Designation: E2670 – 15

Standard Test Method for Objective Quantification of Dental Plaque Using Digital Still Cameras[1]

This standard is issued under the fixed designation E2670; 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

Dental plaque is a biofilm, which grows on teeth and surrounding tissue. In many cases, dental plaque is the underlying cause of many oral diseases, that is, cavities and gum diseases. Thus, controlling dental plaque through its removal and inhibition of re-growth is essential to maintaining good oral health. Today, there are hundreds of products produced to control dental plaque. Examples are; toothbrushes, toothpastes, floss, rinses, gums and routine dental cleanings. One universal design objective maximizes plaque control through enhanced cleaning ability or chemistry which inhibits plaque growth; that is, anti-bacterial agents. Often, the effectiveness of a product or procedure is measured in a clinical trial with traditional methods of estimating plaque coverage. For example, the modified Turesky index is often used. This index is an integer scale ranging from 0 (no plaque) to 5 (complete plaque coverage). The clinical examiner estimates the numerical value or score based on visual observation of the plaque. Unfortunately, there are drawbacks to this approach. First, the scale is non-linear with respect to plaque area coverage. Second, the application of the scale is subjective by nature. Therefore, an objective method of measuring the amount of plaque on teeth represents a significant improvement in the science of plaque measurement.

1. Scope

1.1 This method covers the procedure, instrumental requirements, standardization procedures, material standards, measurement procedures, and parameters necessary to make precise measurements of dental plaque on the teeth revealed by fluorescence. In particular it is meant to measure the amount of plaque and plaque coverage on human teeth.

1.2 Digital images are used to measure the coverage of dental plaque on the teeth using discrimination analysis. All localized discoloration, such as stains, inclusions, pigmentations, etc., may be separated from the measurement and the analysis. All other non-relevant parts, such as teeth, tongue, spaces, dental restorations or prostheses, etc., must be separated from the measurement and the analysis.

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

1.3 The broadband reflectance factors of the teeth and surrounding tissue are measured. The colorimetric measurement is performed using an illuminator system that provides controlled illumination on the teeth and surrounding tissue. A Digital Still Camera (DSC) is used to capture the digital image.

1.4 Data acquired using this method may be used to assess personal plaque coverage for the purposes of identifying overall health status, health status at specific sites in the mouth, or to track changes in personal health status for individuals over time. Pooled data may be used to assess plaque coverage, health, disease among populations in epidemiological surveys, evaluation of comparative product efficacy, or safety and treatment response in clinical trials involving plaque coverage or disease.

1.5 The apparatus, measurement procedure, and analysis technique described herein are generic. The intent is not to exclude a specific apparatus, measurement procedure, or analysis technique.

1.6 The values stated in SI units are to be regarded as standard. The values in parenthesis are for information only.

1.7 *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 determine the applicability of regulatory limitations prior to use.*

[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 Display, Imaging and Imaging Colorimetry.

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2. Referenced Documents

2.1 *ASTM Standards:*[2]

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

E284 Terminology of Appearance

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

ISO/IEC 15444-1:2000–JPEG2000 Information technology — JPEG 2000 image coding system — Part 1: Core coding system, commonly known as JPEG 2000 jp2 file format

2.3 *ISCC Publications:*[4]

Technical Report 2003-1 Guide to Material 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:* Terms included in this section that are peculiar to this standard.

3.2.1 *angle of incidence, n*—θ_1 and θ_2 optional, the polar angle between the central ray of the illuminator(s), I_1 and I_2, and the Z axis, which is the optical axis of the camera.

3.2.1.1 *Discussion*—These are shown in Fig. A1.1.

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

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

3.2.3.1 *Discussion*—The bit depth determines the maximum number of colors that may be encoded by the system. For example, a 24 bit system comprising 8 bits per channel can encode $2^8 \times 2^8 \times 2^8$ or about 17 million colors; far more than are distinguishable by the human observer.

