Designation: E2466 – 13

Standard Test Method for Colorimetry of Teeth Using Digital Still Camera Technology[1]

This standard is issued under the fixed designation E2466; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

Tooth color is an important parameter used to ascertain certain medical and esthetic information. CIE colorimetric values for the teeth are derived from the native RGB signals generated by a digital still camera, DSC, by broadband measurement of the reflectance of teeth. The illumination angle is 45 degrees and CIELAB colorimetric coordinates are computed using equations contained in Practice E308. This test method, E2466, specifies the procedure used for the measurement of tooth color *in-vivo* and *in-vitro* with illumination at 45 degrees relative to the sample plane which is also the normal of the mouth, under an approximate equal energy spectrum. This test method is appropriate for anterior and posterior teeth.

1. Scope

1.1 This test method covers the procedure, instrumental requirements, standardization procedures, material standards, measurement procedures, and parameters necessary to make precise measurements of *in-vivo* tooth color and tooth whiteness. In particular it is meant to measure the color of teeth in selected human subjects.

1.2 Digital images are used to evaluate tooth color of both posterior and anterior dentition (teeth). All other non-relevant parts, such as gums, spaces, etc., must be separated from the measurement and the analysis. All localized discoloration; such as stains, inclusions, etc., may be separated from the measurement and the analysis.

1.3 The broadband reflectance factors of teeth are measured. The colorimetric measurement is performed with a digital still camera while using an illuminator(s) that provides controlled illumination on the teeth. The measured data from a digital image are captured using a DSC. This test method is particularly useful for the gamut of tooth color which is:

1.3.1 CIE L* from 55 to 95,

1.3.2 CIE a* from 3 to 12,

1.3.3 CIE b* from 8 to 25 units.

1.4 The wavelengths for this test method include that portion of the visible spectrum from 400 to 700 nm.

1.5 Data acquired using this test method is for comparative purposes used during clinical trials or other types of research.

1.6 This test method is designed to encompass natural teeth, artificial teeth, restorations, and shade guides.

NOTE 1—This procedure may not be applicable for all types of dental work.

1.7 The apparatus, measurement procedure, data analysis technique are generic, so that a specific apparatus, measurement procedure, or data analysis technique may not be excluded.

1.8 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D2244 Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates

E179 Guide for Selection of Geometric Conditions for Measurement of Reflection and Transmission Properties of Materials

[1] This test method is under the jurisdiction of ASTM Committee E12 on Color and Appearance and is the direct responsibility of Subcommittee E12.06 on Image Based Color Measurement.

Current edition approved Jan. 1, 2013. Published January 2013. Originally approved in 2006. Last previous edition approved in 2011 as E2466 – 06 (2011). DOI: 10.1520/E2466-13.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

E284 Terminology of Appearance
E308 Practice for Computing the Colors of Objects by Using the CIE System
E313 Practice for Calculating Yellowness and Whiteness Indices from Instrumentally Measured Color Coordinates
E1345 Practice for Reducing the Effect of Variability of Color Measurement by Use of Multiple Measurements
E1767 Practice for Specifying the Geometries of Observation and Measurement to Characterize the Appearance of Materials

2.2 *ISO Publications:*[3]
ISO 17321-1 Colour characterization of digital still cameras (DSCs) – Part 1: Stimuli, metrology, and test procedures

2.3 *ISCC Publications:*[4]
Technical Report 2003-1 Guide to Material Standards and Their Use in Color Measurement

3. Terminology

3.1 Terms and definitions in Terminology E284 are applicable to this test method.

3.2 *Definitions:*

3.2.1 Terms included in this section are peculiar to this standard.

3.2.2 *angle of incidence, n*—θ_1 and optional θ_2, the polar angle between the central ray of the illuminator(s), I_1 and I_2, and the Z axis which is normal to the camera. See Fig. A1.1.

3.2.3 *anterior teeth, n*—anterior teeth are the six upper and six lower front teeth; the anterior teeth consist of incisors and cuspids (canines).

3.2.4 *bit depth, n*—the number of digital bits used to store information contained in each pixel.

3.2.4.1 *Discussion*—The higher the depth, the more colors are in an image. With 8 bit-per-channel color, there are a total of 256 bits available for color representation in each of the R, G, B channels. RGB 8 bit-per-channel color is sometimes called "24 bit color."

3.2.5 *canine, n*—the third tooth from the center of the mouth towards the back of the mouth; these are the front teeth that have one rounded or pointed edge used for biting.

3.2.6 *facial surfaces, n*—of or toward the face, used to designate the side of the tooth that is facing away from the tongue side.

3.2.7 *in-vitro, adj or adv*—in an artificial environment outside of the human body.

3.2.8 *in-vivo, adj or adv*—within a living body; that is, measurements made of a living tooth in a living body.

3.2.9 *maxillary anterior teeth, n*—the four front upper incisors and the canine teeth. See Fig. A1.5.

3.2.10 *native digital still camera spectral response function, n*—the function relating scene radiance to image intensity of an imaging system is called the digital still camera spectral response function.

3.2.11 *polarization, n*—the orientation of the vibration pattern of light waves in a singular plane.

3.2.12 *polarizer filter, n*—a component that blocks one of the two planes of vibration of an electromagnetic wave, producing linearly polarized light.

3.2.12.1 *Discussion*—A polarizing filter can be used in sunglasses to reduce glare.

3.2.13 *posterior teeth, n*—posterior teeth are the large teeth in the back of the mouth.

3.2.14 *spatial whitening response, n*—the evaluation of color or color change used to determine unit dosing.

4. Summary of Test Method

4.1 This test method describes the procedures for broadband reflectance measurement of teeth, *in-vivo* and *in-vitro*. The standardization of the instrumentation used to measure a subject's teeth is defined. The basis for the selection of specimens and the measurement protocol given. The data from the reflectance measurements are converted to colorimetric values. The results are reported in terms of CIE tristimulus values, other colorimetric coordinate system values, and colorimetric indices.

5. Significance and Use

5.1 The light reflected from the facial anterior teeth can be used to calculate color coordinates. Monitored over time, changes in color can be observed. These data reveal information about the efficacy of a product, treatment study, or epidemiology of tooth color. For example, clinical studies of consumer tooth whitening systems evaluate the efficacy of manufacturers' products.

5.2 The change in color of the facial surfaces of anterior teeth can be used to optimize the efficacy of tooth whitening systems. For example, the data can provide the answer the question: "What is the optimum percentage of whitening agent in a consumer tooth whitening system?"

5.3 This procedure is suitable for use in research and development, marketing studies, comparative product analyses, and clinical trials.

5.4 Prior research shows that a popular visual assessment method of determining tooth color, changes in tooth color, and whiteness among clinicians yields less than desirable results (**1-4**). These assessment tools are designated "shade guides." They consist of tooth-shaped, synthetic objects in the form of teeth all of slightly different colors or different shades from one another. A "shade" is generally regarded as a color slightly different from a reference color (on a comparative basis). The colors of the synthetic teeth in these "shade guides" do not

[3] Available from International Imaging Industry Association (I3A), 701 Westchester Avenue, Suite 317W, White Plains, NY 10604, 914-285-4933, isotc42@i3a.org.

