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A Novel Regression Model From RGB Image Data To Spectroradiometric Correlates Optimized For Tooth Colored Shades

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Abstract

Objectives—Objectives of this study were to correlate RGB data from the VITA Linearguide 3D Master and VITA Bleached Guide 3D Master shade guides with their spectroradiometric correlates through a regression model while indicating a methodology for validation of accuracy of digital imaging systems. Additional objectives were to provide summary RGB data and to determine a relationship between lightness and RGB values for these shade guides.

Methods—Radiant energy measurements and images were taken with a Canon Rebel T3i and Macro Ring Lite MR-14EX for each shade tab. RGB data was extracted using Image J and compared with spectroradiometric measurements. Regression models relating the RGB data to spectroradiometric counterparts in CIE XYZ and absolute reflectance were developed using SAS 9.3. Image data was statistically analyzed to determine a relationship between RGB values and lightness.

Results—Regression models with R^2 values greater than .99 for RGB to XYZ and greater than .95 for RGB to absolute reflectance were developed. Summary RGB data for the shade guides including Pearson correlation coefficients ranging between $-.92$ and $-.97$ for RGB related to lightness was determined.

Conclusions—A relationship between RGB and lightness for the shade guides was found. Regression models were developed that allow tooth color information to be translated from digital images to accurate shade tab correlates for color matching purposes in dentistry. This allows for optimal color accuracy when using digital imaging to translate color information and provides a method of validating digital imaging systems for color accuracy.

Keywords

digital images; RGB; color matching; regression model; color accuracy; CIEDE2000; CIEL*a*b*; spectroradiometry

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Introduction

Digital imaging for use in color matching of craniofacial and dental materials is a topic of present interest and continual development. Digital cameras are user friendly, relatively inexpensive, and readily available. The color information obtained from digital images can be easily manipulated into information that is relevant in a dental setting. For these reasons digital cameras are currently a good target device for the advancement of color matching in dental and craniofacial settings. Information obtained from a digital camera is generally input in a RGB color space that is device dependent and must be converted to a device independent standard color space (1). Because this information is device dependent, accurate color data management requires appropriate adjustment and calibration in order to be able to accurately utilize the color information extracted from a digital image (2, 3). Because there are so many digital imaging devices that can be used, obtaining accurate color information that is device independent is necessary in order to standardize color information.

There are several categories of devices that are currently used in clinical settings for shade matching in dentistry. Spectrophotometers are considered to be amongst the most accurate and functional devices for these purposes (4). These devices measure the amount of light energy that is reflected from a specific object along the spectrum of visible light in 1-25 nm intervals (5, 6). A spectrophotometer is made up of an optical radiation source, a light dispersing source, an optical measuring system, a detector, and a means of converting light to a signal for analysis and manipulation that is useful to the investigator (7). In the dental setting, the measurements obtained clinically are often compared to shade guide data to find the optimal shade tab counterpart (8). Colorimeters are another device used for color measurement and shade matching. The data that they acquire is often very precise because contact is made with the actual tooth (9). However, these devices do not measure spectral reflectance and are less accurate than spectrophotometers (10). Conventional colorimeters that utilize CIE recommended geometries for reflection measurements are generally not best for use of measuring objects with a translucent nature due to inaccuracies caused by the optical phenomenon of edge effects (11).

For color analysis involving digital camera sources, conversion equations from the red, green, blue (RGB) color space system to the CIELAB color space system are useful and necessary (12). Once the RGB values are converted to XYZ values, they can be easily converted to the CIELAB values (13).

Because RGB data obtained from a digital camera is device dependent, there is a need for the design and constant refinement of more complex calibration models that render optimal accuracy (2, 3). In a study by Wee et al., four calibration models were evaluated with three different digital cameras using the cameras' RGB values compared to the CIELAB values as a reference standard for accuracy measurements defined by E (1). A second order polynomial regression (PRM2), a second order polynomial regression with eleven terms (PRM2-11), a third order polynomial regression (PRM3), and a model based on tetrahedral interpolation (TI) technique were all compared for accuracy (1, 14).

In general, accuracy was improved by increasing the terms and raising the order of the regression model with proper terms being more important than increase of terms (1, 3). In this study, three out of 12 calibration/camera pairs were found to be below the E acceptability limit of 2.1 lending to the idea that inexpensive digital cameras used in combination with specific calibration methods have potential in the clinical processes involving color replication (1, 15).