3.2.4 *biofilm, n*—a complex aggregation of microorganisms.

3.2.4.1 *Discussion*—Biofilms have been implicated in the formulation of dental plaque and gingivitis.

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 *dental plaque, n*—a biofilm consisting of bacteria in an intrabacterial matrix, which adheres to teeth.

3.2.7 *disclosing agent, n*—a dye which binds to, adsorbs to or is physically retained in the plaque matrix.

3.2.7.1 *Discussion*—Common disclosing agents are fluorescein, erythrosine, fast green, and methylene blue.

3.2.8 *facial surfaces, n*—the surfaces of teeth and gingiva that are oriented outward toward the lips (labial) and cheeks (buccal), and facing away from the tongue or roof of the mouth.

3.2.9 *in-vivo, adj*—within a living body.

3.2.9.1 *Discussion*—Pertaining to measurements made in a living body.

3.2.10 *NIR cutoff filter, n*—an optical filter that does not pass wavelengths longer than 700 nm.

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

4. Summary of Test Method

4.1 This method describes the procedures for in-vivo broad band reflectometry of the subjects' teeth, plaque, and surrounding tissue.

4.2 This method describes the standardization of the measurement instrumentation used to measure a subject's teeth.

4.3 The DSC captures and stores the RGB values of the images. The data from the reflectance measurements are analyzed to discriminate between plaque, teeth, and surrounding tissue.

4.4 Discrimination analysis allows one to calculate percentage of plaque coverage on teeth.

4.5 Guidelines are given for disclosing of plaque.

5. Significance and Use

5.1 The light reflected from the teeth and emitted from the plaque on the teeth is captured by a DSC. Digital data extracted from the images can be used to discriminate and classify pixels. Monitored over time, changes in plaque coverage can be observed. An example is a clinical study of the efficacy of tooth brushes to remove dental plaque.

5.2 Assessing the quantity and coverage of dental plaque on teeth can be used to optimize the design of products and procedures intended to reduce dental plaque coverage.

5.3 Clinical assessment, for example, the modified Turesky Plaque Index,[5,6] is a subjective, non- linear, integer based scale that may require extensive examiner training and recertification. The method described here provides increased precision, repeatability, and reproducibility in comparison to other methods.

5.4 This procedure is suitable for use in research and development, marketing claims and advertising, comparative product analysis, and clinical trials.

[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.

[3] Available from International Imaging Industry Association (13A), 701 Westchester Ave., Suite 317W, White Plains, NY 10064, www.13A.org.

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

[5] Turesky S., Gilmore, N. D., Glickman I., "Reduced plaque formation by the chloromethyl analogue of Vitamin C," *Journal of Periodontology*, Vol. 41, 1970, pp. 41-43.

[6] QuigleyG. A., and Hein J. W., "Comparative cleansing efficiency of manual and power brushing," *Journal of the American Dental Association*, Vol. 65, 1962, pp. 26-29.

6. Interferences

6.1 The interferences identified below 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. If the standard laboratory conditions listed below 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.

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

6.1.1.1 *Extraneous Radiation*—Light including near infrared from sources other than the illuminator(s) must be shielded from the test apparatus.

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

6.1.1.3 *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.

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

6.1.2 *Retractors*—The surface finish of the retractors affects the experimental test results. It has been determined that a glossy finish on the surface of the retractors may introduce a bias into the test results.

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

FIG. 1 Subject Positioned in Chin Rest

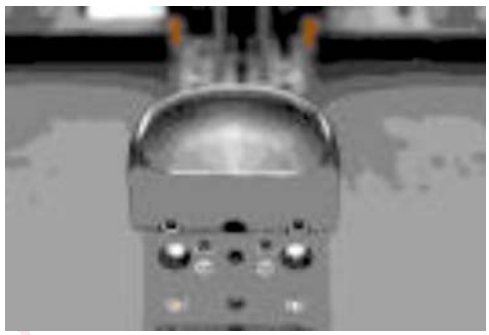

FIG. 2 Chin Rest

FIG. 3 Matte Lip Retractors

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 recommended in Practice E1767. The DSC System Geometry (Coordinate System) and Angular Convention are shown in Fig. A1.1, included in Annex A1.