[4] Available from ISCC, Inter-Society Color Council, 11491 Sunset Hills Rd., Reston, Va, 20190, iscc.org.

progress linearly as observed visually or logically in a CIE colorimetric coordinate system,[5] and they are metameric to real teeth.

5.5 *Translucency*—Human teeth are translucent and the degree of translucency varies widely between subjects. However, translucency does not vary over the short term and is not therefore a consideration in this test method.

6. Interferences

6.1 If the standard laboratory conditions listed in 6.2 change during the test or from test to test by an appreciable amount, these conditions may cause interferences, and the accuracy and precision requirements of this test method may not be achieved. In some cases these effects may only be observed during the performance of the test.

6.2 *Factors Effecting Test Results*—The following factors are known to affect the test results.

6.2.1 *Environmental:*

6.2.1.1 *Extraneous Radiation*—Extraneous light from other sources and near-infrared (NIR) radiations must be shielded from the test apparatus.

6.2.1.2 *Vibrations*—Mechanical oscillations that cause components of the apparatus to move independently from one another may cause errors in test results.

6.2.1.3 *Thermal Changes*—Temperature changes occurring during a test or differences in temperature between testing locations may affect the reflectance factor of the standardization, calibration, and verification plaques, and the apparatus spectral response function.

6.2.1.4 *Power Input Fluctuations*—Large changes in the line frequency or supply voltage may cause the apparatus to report erroneous results.

6.2.2 *Retractors*—The surface finish of the retractors affects the experimental test results. It has been determined that a neutral (clear) finish on the surface of the retractors may introduce a bias into the test results.

6.3 *Standardization*—The system must allow for successful standardization.

6.4 *Equipment Operation*—If the system cannot be standardized, a series of checks must be performed (lighting, camera, etc.) to identify the reason. The component of the system in error will be adjusted or replaced to bring the system back into calibration.

6.5 *Controlling Factors:*

6.5.1 These interferences may be eliminated and problems avoided by controlling and regulating each factor within the constraints of the allowable experimental error. The values and limits for these factors are typically determined experimentally.

7. Apparatus

7.1 *General*—The components described in this section are described generically. The intention is not to exclude any component from being used, or to exclude any type of instrument that may be available commercially. Between 4 and 6 different components or component assemblies are required to accomplish the measurement.

7.2 *Geometry*—The geometry of the system is 45:0 as described in Practice E1767 and Guide E179. The DSC System Geometry (Coordinate System) and Angular Convention are shown in Fig. A1.1.

7.3 *Components*—A block diagram of these component assemblies is shown diagrammatically in Fig. A1.2.

7.3.1 *Source Illumination Assembly*—Contains the source of illumination and associated optics to produce irradiance, *E*, on the sample over a specified spot area, designated *A*. The source is broadband and continuous in nature. A diagrammatic representation of the components of a typical Source Illumination Assembly Unit is shown in Fig. A1.3.

7.3.2 *Source Beam(s)*—A collimated or slightly converging beam(s) focused on the sample plane. Since the shape and position of the specimens being measured vary widely, a small convergence angle minimizes local variations in intensity. Two beams located at 45° relative to the normal of the sample plane are required to examine posterior teeth (on each side of the mouth) and to achieve the uniformity requirements.

7.3.3 *Position*—Typically the Source Illumination Assemblies are in a fixed position relative to the sample (Subject) holder and the DSC. Therefore, small variations in θ are minimized. The angle θ is the subtended angle between the Source Illumination Assembly Units and the DSC. Refer to Fig. A1.1.

7.3.4 *Source Optical Elements*—The optical elements must condition the radiation from the source so that it is spatially uniform within ±10 %. The distance, d, from the DSC to the sample plane must be selected to maintain the uniformity requirements. Refer to Fig. A1.6.

7.3.5 *Spectral Power Distribution*—The exact spectral nature of the illuminator is immaterial for the measurement of teeth and non-fluorescent specimens so long as the source is stable with time and has adequate energy at all wavelengths in the region required for measurement. An approximation to D50 provides an equal energy spectrum over the area of interest for DSCs. Commonly used light sources include incandescent lamps, either operated without filters or filtered to simulate standard illuminants, flashed or continuous-wave xenon-arc lamps and discrete pseudo-monochromatic sources, such as light emitting diodes (LEDs).

7.3.6 *Polarization*—The linear polarizer provides and controls the polarization state of the incident light. This polarizer on the illuminators plus a cross polarizer filter on the lens system of the DSC eliminates glare caused by reflection of the subject's teeth during imaging. Wavelength range, extinction ratio, transmittance, and beam deviation are important parameters and must be selected.

7.3.7 *Heat Rejection Filters*—These filters remove undesired near-infrared (NIR) radiation including heat that adversely affects the subject and provide spectral shaping of the spectral power distribution of the source illumination.

7.3.8 *Selective Blue Filters*—These filters condition the spectral power distribution of the illumination so that the

[5] Available from University of Michigan, http://www.lib.umich.edu/dentlib/Dental_tables/Colorshadguid.html.