The specific objectives of this study were to develop a regression model that would relate digital RGB data from the VITA Linearguide 3D Master and VITA Bleached Guide 3D Master shade guides with their spectroradiometric correlates and to define a methodology of validating a digital image system for color accuracy. An additional aim was to provide summary RGB data and its relationship to lightness for the VITA Linearguide 3D Master and the VITA Bleached Guide 3D Master shade guides.

Materials and Methods

Each of thirty five shade tabs included in a VITA Linearguide 3D Master shade guide and each of fifteen shade tabs included in a VITA Bleached Guide 3D Master shade guide were characterized by measuring the radiant energy using the spectroradiometer (PR 705; Photo Research Inc, Chatsworth, Calif) and a Xenon arc lamp (300W; Oriel Instruments, Stratford, Conn), with a connected fiber optic light cable. The spectroradiometer and optic light cable were fixed onto an optical table (Mecom Inc., Rising Sun, Ohio) and were placed inferiorly to the horizontal plane at a 45-degree angle in order to result in a 0-degree observation and a 45-degree illumination optical configuration for measurement. A measurement of radiant energy was produced for this central point on the standard from 380 nm to 780 nm in increments of 2 nm (Spectrawin 2.0; Photo Research Inc.) (16). The central ninth of each shade guide tab was measured. The radiant energy data was immediately converted to spectral reflectance and then to CIE XYZ values (17).

Digital images were taken of the same points on the shade tab specimens using a Canon Rebel T3i with an aperture setting of F22, an ISO of 200, a shutter speed of 1/200, the focal length set to .39, and the white balance set to a standard gray card. A Canon Ring Lite MR-14EX flash was used with a ¼ flash output. RGB values were extracted from the images of the central ninth of each of fifty shade tabs with Image J Image Analysis Software. Two to three measurements of RGB data from the images for each of eighteen shade tabs were taken using the central ninth of each shade tab. Duplicated shades within the two shade guides were treated as individual shade tabs and measured separately. Averages of multiple measurements were taken for each shade tab in its relative holder where multiple measurements were taken. Intraclass correlation coefficients for shade tabs that were measured multiple times and for shade tabs that were duplicated within the shade guides were determined using the SAS GLM procedure (PROC GLM, SAS ® Proprietary Software 9.3, SAS Institute Inc., Cary, NC, USA). This procedure was done in order to determine the reliability of the RGB determination methodology used and in order to analyze the variability in same shade designations within the VITA Linearguide 3D Master and the VITA Bleached Guide 3D Master shade guides (18). The means of the RGB values were determined for each shade represented in the two shade guides used. These means were then

used for the regression model determination. A linear regression model without y-intercept relating RGB values to XYZ values was generated using linear regression without intercept programming (PROC REG, SAS ® Proprietary Software 9.3, SAS Institute Inc., Cary, NC, USA.) This regression utilized all of the thirty six distinct shades that were included in both shade guides. The R value was determined in order to indicate a level of correlation between the two systems of color description. Using this regression model, the RGB values were then converted to Commission Internationale d'Eclairage XYZ tristimulus values with D65 illumination and a 2-degree observer (13). The spectral reflectance data from the same specimens was also converted to XYZ values in the CIE standard color space (13). This regression would allow digital images to provide color information for a wide range of tooth color shades that can be used to accurately translate color information.

SAS 9.3 was used to determine summary RGB data and its relationship to lightness for each shade tab in the VITA Linearguide 3D Master and the VITA Bleached Guide 3D Master shade guides.

Results

Table 1 contains summarized data from the shade tabs contained in the VITA Linearguide 3D Master and the VITA Bleached Guide 3D Master shade guides.

Table 2 contains the intraclass correlation coefficients for multiple RGB measurements of the same shade tab.

Table 3 contains the intraclass correlation coefficients for multiple shade tabs with the same shade designation.

Figure 1 demonstrates how the slopes of the regression which are the regression coefficients for RGB vary with wavelength in the visible spectrum.

Predictions of reflectance from RGB using the determined regression model at wavelengths 400 nm, 500 nm, and 600 nm can be seen in Figure 2.

Figure 3 shows the predictions of XYZ from RGB using the determined regression model.

