdesign) [17] and Color Grab (Loomatix) available at the Google Play Store. Color Grab app performs real-time color callibration [18], whereas Lux Light Meter has its own callibration mechanism [17].

The first app allowed the measurement of light intensity E in lux (lx) at the test site, and the second app measured RGB (red, green, blue) and HSV (hue, saturation, color intensity value) component values in the shade guide. RGB and HSV values were taken under visible light for the following illuminance values: 130 lx, 165 lx, and 201 lx, and also under the LE-900 ultraviolet lamp with the power input of 90 W; output voltage and current of 12 V DC, 1 A; input voltage of 100-240 V AC, 50/60 Hz, and illuminance of 50 lx.

RGB values were expressed in the range of 0–255. Hue values were expressed in the range of 0–360°, saturation, and color intensity values were expressed in percents (0-100%). RGB values were converted to HSV values based on the transformation algorithm by Smith in [19].

C. Analysis of results

The obtained color components in RGB and HSV color spaces were analyzed visually to indicate the most prominent components. Then, the differences between the shades coded as shown in table III were further analyzed quantitatively by calculating the percentage of unique values of components, Spearman's rank correlation, and Pearson's linear correlation coefficient for the shades in UV and visible light to evaluate the monotonicity and linearity of the changes in color components between the shades which were assigned to an ordinal scale [20], [21].

For the shades in visible light, the Kruskal-Wallis test was additionally conducted to evaluate the significance of changes of the most prominent components in different light intensities. The quantitative analyses were conducted with MATLAB R2020b (MathWorks, Inc., Natick, MA, USA) and Pandas Profiling version 2.11.0 running under Python 3.9.

III. Results

During the study, not all locations in the dental office had the same light intensity because two types of lamps were used and some places were additionally lit by sunlight due to the location of the window. The results of color measurements under visible light are presented in subsection III-A and the results of color measurement under ultraviolet light are presented in subsection III-B.

A. Visible light

The RGB and HSV values of shades in the GC Gradia Direct shade guide measured under visible light are shown in Tab. I and Tab. II.

Each shade in the shade guide has its own value. RGB values are significantly influenced by the changes of light intensity, as observed in table I.

The HSV values of the same shades in the GC Gradia Direct in visible light (see table II) have very similar color intensity value for $E = 130$ lx and $E = 165$ lx. For $E = 201$ lx, the V values of the analyzed shades are more significant and may help distinguish each shade. More prominent feature of the shades are hue and saturation for all analyzed light intensities in visible light.

The relationships of values of color components with the shades for all considered illuminances were also evaluated quantitatively by calculating the Spearman's rank correlation and Pearson's linear correlation coefficients (see table IV), and Kruskal-Wallis test after assigning numbers from 0 to 15 for the shades (see table III). The percentage of distinct component values are shown in table V.

The r values shown in Tab. IV show that the relationship between color components (blue in RGB, hue and saturation in HSV color spaces) and tooth shade is not monotonic and/or linear, except for the hue component in 130 lx ($r = 0.556$, $p < 0.05$), which is monotonic. However, the differences between the blue component, hue, and saturation for each shade as coded in Tab. III in visible light are significant in Kruskal-Wallis test for $p < 0.05$ (see figures 2, 3, and 4 and tables VI, VII, and VIII). In Kruskal-Wallis test results, SS is the sum of squares due to each source, df is the number of degrees of freedom associated with each source, MS are the mean squares for each source, and χ^2 is the test statistic.

TABLE I
RGB VALUES OF GC GRADIA DIRECT SHADES IN VISIBLE LIGHT.

E	Shade	BW	A1	A2	A3	A3.5	A4	B2	B3	C3	CV	CVD	WT	DT	CT	NT	GT
130 lx	Red	255	254	253	253	254	254	254	254	251	253	253	254	254	252	253	240
	Green	255	253	252	247	248	246	254	254	249	248	248	254	254	254	254	241
	Blue	250	241	237	227	225	220	243	238	233	226	224	252	247	248	254	233
165 lx	Red	254	254	250	254	255	254	253	252	245	248	244	254	252	250	251	242
	Green	254	254	253	250	252	246	252	248	239	241	237	254	254	251	252	244
	Blue	250	249	244	226	230	217	235	220	218	212	212	242	252	242	247	240
201 lx	Red	254	248	245	243	211	222	229	230	254	251	243	233	241	249	250	228
	Green	254	252	248	233	206	208	230	219	253	250	209	240	241	250	251	236
	Blue	246	239	225	200	174	168	203	180	235	230	209	225	220	234	236	229