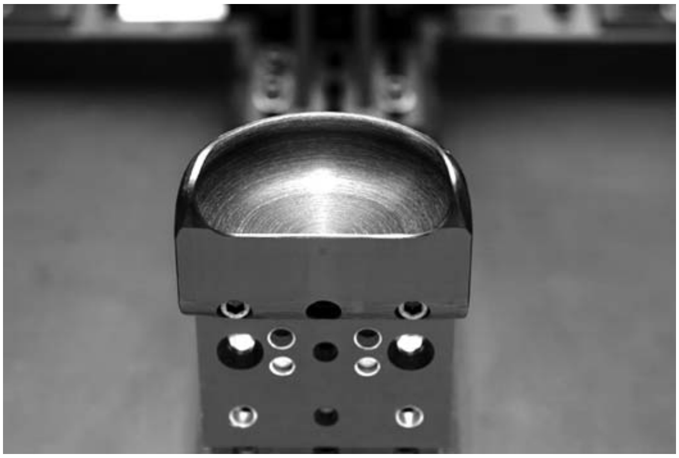

FIG. 1 Chin Rest

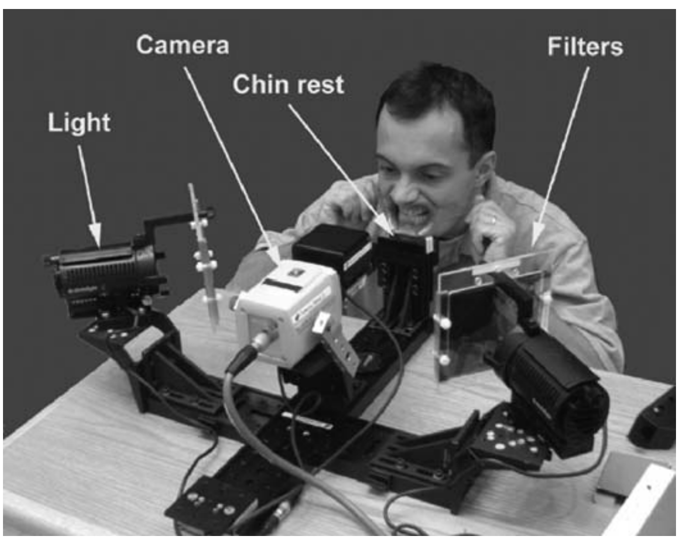

FIG. 2 Subject Positioned in Instrumentation

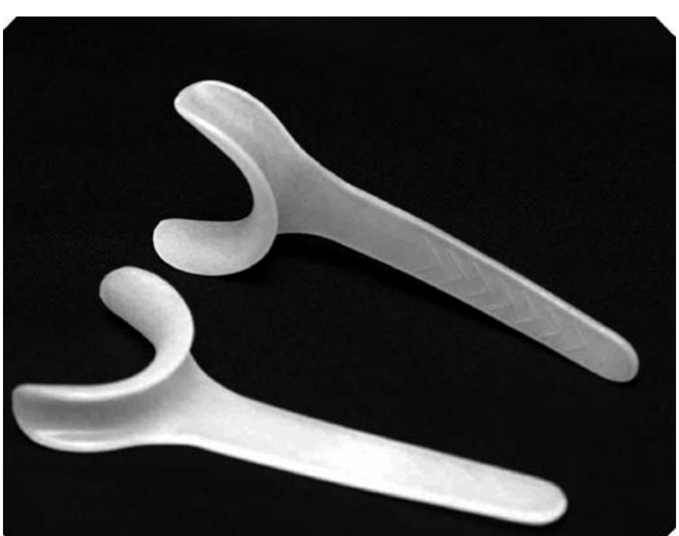

FIG. 3 Matte Lip Retractors

spectral power distribution is similar to an approximate equal energy spectrum, such as illuminant D50.

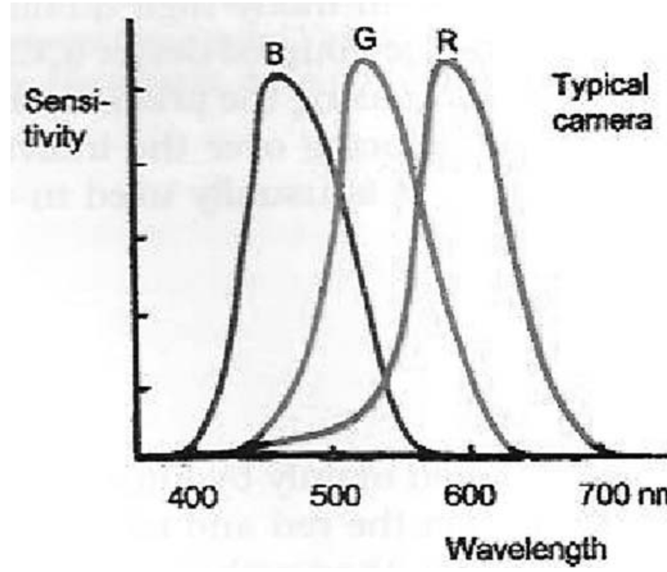

FIG. 4 Typical DSC Native Spectral Response Function

7.4 *Sample Plane Holder*—The sample plane holder provides a secure mount so that it positions the subjects incisors normal to the Z axis and centered along the X and Y axes. This must be done so that the teeth are presented to the DSC in a repeatable and reproducible manner. The sample mount must be kept unobtrusive so that it is "friendly" and not intimidating to the subjects. A chin rest is used to precisely position the subjects relative to the instrumentation. The subjects place their chin on a chin rest which is a quarter-cup shaped rig, as shown in Fig. 1. Fig. 2 shows a subject correctly positioned in the instrument for measurement. Lip retractors,[6] as shown in Fig. 3, are used to expose the majority of the subject's teeth and gingiva to the DSC system. Subjects hold their head straight, join the tips of their upper and lower incisors together and place their tongue against the top of their mouth.

NOTE 2—Some people cannot do that, so they might keep a space between their teeth.

The facial surface of the central incisors should be aligned with a line marked on the chin rest indicating the center along the X axis.

7.5 *Detector Optical Elements:*

7.5.1 The typical detector optical elements are shown in Fig. A1.4 included in Annex A1.

7.5.2 The linear cross polarizer provides and controls the plane of polarization or the E-vector of the electromagnetic wave. This linear cross polarizer eliminates unwanted reflection of the subject's teeth during imaging. The linear cross polarizer must be rotated around the optical axis of the beam to change the plane and state of polarization; therefore eliminating the strong reflection caused by the wetness of teeth during measurement. This cross polarizer must be oriented perpendicular, 90°, to the Source Polarizing elements. The linear cross polarizer assembly is shown in Fig. A1.4.

[6] Retractors with a matte finish have been found satisfactory for this purpose.

7.6 *Digital Still Camera*—The DSC must have several performance characteristics.

7.6.1 *Depth of Focus*—The depth of focus of the camera and lens combination must be sufficient to accommodate the anterior and posterior teeth, and differences in specimen positioning along the optical axis caused by natural variations between subjects.

7.6.2 *Detectors:*

7.6.2.1 *Known Native Spectral Response*—To characterize the broadband measurement the native RGB (spectral) response of the cameras' detectors must be known. Different manufacturers have different spectral responses. (**5**) Typical native spectral response functions of DSCs are shown in Fig. 4. These data are available from the DSC manufacturer or may be derived from a number of measurement methodologies. (**6**)

7.6.2.2 Either a 3 chip RGB DSC or a single chip RGB DSC will perform adequately in this application.

7.6.2.3 *Field of View*—The field of view of the DSC and lens combination must be sufficient to accommodate differences in specimens occurring natural in subjects and include the entire Area A as shown in Fig. A1.6. There can be no exception to this requirement.

7.6.3 *Bit Depth*—The bit depth must be 8 bits or greater per channel to accommodate accurate conversion of the digital signals into CIE color spaces. Bit depth of 8 bits is commonly available.

7.6.4 *Acceptance Aperture*—The aperture of the lens system must be well defined and sufficient to accommodate the angular resolution of the sample and illuminate the detector chip.

7.7 *Computer Interface:*

7.7.1 The interface to the DSC must be capable of being interfaced and controlled by a computer.

7.7.2 White balance and black balance must be settable and reproducible by the computer.

7.7.3 Exposure control must be settable and reproducible by the computer.

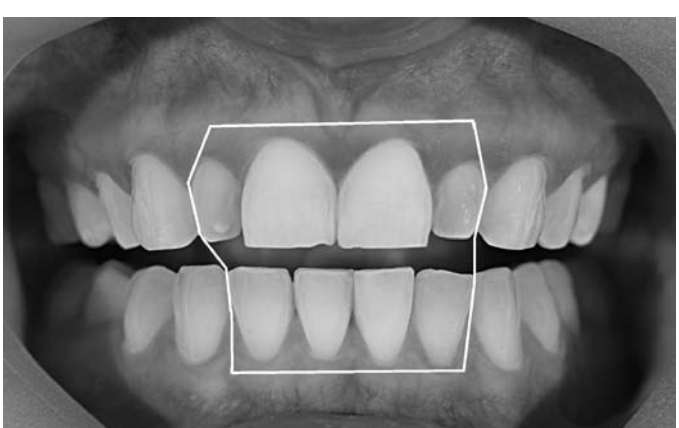

FIG. 5 Example of Mask Including 8 Incisors

7.7.4 Gain control should be selectable and settable by the computer.

7.7.5 It is desirable to have a live video output for validating the positioning of the human subjects and test specimens prior to capturing the image.