7.3 *Components*—A block diagram of component assemblies is shown in Fig. A1.2, included in Annex A1.

7.3.1 *Source Illumination Assembly*—Contains the illumination source and associated optics to produce irradiance, *E*, on the sample over a specified spot area, designated *A*. A diagram of the components of a typical illumination system is shown in Fig. A1.3, included in Annex A1.

7.3.2 *Spectral Power Distribution*—The exact spectral nature of the illuminator is immaterial for the measurement. The source must be stable with time and have adequate energy at the wavelengths of interest. The illumination must excite the disclosing agent. 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 monochromatic or polychromatic sources, such as light emitting diodes (LEDs).

7.3.3 *Sample Plane Holder*—The sample plane holder provides a secure mount so that it positions the subject's 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 can be used to precisely position the subjects relative to the instrumentation (Fig. 1). The subject

places their chin on a chin rest which is a quartercup shaped rig, as shown in Fig. 2, chin rest.

7.3.4 *Lip Retractors*[7](Fig. 3) are used to expose the majority of the subject's teeth to the DSC. The subject holds the head straight, join the tips of the upper and lower incisors together, and places the tongue against the top of the mouth. 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.

7.3.5 *Detector Optical Elements:*

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

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

7.3.6.1 *Depth of Focus*—The depth of focus of the camera and lens combination must be sufficient to accommodate differences in positioning, teeth geometry, and natural variations between subjects.

7.3.6.2 *Detectors*—Either a 3 chip RGB DSC or a single chip RGB DSC will perform adequately in this application.

7.3.6.3 *Field of View*—The field of view of the DSC and lens combination must be sufficient to accommodate differences in positioning, teeth geometry, and natural variations between subjects. This geometry is shown in Fig. A1.6, included in Annex A1. There can be no exception to this requirement.

7.3.6.4 *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. A bit depth of 8 bits is commonly available.

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

7.4 *Computer Interface:*

7.4.1 The DSC must be capable of being interfaced and controlled by a computer.

7.4.2 White Balance and Black Balance must be adjustable by the computer through the interface.

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

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

7.4.5 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.

NOTE 2—For image analysis purposes an uncompressed file format is recommended. Any lossless format may be used. The Tagged Image File Format, TIFF,[8] is a format that allows storage in uncompressed from as well as allowing lossless LZW compression and lossy JPEG compression. Camera RAW is also an acceptable format.

8. Sampling, Test Specimens, and Test Units

8.1 *Selection of Subjects for a Study:*

8.1.1 Generally, a clinical trial is conducted to validate statistically the efficacy of a particular treatment method or product. It can also be used to assess the status of health of an individual or a group.

8.1.2 A clinical trial usually has entrance criteria. Volunteers who meet clinical trial entrance criteria and provide informed consent are chosen. For example, the clinical trial may require subjects of a particular age.

8.1.3 Subjects may be excluded from participation in a clinical trial due to restorative dentistry involving facial surfaces of the anterior teeth.

8.2 *Sampling:*

8.2.1 The subjects are to disclose the plaque using the disclosing agent in accordance with the test protocol.

8.2.2 The region of interest is determined from the clinical protocol; for example, eight (8) anterior teeth, for example:

(1) In-vivo tooth measurement of dental plaque coverage.

(2) Choose the number of teeth included in the evaluation – Reference Fig. 4.

(3) Typically a software mask is created to identify the measured areas.

(4) The gum areas near the teeth are also included.

8.2.3 *Sub Sampling:*

8.2.3.1 The averages of the R, G, B values for each class and the number of pixels in each class needs to be calculated. The chart in 8.3.3.2 is an illustrative example of the calculation results that determine the average R, G, and B raw data values. Each study will have unique sub-sampling requirements depending upon the objectives of the study.