TABLE II
HSV VALUES OF GC GRADIA DIRECT SHADES IN VISIBLE LIGHT

E	Shade	BW	A1	A2	A3	A3.5	A4	B2	B3	C3	CV	CVD	WT	DT	CT	NT	GT
130 lx	H [°]	60	55	56	46	48	46	60	60	53	49	50	60	60	80	180	67
	S [%]	2	5	6	10	11	13	4	6	7	11	11	1	3	2	0	3
	V [%]	100	99.6	99.2	99.21	99.6	99.6	99.6	99.6	98.43	99.21	99.21	99.6	99.6	99.6	99.6	94.5
165 lx	H [°]	60	60	120.7	51.42	52.8	47.02	56.67	52.5	46.67	48.33	46.87	60	120.4	120.2	120.2	120.4
	S [%]	1.57	1.96	3.55	11.02	9.8	14.56	7.11	12.69	11.02	14.51	13.11	4.72	0.78	3.58	1.98	1.63
	V [%]	99.6	99.6	99.21	99.6	100	99.6	99.21	98.82	96.07	97.25	95.68	99.6	99.6	98.43	98.82	95.68
201 lx	H [°]	60	78	68	46	52	44	62	47	57	57	0	88	60	63.75	64	127.5
	S [%]	3	5	9	18	17.53	24.32	11.73	21.73	7.48	8.36	13.99	6.25	8.71	6.4	5.97	3.38
	V [%]	99.6	98.82	97.25	95.29	82.74	87.05	90.19	90.19	99.6	98.43	95.29	94.11	94.50	98.03	98.43	92.54

TABLE III
CODE ASSIGNMENTS FOR AVAILABLE TOOTH SHADES.

Shade	BW	A1	A2	A3	A3.5	A4	B2	B3	C3	CV	CVD	WT	DT	CT	NT	GT
Code	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

TABLE IV
SPEARMAN'S RANK CORRELATION AND PEARSON'S LINEAR CORRELATION BETWEEN THE SHADES IN VISIBLE LIGHT.

Spearman's rank correlation						
Illuminance	130 lx		165 lx		201 lx	
Component	r	p	r	p	r	p
Blue	0.219	0.415	-0.049	0.858	0.196	0.466
Hue	0.556	0.025	0.218	0.417	0.253	0.344
Saturation	-0.380	0.147	-0.100	0.713	-0.265	0.321
Pearson's linear correlation						
Blue	0.235	0.382	-0.012	0.965	0.090	0.741
Hue	0.478	0.062	0.499	0.049	0.252	0.347
Saturation	-0.364	-0.153	-0.153	0.713	-0.227	0.398

TABLE V
PERCENTAGES OF UNIQUE VALUES OF COLOR COMPONENTS.

Visible light			
Illuminance	130 lx	165 lx	201 lx
Component	Uniqueness [%]	Uniqueness [%]	Uniqueness [%]
Blue	93.8	87.5	93.8
Hue	68.8	87.5	87.5
Saturation	68.8	100	100
Ultraviolet light			
Illuminance	50 lx		
Component	Uniqueness [%]		
Green	100		
Hue	87.5		

TABLE VI
RESULTS OF KRUSKAL-WALLIS TEST FOR BLUE.

Source	SS	df	MS	χ^2	p
Columns	5600	15	373.333	28.6	0.0181
Error	3603.5	32	112.609		
Total	9203.5	47			

B. UV light

Because the changes of the measured RGB components of the shades were the most prominent for B component, the color measurement was retaken under ultraviolet light. The RGB and HSV values are shown in table IX.

In RGB color space, the most prominent features of the analyzed shades are green component values, whereas the most prominent features of the shades in HSV color model are hue, for shades BW, A1 and NT, and saturation with the color intensity value for A4 shade. These observations were

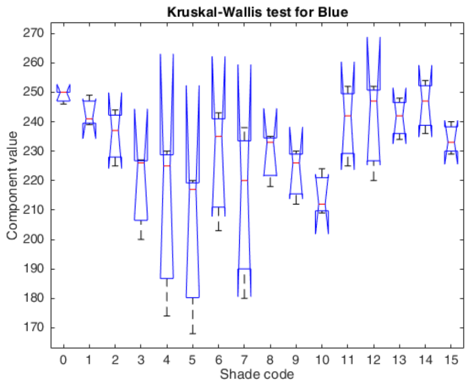

Fig. 2. The boxplot for blue component between the analyzed shades.

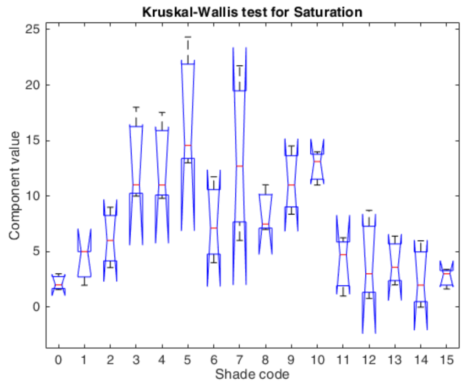

Fig. 4. The boxplot for saturation between the analyzed shades.