7.7.6 For image analysis purposes, it is recommended that image files be stored without compression, but any lossless file format may be used.

8. Sampling, Test Specimens, and Test Units

8.1 *Selection of Subjects:*

8.1.1 Generally, healthy volunteers who provide informed consent and meet study entrance criteria are chosen for the study. For example, study entrance requirements may require candidates to have a tooth color within a certain specified range and no visible defects in the facial surfaces of the anterior teeth; such as, inclusion, fissures, staining, etc.

8.1.2 Candidates may be excluded due to tooth sensitivity, prior participation in a study, or restorative dentistry involving the facial surfaces of the anterior teeth.

8.2 *Sampling:*

8.2.1 The Region of Interest is determined from the clinical protocol; for example, 8 anterior teeth.

8.2.1.1 *Example—In-vivo* tooth color measurement. Reference Fig. 5.

8.2.1.2 Choose the number of teeth included in the evaluation.

8.2.1.3 Typically a software mask is created to identify the measured areas. These can include some or all the incisors and include or exclude the canines.

8.2.1.4 The gum areas near the teeth are also masked and excluded. Typically, the distance between the mask edge and the gum line is between 1 and 3 mm.

8.2.2 *Sub Sampling*—The average R, G, B values for each tooth and the number of pixels in each tooth needs to be calculated. Table 1 is an example of the calculation results that determine the average R, G, and B raw data values and the computation to L*, a*, b* coordinates. Each study will have unique sub-sampling requirements depending upon the objectives of the study.

8.3 *Identifying Areas of Interest*—Areas of interest means identifying the specimen tooth, whose digital form is pixels, to be examined, measured, and subsequently classified.

8.3.1 *Pixel Classification*—Pixel classification is accomplished by calculating the scalar distance in RGB color space from the pixel to be classified to the median of each pre-defined class. Classes are statistically established using a priori identification to segregate the teeth from plaque, gums, spaces, etc. This procedure is usually called discriminant analysis. The pixel is classified into the group to which the scalar distance in RGB space between the pixel being examined and the average value for a class is at a minimum.

TABLE 1 Sub Sampling

Filename	Subject	Visit	Tooth Pixels	# Pixels	% Tooth A	Tooth A Red	Tooth A Green	Tooth A Blue	L*	a*	b*
2005V05.TIF	1003	5	158611	26798	16.90 %	204.1	183.6	155.3	71.48	6.37	18.76
2005V05.TIF	1003	10	169855	112167	66.04 %	208.5	192.4	167.6	75.89	4.69	15.20
2005V05.TIF	1003	15	166105	107741	64.86 %	206.6	191.7	166.7	75.40	4.25	15.06
2005V05.TIF	1003	20	167800	111798	66.63 %	205.8	190.4	166.4	75.30	4.53	14.65
2005V05.TIF	1004	5	109917	20775	18.90 %	214.3	191.9	160.5	73.11	6.97	18.91

8.3.2 Mathematically, the notation used to describe the test method is:

R,G,B = intensity value for Red, Green and Blue for each pixel (0-255 scale),
x = 1 × 3 matrix of Red, Green and Blue values of pixel x,
t = subscript denoting class (that is, plaque, gums etc.),
m_t = 1 × 3 matrix containing mean RGB values of class t,
S = RGB covariance matrix of class t, and
S_t = determinant of Covariance matrix.

The mean RGB colors contained in m_t and the covariance matrix S_t for each class is calculated from pixels from representative images. Ten subjects for a total of 7500 pixels were used to define means and variances of each of the classes.

The covariance matrix $\mathbf{S}_t$ for class t is:

S_t =

	R	G	B
R	Cov (R,R)	Cov (R,G)	Cov (R,B)
G	Cov (R,G)	Cov (G,G)	Cov (B,G)
B	Cov (R,B)	Cov (B,G)	Cov (B,B)

$$\text{Cov}\,(X,Y) = 1/n*(X_i - u_x)(Y_i - u_y) \quad (1)$$

where:

X_i and Y_i = i-th Red Green or Blue value in class t, and
u_x and u_y = the mean Red, Green or Blue value of class t.

The inverse matrix (S_t^{-1}) is defined such that $S_t^{-1}*S_t$ is the identity matrix:

	R	G	B
R	1	0	0
G	0	1	0
B	0	0	1

The generalized squared distance from pixel x to class t is given by the following equation:

$$D_t^2 = (x) = (x - m_t)'*S_t^{-1}*(x - m_t) + logS_t \quad (2)$$

The pixel is then segregated into the class where the distance is at a minimum.(7)

9. Preparation of Apparatus

9.1 *Warm up:*

9.1.1 Temperature stabilizes the equipment and the facility to a temperature between 20 and 23.9°C (68 and 75°F). Approximately one hour is required for the equipment to reach thermal equilibrium.

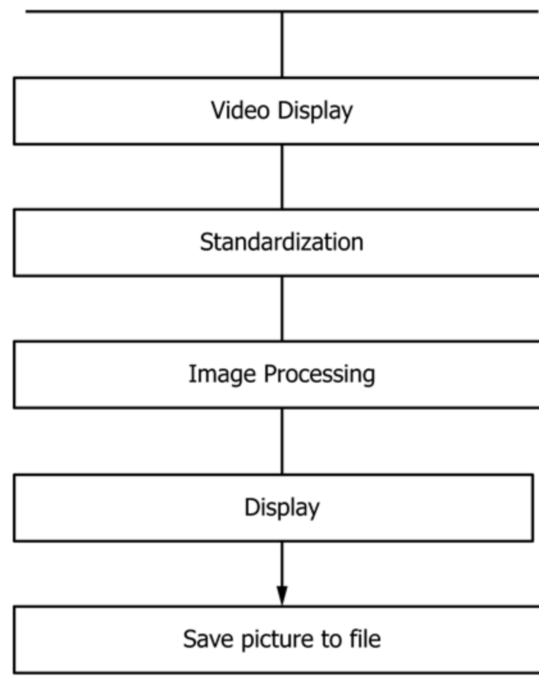

FIG. 6 Typical Digital Still Camera Application Software Workflow

9.2 *Software:*

9.2.1 Turn on the computer and launch the appropriate applications.

9.2.2 The software used to capture the images may be custom in nature, developed specifically for the application. Available commercial software programs may be used.