Table 4 displays the R-squared values for the regressions from RGB to XYZ and to absolute reflectance at wavelengths 400 nm, 500 nm, and 600 nm.

Table 5 displays basic statistics for the RGB data with the lightness number from the shade guide (L3D).

Table 6 displays the correlation coefficients squared for L3D related to RGB values and the P-values from a test of the hypothesis of no correlation.

Discussion

The regression data from RGB to both XYZ and reflectivity spectra is the foundation for translation of the theoretical color matching to a clinical color matching system that uses

digital imaging. The regression model allows for a color range that is relevant over all tooth shades that can be represented in the VITA Linearguide 3D Master and the VITA Bleached Guide 3D Master shade guides. The high R squared values for predictions of reflectance indicate that the regression is a good fit and explains a high proportion of the variance in reflectance. The charts indicating RGB values for each shade in the shade guide provide a summary of this data for the entire shade guide. The high intraclass correlation coefficients for multiple measurements of the same shade tab indicate a reliable system of measurement. The intraclass correlation coefficients for multiple shade tabs with the same shade designations indicate high reliability and little variability for G and B measurements while measurements of R had the most variability. In addition, the high correlation coefficients between the RGB values each with the L3D value indicate a statistically significant relationship between the RGB values and the lightness or value number indicated on the shade guide.

Conclusions

Summarized RGB data was derived for the VITA Linearguide 3D Master and the VITA Bleached Guide 3D Master shade guides and a statistically significant relationship between RGB and lightness was also determined for these shade guides.

A regression model was derived using a range of shades relevant to tooth color in order to translate RGB data to spectral reflectivity data and XYZ data. This model could serve as the foundation for a means of translating clinical color information from a digital image to information that could be used by a shade selection program to give a prediction of the best shade to select for an optimal color match.

These regression models are especially sensitive to shade ranges relevant to tooth color as the VITA Linearguide 3D Master and the VITA Bleached Guide 3D Master shade guides were the main sources of shade information as input for the regression models. This regression renders the color information from a digital image clinically relevant for a wide range of tooth color shades that can be used to accurately translate color information for color matching purposes in restorative and prosthodontic dentistry. In addition, this methodology serves as a means of validating the color accuracy of digital imaging systems.

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Figure 1.
RGB Regression Slopes Varied by Wavelength

Figure 2.
Predicted Reflectance Varied by Actual Reflectance at Wavelengths 400, 500, and 600 nm

Figure 3.
Regression Predicted Tristimulus Value Varied by Actual Tristimulus Value

Table 1

Summary of Frequency, Mean, and Range of Shade Tabs from the VITA Linearguide 3D Master and the VITA Bleached Guide 3D Master Shade Guides

Variable	N	Mean	Minimum	Maximum
XCap	50	40.52	26.73	58.43
YCap	50	42.21	26.91	61.60
ZCap	50	31.95	14.08	61.60
L*	50	70.50	58.89	82.70
a*	50	1.54	-1.06	5.23
b*	50	18.33	4.75	30.05

Table 2

Intraclass Correlation Coefficients for Multiple RGB Measurements of the Same Shade Tab.

	Shrout-Fleiss Reliability Single Score
R	0.94
G	0.97
B	0.98

Table 3

Intraclass Correlation Coefficients for Multiple Shade Tabs with the Same Shade Designations

	Shrout-Fleiss Reliability Single Score
R	0.84
G	0.97
B	0.97

Table 4

Regression R-Squared Values

Dependent Variable	R-Squared
X-Cap	1.00
Y-Cap	1.00
Z-Cap	0.99
Absolute Reflectance 400 nm	0.96
Absolute Reflectance 500 nm	0.97
Absolute Reflectance 600 nm	0.95

Table 5

Simple Statistics for RGB Values with Lightness Number From Shade Guide (L3D)

Variable	N	Mean	Std Dev	Min	Max
B	36	43766	6933	32230	57330
G	36	51112	4143	43564	58475
R	36	55540	2137	50377	59179
L3D	36	2.74	1.49	0	5.00

Table 6

Pearson Correlation Coefficients Squared for RGB Related to L3D and the P-Values from a Test of the Hypothesis of No Correlation

	R	G	B
L3D	0.85 [P<.0001]	0.97 [P<.0001]	0.94 [P<.0001]