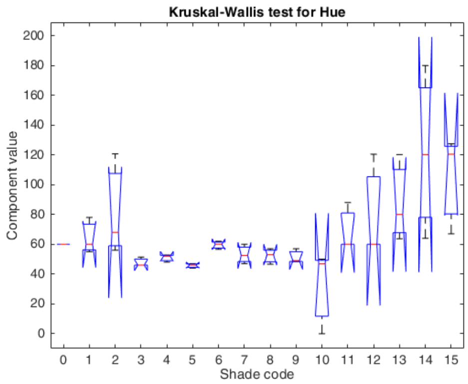

Fig. 3. The boxplot for hue between the analyzed shades.

TABLE VII
RESULTS OF KRUSKAL-WALLIS TEST FOR HUE.

Source	SS	df	MS	χ^2	p
Columns	7431.17	15	495.411	38.27	0.008
Error	1695.83	32	52.995		
Total	9127	47			

TABLE VIII
RESULTS OF KRUSKAL-WALLIS TEST FOR SATURATION.

Source	SS	df	MS	χ^2	p
Columns	6971	15	464.733	35.59	0.0002
Error	2235.5	32	69.859		
Total	9206.5	47			

confirmed by calculating the uniqueness of component values expressed as the percentage of the unique values in table V.

The r values shown in table X show that the association between analyzed variables (green in RGB, hue in HSV, color spaces, and tooth shades) is not monotonic and/or linear for $p < 0.05$.

IV. DISCUSSION

We measured the colors of the GC Gradia Shade Guide in a dental office using a smartphone. Measuring color changes using a smartphone is a challenging task due to the light conditions and non-linear relationship between the light intensity and the RGB of the shade [22]. Aforementioned statement also applies to HSV and CMYK color spaces. These observations were confirmed quantitatively by the Spearman's rank correlation and Pearson's linear correlation coefficients presented in tables IV and X.

The values of components in RGB, HSV and CMYK color spaces depend on the power of the light source, the influence of the daylight, position of the light source, and the distance between the camera and the measured object.

The most prominent features of shades under visible light are the value of blue component in RGB color space, hue, and saturation in HSV color space. These findings were also supported by calculating the uniqueness of values of color components and the results of Kruskal-Wallis tests.

The most prominent feature in ultraviolet light was the green component in RGB model, and hue component in HSV model. That finding was confirmed by calculating the uniqueness of color component values shown in table V. That means that each shade of tooth may be identified by the most prominent changes in RGB and/or HSV components, namely blue, hue, and saturation in visible light, and green and hue in ultraviolet light.

The findings of our study may help develop a model of teeth shades to improve dental care by optimizing the process of color matching in the preparation of dental fillings despite using other approaches to spectrophotometry than described in the literature [11], [12].

The most significant limitation of our study is no evaluation of the influence of daylight on the measured color components and the fact that using smartphone apps in illuminance measurement is not recommended due to the discepancies in measured values between the devices and various apps [23], [24]. However, smartphone cameras are suitable for color measurements [15], [16].

In future studies, we consider other shade guides, more light intensities, and minimizing the influence of daylight and non-uniform light distribution on color measurement. We

TABLE IX
RGB AND HSV VALUES OF GC GRADIA DIRECT SHADES IN UV LIGHT AND E = 50LX.

Shade	BW	A1	A2	A3	A3.5	A4	B2	B3	C3	CV	CVD	WT	DT	CT	NT	GT
Red	12	36	0	0	0	0	0	0	0	0	0	0	0	0	7	0
Green	214	204	175	133	105	66	189	179	120	56	25	13	185	208	199	128
Blue	255	255	255	255	255	255	255	255	255	255	255	217	255	255	255	255
H [°]	190	194	199	209	215	224	196	198	212	227	234	236	196	191	194	210
S [%]	95.29	85.88	100	100	100	100	100	100	100	100	100	100	100	100	97.25	100
V [%]	100	100	100	100	100	100	100	100	100	100	100	85,09	100	100	100	100

TABLE X
SPEARMAN'S RANK CORRELATION AND PEARSON'S LINEAR CORRELATION BETWEEN THE SHADES IN ULTRAVIOLET LIGHT.

	Spearman's		Pearson's	
Component	r	p	r	p
Green	-0.182	0.415	-0.190	0.482
Hue	-0.155	0.567	-0.180	0.505
Magenta	0.182	0.498	0.189	0.484

also consider the development of a mobile app for tooth color measurements which may be used to lower the cost of matching optimal shades of teeth in comparison with buying a commecially available dental spectrophotometer, especially in whitening the color of teeth or filling the cavities with dental fillings.

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