9.2.3 Typical software workflow for DSC acquisition and processing. See Fig. 6.

9.3 *Hardware:*

9.3.1 Display the live video image. Start the software that provides the "video display."

9.3.2 *Align the Source Illumination Unit:*

9.3.2.1 Adjust the illumination on the measurement plane so it is centered and uniform.

9.3.2.2 Using the illumination adjustment screws fine tune the position of the illuminated area so that it is aligned with the center of the sample plane. A centering target is necessary to locate the center of the measurement plane in the horizontal and vertical axes. The horizontal axis of the test target allows the illuminators to be aligned in the vertical axis. The horizontal axis of each illuminator is offset from the geometric axis of the test fixture so that the beams from each illuminator overlap. This minimizes the non-uniformity of the energy distribution in the measurement plane.

9.3.2.3 Adjust the position of the source illumination assembly unit (lighting source element) so that the intensity of each source illumination assembly unit is uniform over the measurement plane.

9.3.2.4 Secure the adjusting screws and verify that the alignments of the source illumination units are correct with the alignment screws secure.

9.3.3 *Aligning the Digital Still Camera Unit:*

9.3.3.1 Adjust the DSC alignment screws to align the optical axis of the digital camera system so that it is perpendicular to the subject (measurement plane).

9.3.3.2 The software should provide an alignment "cross hair" in the exact center of the viewed image to center the DSC precisely.

9.3.3.3 Secure the alignment screws.

9.3.3.4 Verify that the alignment of the DSC is correct with the alignment screws secure.

9.3.4 *Adjust the Optical Elements:*

9.3.4.1 Depending upon the actual configuration it may be necessary to align and focus the lens first. See 9.3.6.

9.3.5 *Align the Polarizers:*

9.3.5.1 Adjust the illuminator's polarizers so that they are cross polarized relative to the DSC. This will minimize the effect of reflections.

9.3.5.2 Install the polarization detection and alignment test fixture A chrome sphere is installed in the sample plane. A sphere ensures that reflections from the source illumination units will be seen by the DSC. This reflection component is minimized by adjusting the polarizers to the cross polarizer position so that the reflection is extinct.

9.3.5.3 Polarization Detector and Alignment Test Fixture. See Fig. 7.

9.3.5.4 Position the polarizers so that the indicator marks are on the top. The indictor marks indicate the nominal polarization axis of the polarizers. Aligning these filters nominally aligns the polarization axes of the polarizing filters with the vertical axis of the test fixture. Placing the polarizers in the "pointing up" position is a good starting point.

9.3.5.5 Adjust the polarizer retaining screw and rotate the polarizer on the DSC, shown as detector optical elements in

FIG. 7 Polarization (E-Vector) Detection and Alignment Test Fixture

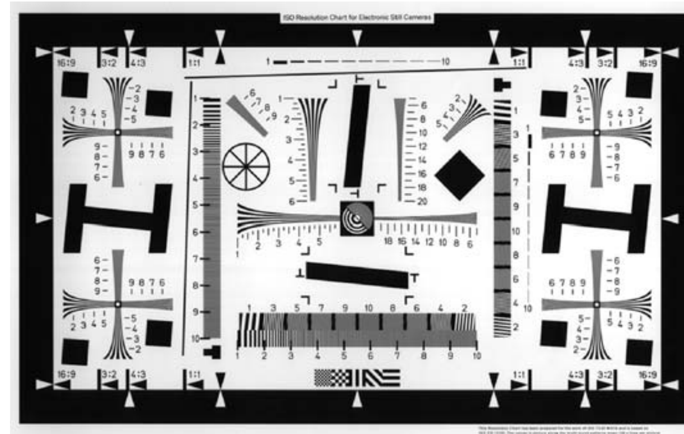

FIG. 8 Resolution Chart

Fig. A1.4 until the reflection caused by the polarizing test fixture disappears; that is, goes to extinction or a minimum.

9.3.5.6 Secure the polarizer retaining screw on the DSC.

9.3.5.7 Adjust the polarizer retaining screw and rotate the polarizer on the left source illumination assembly unit until the reflection caused by the gloss of the polarizing test fixture disappears; that is, goes to extinction or a minimum. Secure the polarizer retaining screw on the left source illumination assembly unit.

9.3.5.8 Adjust the polarizer retaining screw and rotate the polarizer on the right source illumination unit until the reflection caused by the gloss of the polarization detection and alignment test fixture disappears; that is, goes to extinction or a minimum. Secure the polarizer retaining screw on the right source illumination assembly unit.

9.3.5.9 Adjust the polarizer retaining screw and rotate the polarizer on the DSC until the reflection caused by the gloss of the polarization detection and alignment test fixture goes to extinction or a minimum. Secure the polarizer retaining screw on the DSC optical element assembly.

9.3.5.10 Secure the polarizer retaining screw on the DSC. The polarizers are correctly aligned.

9.3.6 *Focus the DSC Lens:*

9.3.6.1 Place a focusing target in the sample plane. A resolution chart as shown in Fig. 8[3] is adequate for these purposes.

9.3.6.2 Loosen the DSC focusing mechanism and adjust the focusing ring of the lens system until the displayed image is the sharpest.

9.3.6.3 Secure the focusing ring on the camera lens system and validate that the focus of the image did not change. Readjust if necessary.

10. Conditioning

10.1 *Apparatus:*

10.1.1 The system is ready for standardization after all electronic components are turned "on" and allowed to stabilize after one hour of warm up at the beginning of each study day.

10.2 *Human Subjects*—The human subjects to participate in the study are to prepare themselves for examination and measurement by brushing their teeth with water only, prior to image capture.

11. Calibration and Standardization

11.1 Calibration and its verification are essential steps in ensuring that precise and accurate results are obtained by colorimetric measurements. They require the use of physical standards. Physical standards are supplied by commercial instrument manufacturers, standardizing laboratories, and other sources.[7] It remains the user's responsibility to obtain and use the physical standards necessary to keep their instrument in optimum working condition.

11.2 Calibration consists of uniformity adjustments, black correction, zero (0) calibration, full scale (100 %) calibration, and color correction.

11.3 *Radiometric Scale:*

11.3.1 *Zero (0) Calibration*—All photometric devices have some inherent photocurrent, even in the absence of light, called dark current. This so called "dark current" must be measured and subtracted from all subsequent readings computationally. The zero and 100 % calibration plaques are usually contained within the test targets used for color calibration.

11.3.2 *Full Scale (100 %) Calibration. Radiometric Scale Calibration*—A physical standard is normally used for calibration. The 100 % calibration plaque is usually contained within the test target used for color calibration.

11.3.3 *Uniformity Adjustment*—The system response may be non-uniform over the sampling area. This can be attributed to a number of factors, including: lighting, optical system, and detector response. A physical standard whose reflectance is nearly constant over its surface is imaged and any non-uniformity in the output over the sampling plane is compensated for mathematically.