8.3 *Identifying Areas of Interest:*

8.3.1 Areas of interest mean identifying the number of pixels and their RGB values for each class.

8.3.2 Typical classes are teeth, plaque on teeth, gingiva, and plaque on gingiva.

8.3.3 *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. See 8.2.3.1. Classes are statistically established using a priori identification to segregate the teeth from plaque, plaque on teeth, 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.

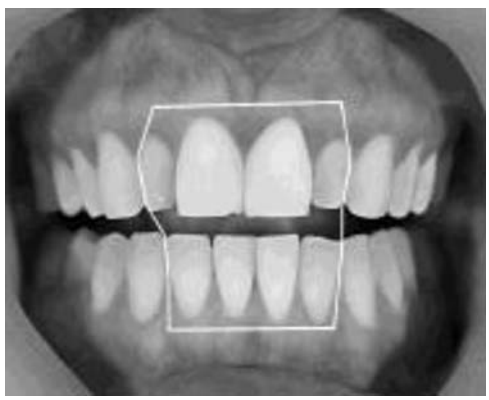

FIG. 4 Example of Masking

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

[8] TIFF, Tagged Image File Format, Adobe Systems Incorporated, San Jose, CA, www.adobe.com.

8.3.3.1 The notation used to describe the terms of discrimination analysis in this method is:

R,G,B = Intensity value for Red, Green and Blue for each pixel, 0-255
x = 1 × 3 matrix of Red, Green and Blue values of pixel x
$\mathbf{m}_t$ = 1 × 3 matrix containing mean RGB values of class t
$\mathbf{S}_t$ = RGB covariance matrix of class t,
$|\mathbf{S}_t|$ = determinant of covariance matrix of $\mathbf{S}_t$, and
$\mathbf{u}_t$ = number of pixels in class t.

8.3.3.2 The sampled RGB color values are used to calculate the covariance matrix $\mathbf{S}_t$ for each class from pixels from representative images.

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

$$\mathbf{S}_t: = \begin{bmatrix} \mathrm{Cov(R,R)} & \mathrm{Cov(R,G)} & \mathrm{Cov(R,B)} \\ \mathrm{Cov(R,G)} & \mathrm{Cov(G,G)} & \mathrm{Cov(B,G)} \\ \mathrm{Cov(R,B)} & \mathrm{Cov(B,G)} & \mathrm{Cov(B,B)} \end{bmatrix}$$

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

where:

i = 1 to n_t,
X_i *and* Y_i = the 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 ($\mathbf{S}_t^{-1}$) is defined such that $\mathbf{S}_t^{-1}{*}\mathbf{S}_t$ is the identity matrix:

$$\begin{bmatrix} 1\,0\,0 \\ 0\,1\,0 \\ 0\,0\,1 \end{bmatrix}$$

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

$$D_t^2\,(x) = (x - m_t)'{*}\mathbf{S}_t^{-1}{*}(x - m_t) + log_e\,|\mathbf{S}_t| \quad (2)$$

The pixel is then segregated into the class where the distance between the RGB values of pixel x to the mean of the RGB values of class t are at a minimum.[9]

9. Preparation of Apparatus

9.1 *Warm up:*

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

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 is custom in nature and developed specifically for the application. The work flow for a typical application is illustrated in Fig. 5.