11.4 *Global Color Calibration:*

11.4.1 The use of a Digital Still Camera, DSC, as a colorimeter requires the "raw"[8] sensor output of the camera be processed so that the data are device independent values; that is, CIE tristimulus values, typically CIE *X, Y and Z.*

11.4.1.1 The power distribution of the energy impinging on the detector elements is a product of the spectral power distribution of the source, $P(\lambda)$, the reflectance of the object, $R(\lambda)$, which gives:

$$R = \int_{400}^{700} P(\lambda)R(\lambda)D_{R_{Raw}}(\lambda)d\lambda \quad (3)$$

$$G = \int_{400}^{700} P(\lambda)R(\lambda)D_{G_{Raw}}(\lambda)d\lambda \quad (4)$$

$$B = \int_{400}^{700} P(\lambda)R(\lambda)D_{B_{Raw}}(\lambda)d\lambda \quad (5)$$

where:

$D_{(R,\ G,\ or\ B_{Raw})}$ = the spectral responsivities of the camera RGB channels respectively.

Typically the integration range is from 400 to 700 nm. To remove the dependency regress the camera outputs from the known calibration targets to approximate the Luther condition; that is, that there is a linear transformation from the raw DSC outputs to the *CIE XYZ* values. The device independent values are defined and calculated in a similar manner as the following equations:

$$X = \int_{400}^{700} P(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda \quad (6)$$

$$Y = \int_{400}^{700} P(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda \quad (7)$$

$$Z = \int_{400}^{700} P(\lambda)R(\lambda)\bar{z}(\lambda)d\lambda \quad (8)$$

There are several papers published on methods used to characterize cameras.**(8-10)**

11.5 *Localized Color Calibration*—Time based standardization is accomplished by regressing DSC raw data of the color standards to determined colorimetric values. The selected color standards surround the area in color space of the specimens being examined. In this case they are near white as defined in Section 1. The determined colorimetric values of the color standards are established after a validated system has reached operational equilibrium. When several different systems are deployed, the average data from multiple systems is one of the best methods for establishing these determined colorimetric values. The parameters for the regression equations are generated by capturing digital images of the color standards and extracting the average DSC RGB values.

11.5.1 The power distribution of the energy impinging on the detector elements is a product of the spectral power distribution of the source, *P(λ)*, the reflectance of the object, *R(λ)*, which gives:

$$R = \int_{400}^{700} P(\lambda)R(\lambda)D_{R_{Raw}}(\lambda)d\lambda \quad (9)$$

$$G = \int_{400}^{700} P(\lambda)R(\lambda)D_{G_{Raw}}(\lambda)d\lambda \quad (10)$$

$$B = \int_{400}^{700} P(\lambda)R(\lambda)D_{B_{Raw}}(\lambda)d\lambda \quad (11)$$

where:

$D(R_{Raw},\ G_{Raw},\ or\ B_{Raw})$ = the spectral responsivities of the camera RGB channels, respectively.

Typically the integration range is from 400 to 700 nm.

11.5.2 Absolute artifact standards are collected that represent the colorimetric range of CIELAB color space to be examined as specified in 11.5. Color atlases such as the Munsell Book of Color[9] have been found useful for this purpose.

11.5.3 The determined colorimetric values are calculated from the following:

$$S_{tandardized} = f(R_{captured}, G_{captured}, B_{captured}) \quad (12)$$

where:

f = a polynomial regression of the captured RGB values of the DSC of the color standards at the time of calibration regressed against the absolute standard values for the same color standards when the system was initially calibrated.

[7] ISCC Publications, Technical Report 2003-1*Guide to Material Standards and Their Use in Color Measurement*.

[8] In this case "raw" sensor output refers to the output of the DSC before the signal is adjusted for white point correction.

[9] Munsell Book of Color is available from GretagMacbeth at www.gretagmacbeth.com.

NOTE 3—In this case, the polynomial f is determined by regression analysis of the values obtained from the DSC against the standard absolute values of the Munsell Chips.

11.5.4 The use of a DSC as a colorimeter requires the "raw"[8] sensor output of the camera be processed so that the data are device dependent values. These DSC RGB values are converted to CIELAB values by using multiple regression techniques:

$$L^* = f(R_i, G_i, B_i) \tag{13}$$

$$a^* = f(R_i, G_i, B_i) \tag{14}$$

$$b^* = f(R_i, G_i, B_i) \tag{15}$$

where:

i = chip number, and
f = a regression function of the absolute calibrated CIELAB values for the Munsell color chips against their predetermined RGB values.

There is a published paper using a similar method of characterizing digital still cameras. This technique is used with other digital devices.(11)

11.6 *Verification*—After the zero, full-scale, and color calibration are performed the linearity of the scale should be verified by measuring one or more calibrated standards having intermediate reflectance factors. The linearity verification test should be made using different material standards than those used to calibrate the DSC.

The precision of the measurement system, including calculation of CIE tristimulus values, should be determined by periodic measurement of calibrated verification standards. Examples of suitable verification standards include reflecting ceramic colour standards.[10]

11.7 *Procedure*—The procedure detailed below contains steps required to acquire data. All operations are required in the order presented. Other systems may require additional steps.

11.7.1 Initialize the system.

11.7.1.1 Turn on the lights at least 1 hour before taking measurements.

11.7.1.2 Allow the system and the environment to thermally stabilize.

11.7.2 Turn on the computer system.

11.7.3 Launch the image capture application.

11.7.3.1 Display the live video image.

11.8 Validate the equipment is set up correctly.

11.9 Standardize the system.

11.9.1 Uniformity.

11.9.1.1 Place the uniformity tile in the measurement plane and capture the image.

11.9.2 Color Standardization.

11.9.2.1 Place the black "0" calibration device in the measurement plane and capture the image.

11.9.2.2 Place the full scale "100 %" calibration device in the measurement plane and capture the image.

(1) Place the color target in the measurement plane and capture the image.

11.9.3 Prepare the human subjects.

11.9.3.1 A set of retractors is used to expose the measurement area of the teeth. Have the subject place retractors in their mouth, then position themselves in the measurement plane.

11.9.3.2 Ensure that the subject is at the correct height, that their chin is on the chin-rest, their forehead against the registration bar, and that they are oriented perpendicular to the camera.

11.9.4 Capture the image.

11.9.4.1 The image of the subject's teeth must be captured within 30 seconds from the moment the subject is positioned to minimize the effects of dehydration of the teeth.

11.9.4.2 Actuate the software to capture the image.

11.9.5 Validate the quality of the image.

11.9.5.1 Visually examine the image and ensure that the subjects' teeth are centered, fully exposed, the image in focus, and there are no unexpected shadows in the image. Additionally, the tooth area must be exposed for analysis by digital imaging processing.

12. Calculation or Interpretation of Results

12.1 *Color Coordinates:*

12.1.1 *Data Calculation*—Perform any desired calculations of color coordinates that are not made automatically by the software (see Practices D2244 and E308).

12.2 *Interpretation of Results:*

12.2.1 Evaluate the change in color and color appearance in terms of component values of CIELAB or an index; such as, DE*, or WI* in accordance with Practice D2244 and E313. The magnitude and direction of color change is evaluated against the protocol.

13. Report

13.1 Include the following information in the report. Mandatory and Recommended information are so indicated. These metadata are to be included in every image.

Number	Section	Mandatory	Desired
13.1	**Format**		
13.1.1	Compression Scheme	X	
13.2	**Photometric interpretation**		
13.2.1	Color Space		X
13.2.2	Color Profile		X
13.2.3	Reference White	X	
13.2.4	Reference Black		X
13.3	**Segments**		
13.3.1	Number of Rows		X
13.3.2	Number of Cells		X
13.3.3	Number of Columns		X
13.3.4	Pattern		X
13.4	**File**		
13.4.1	File Size	X	
13.4.2	Check Sum		X
13.4.3	Image Identifier		X
13.4.4	Orientation		X
13.4.5	Display Orientation		X
13.5	**Computer**		
13.5.1	Host Computer	X	
13.5.2	OS		X
13.5.3	Capture Software	X	
13.5.4	Capture Software Version		X

[10] BCRA Standards are available from multiple sources. See ISCC Technical Report 2003-1, *Guide to Material Standards & Their Use in Color Measurement*.

Number	Section	Mandatory	Desired
13.6	**Digital Camera**		
13.6.1	Manufacturer		X
13.6.2	Manufacturer Model Number		X
13.6.3	Manufacturer Serial Number	X	
13.6.4	F# (number)		X
13.6.5	Resolution		X
13.6.6	Exposure Setting		X
13.6.7	Focal Length		X
13.7	**Image Capture**		
13.7.1	13.5 Date	X	
13.7.2	13.6 Time	X	
13.7.3	13.7 Operator	X	
13.7.4	13.8 Location	X	
13.8	**Calibration**		
13.8.1	R, G, B		X
13.8.2	White Point	X	
13.9	**Calibration Target**		
13.9.1	Target ID		X
13.9.2	Target Serial Number	X	
13.10	**System**		
13.10.1	Last Calibration	X	
13.10.2	Last Standardization	X	
13.11	**Image Processing**		
13.11.1	Date Processed	X	
13.11.2	Time Processed	X	
13.11.3	Who processed		X
13.11.4	Software Name		X
13.11.5	Software Version		X
13.11.6	Processing Actions		X

13.2 The information presented in 13.1 may be recorded in the technical metadata part of an image file. JPEG2000[11] is the normative reference for metadata.

14. Precision and Bias

14.1 The repeatability data were obtained in June 2005 using a BCRA Series II white standard used as the test specimen. 30 consecutive measurements were gathered in the shortest possible period of time.

14.2 The reproducibility data were obtained over the period of April to May 2005. The specimens tested are a sub-set of the BCRA Ceramic Tiles Series II standards. The instrument population consisted of 3 DSC colorimeters in a single laboratory.

14.3 *Repeatability*—Two test results obtained under repeatability conditions, which are defined as measurements made in the same laboratory using the same test method by the same operator using the same equipment in the shortest possible period of time using specimens taken from one lot of homogeneous material, should be considered suspect to a 95 % repeatability limit if their values differ by more than 0.045 unit, ΔE^*ab.

14.4 *Reproducibility*—Two test results made under reproducibility conditions, which are defined as measurements made in different laboratories using different equipment using the same test method, each by a different operator using specimens taken from one lot of homogeneous material, should be considered suspect to a 95 % reproducibility limit if their values differ by more than the values given in Table 2 under the column headed "Reproducibility Limits." Table 2 contains Specimen names, CIELAB Colorimetric Values, and Reproducibility Limits for the specimens used in the test method.

14.5 *Context Statement*—The precision statistics cited for this test method must not be treated as exact mathematical quantities that are applicable to all DSC colorimeters, uses, and materials. There will be times when differences occur that are greater than those predicted by the interlaboratory study leading to these results would imply. Sometimes these instances occur with greater or smaller frequency than the 95 % probability limit would imply. If more precise information is required in specific circumstances, those laboratories directly involved in a material comparison must conduct interlaboratory studies specifically aimed at the material of interest.

14.6 *Improving Precision*—Practice E1345 may be useful for improving measurement precision.

14.7 *Bias*—Since there is no accepted reference material, method, or laboratory suitable for determining the bias for the procedure in this test method for measuring the whiteness of tooth color with a digital still camera, the bias is unknown and undeterminable at this time. Therefore, no statement of bias is being made.

15. Keywords

15.1 colorimetry; DSC; digital camera; digital; teeth; whiteness; whitening

TABLE 2 Reproducibility Limits

Specimen	Mean CIE L*	Mean CIE a*	Mean CIE b*	95 % Reproducibility DE^*_{ab}
Pale Grey	84.1	-0.3	0.5	1.46
Medium Grey	61.1	0.0	0.4	1.02
Deep Grey	36.5	-0.5	0.3	1.14
Deep Pink	47.1	26.5	5.9	2.57
Red	48.3	44.9	23.3	4.28
Orange	70.0	41.8	56.4	2.67
Bright Yellow	86.0	0.8	73.7	2.37
Green	57.1	-28.6	11.9	2.09
Cyan	54.5	-16.1	-31.7	3.17
Deep Blue	11.0	13.8	-30.1	3.42
White	97.2	-0.2	1.5	2.22
Black	20.6	4.5	-1.8	2.10
Matte White	96.9	-0.1	2.5	2.10
Neutral Gray	85.8	-1.5	6.4	1.86
			Average	2.32

[11] JPEG2000 is available from http://jpeg.org/JPEG2000.html.

ANNEX

(Mandatory Information)

A1. DIGITAL CAMERA SYSTEM COMPONENTS, GEOMETRY, AND NOMENCLATURE ILLUSTRATIONS

A1.1 DSC System Geometry (Coordinate System) and Angular Convention

A1.1.1 It is common practice to define the geometry of an optical system (Fig. A1.1).

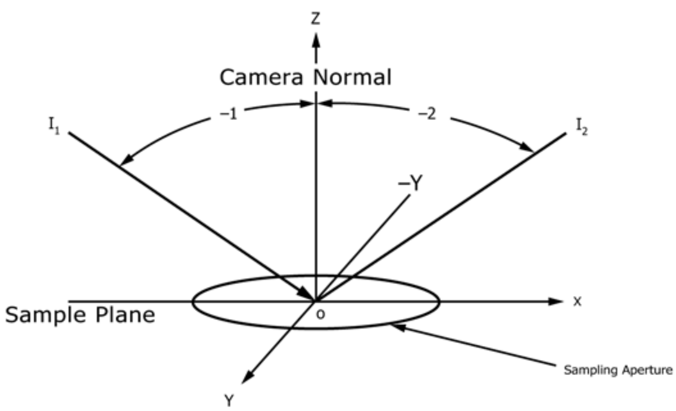

FIG. A1.1 Angular Coordinate Conventions

A1.1.2 The camera normal is perpendicular to the sample plane. The incident radiation is offset in the about the Y axis by 45 degrees. See Guide E179.