9.3 *Hardware Preparation:*

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

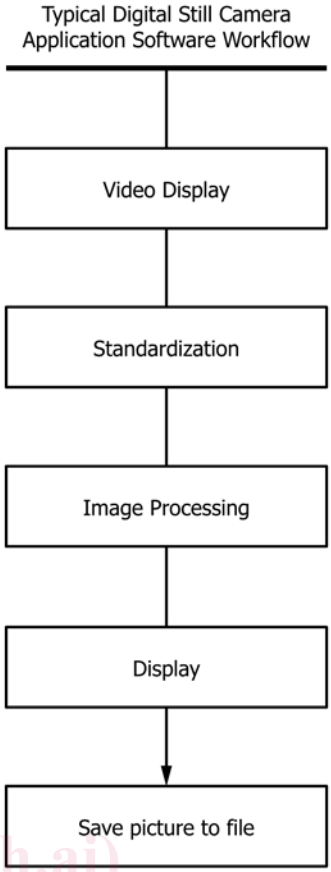

FIG. 5 Typical Digital Still Camera Application Software Workflow

9.3.2 Align the source illumination units.

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, adjust 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 the alignments of the source illumination units.

9.3.3 Aligning the DSC 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] Those interested in discovering more on discrimination analysis are referred to Huberty, Carl J., *Applied Discrimination Analysis*, Wiley, www.wiley.com.

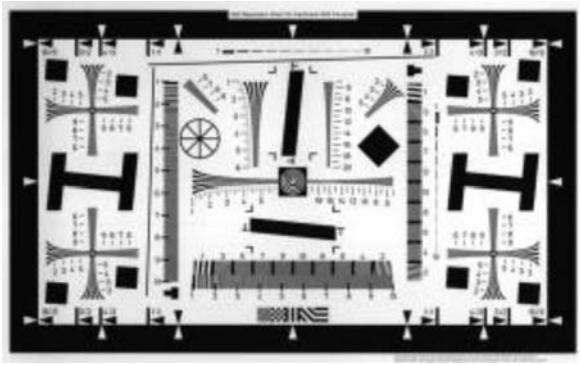

FIG. 6 Example of Focusing (Resolution) Target

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 9.3.5.

9.3.5 Focus the DSC Lens.

9.3.5.1 Place a focusing target in the sample plane. A resolution chart[10] as shown in Fig. 6 is adequate for these purposes.

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

9.3.5.3 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 at the beginning of each study day.

10.2 *Human Subjects*—The human subjects to participate in the study are to avoid any actions that contribute to disrupting the accumulated plaque that are not specified in the protocol.

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.[11] 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 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 standard 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 standard 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 DSC as a colorimeter requires the "raw"[12] sensor output of the camera be processed so that the data are transformed to CIE tristimulus values, typically CIE *X*, *Y* and *Z*. This enables the DSC to be used as a colorimeter for the range of colors required in the study of dental plaque.

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:

$$R = \int P(\lambda)R(\lambda)D_{R_{Raw}}(\lambda)d(\lambda) \quad (3)$$

$$B = \int P(\lambda)R(\lambda)D_{B_{Raw}}(\lambda)d(\lambda) \quad (4)$$

$$G = \int P(\lambda)R(\lambda)D_{G_{Raw}}(\lambda)d(\lambda) \quad (5)$$

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. Regress the camera outputs from the known calibration targets to approximate the Luther condition so that there is a linear transformation from the raw DSC outputs to the *CIE XYZ* values. The device values are defined and calculated in a similar manner as the following equations:

$$X = \int P(\lambda)R(\lambda)\bar{x}(\lambda)d(\lambda) \quad (6)$$

$$Y = \int P(\lambda)R(\lambda)\bar{y}(\lambda)d(\lambda) \quad (7)$$

$$Z = \int P(\lambda)R(\lambda)\bar{z}(\lambda)d(\lambda) \quad (8)$$

Several methods used to characterize cameras are reported in the literature.[13,14,15]

[10] ISO 17321-1. Standards are available from International Imaging Industry Association (I3A), 701 Westchester Ave., Suite 317W, White Plaines, NY 10604, www.iso.org.

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

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

[13] Pointer, M. R., Practical Camera Characterization for Colour Measurement, IS&T's 2001 PICS Conference Proceedings.

[14] Hong, G., A Study of Digital Camera Characterization Based on Polynomial Modeling, Color Research and Application, 2000.