A1.2 Typical Block Diagram for a Digital Still Camera Based Colorimeter

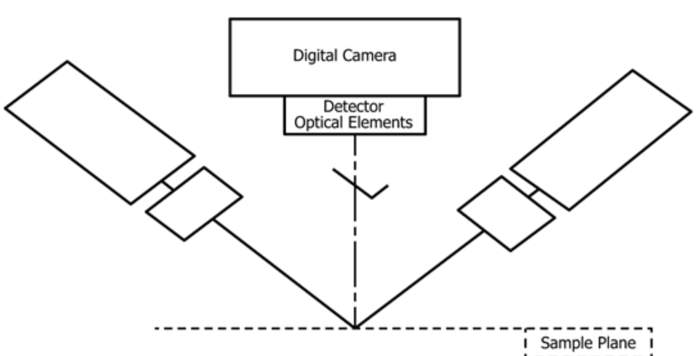

FIG. A1.2 Typical Block Diagram-Camera Based Colorimeter

NOTE A1.1—The illumination angle may have to be changed from the nominal 45 degrees when examining the posterior teeth.

A1.3 Typical Block Diagram for Source Illumination Unit

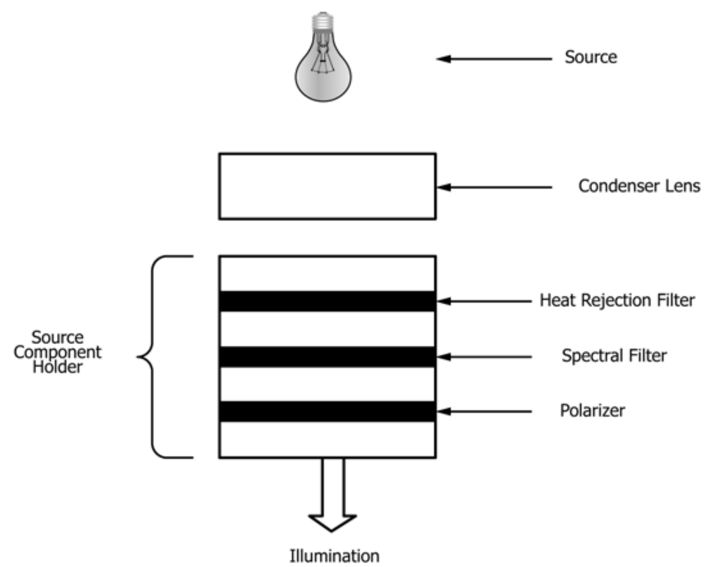

FIG. A1.3 Typical Source Illumination Assembly Unit

A1.4 Typical Block Diagram for Detector Optical Elements

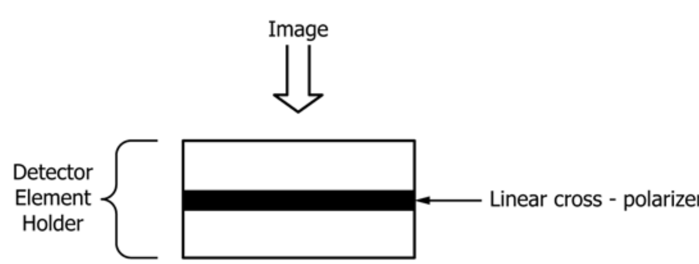

FIG. A1.4 Typical Detector Optical Elements

A1.5 Nomenclature and Identification of Teeth

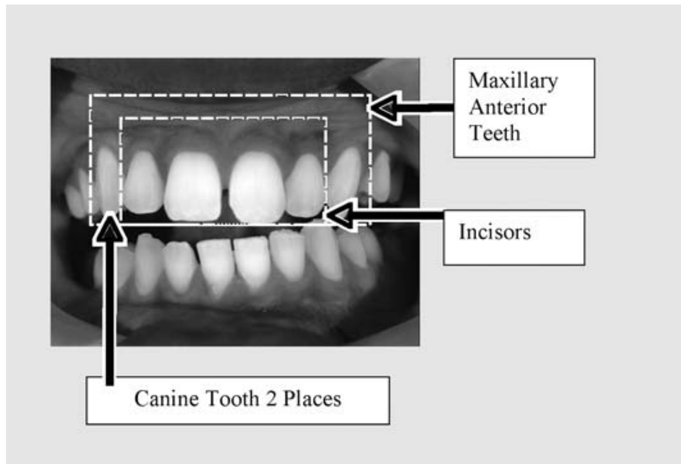

FIG. A1.5 Nomenclature and Identification of Teeth

A1.6 Digital Camera System Geometry

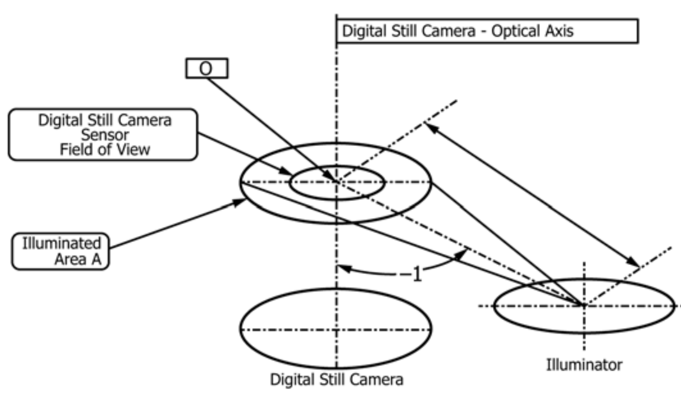

FIG. A1.6 Digital Still Camera System Geometry

REFERENCES

(1) O'Brien, W.J., Groh, C. L., and Buenke, K.M., *A One Dimensional Color Order System for Dental Shade Guides*, Dental Materials 5: pp. 371-374, 1989, 2004http://www.healthmantra.com/ypb/jan2002/shade%20selection.htm.

(2) Vislio, David, Gaffar, Abdul, Fakhry-Smith, Sarah, and Xu Tao, *Present and Future Technologies*, Compendium June 2000, p. 537-538.

(3) Nathoo, Salim, Chmielewski, B.A, and Rustogi, Keday, N., *Clinical Evaluation of Colgate Palmolive Tooth Whitening System and Rembrandt Lighter Bleaching Gel*, Compendium 1994 , Supplement 17, p. S6444.

(4) Barissan, J.C., Journal of Clinical Research.

(5) Hunt, Dr. R.W.G., *The Reproduction of Colour*, p. 556, John Wiley & Sons, West Sussex, England.

(6) DiCarlo, Jeffrey M., Montgomery, Glen Eric, and Trovinger, Steven W., *Emissive Chart for Imager Calibration*, Proceedings. 12th Color Imaging Conference. 2004.

(7) Those interested in discovering more on discriminant analysis are referred to Huberty, Carl J., *Applied Discriminant Analysis*, Wiley, www.wiley.com.

(8) Pointer, M.R., *Practical Camera Characterization for Colour Measurement*, IS&T's 2001 PICS Conference Proceedings.

(9) Hong, G., *A Study of Digital Camera Characterization Based on Polynomial Modeling*, Color Research & Application, 2000.

(10) Wendell, Brian A., Farrell, J., *Water into Wine: Converting Scanner RGB to Tristimulus XYZ*, Proceedings of the SPIE, San Jose, 1993.

(11) Berns, R. S, and Reiman, D. M., *Color Managing the Third Edition of Billmeyer and Saltzman's Principles of Color Technology, Color Research and Application*, Vol 27, p. 362 (October 2000).