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Introduction to Optical Analysis of Dental Materials: A Review

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Abstract: Optical properties such as color, translucency and surface gloss are critical factors in determining the esthetics of dental materials. Therefore, it is very important to understand the basics of optical measurement instruments. This review provides a simple introduction to the basic concepts for measurement of color, translucency, and gloss.

Keywords: *Optical properties, dental materials.*

I. Introduction

prosthetic materials of an important appearance characteristic of natural oral structures. Within the clinical setting when an indirect restoration is planned for an area of the face which is readily observed and the restoration would be easily assessed for harmony to adjacent existing natural structure, it would be ideal to quantify valid color information quickly and reliably using the patient's existing natural structure which has characteristics throughout the visible spectrum. Then this information could be used to facilitate the color formulation of the restoration such that the restoration could be made to have identical colors under various illumination conditions, within at least acceptable limits but more preferably within limits of perceived color difference (1).

Light illuminating an object can be (2):

Absorbed within it (a process largely responsible for color).

Transmitted through it (relating to the properties of transparency, opacity, and clarity).

Scattered within it (related to diffuse reflectance and transmittance, translucency, and some definitions of haze).

Re-radiated with lower energy (e.g., fluorescence).

Specularly (also called regularly) reflected (responsible for gloss).

The aim of this chapter is to illustrate the evaluation of three optical parameters, which are:

1- Color.
2- Translucency.
3- Gloss.

1- Color measurement:

The conversion of spectrophotometric measurements to three color parameters is described by the International Commission on Illumination (CIE) color space.
CIEXYZ and CIELAB are color-spaces designed to roughly fit with human luminance and color perception. CIEXYZ images are essentially images where the sensitivities are described by the CIE X, Y and Z receptors (which are hypothetical receptors designed to fit with human color discrimination behavior, corresponding to long-wave, medium-wave and short-wave respectively) (3).

CIELAB images can be created from CIEXYZ, where L describes the luminance channel, A describes a color opponent channel between red and green, and B describes a second color opponency channel between blue and yellow. This fits with various theories of how human color vision works (4).

A distinct advantage of the CIE L* a* b* color space is the simplicity of calculating a color difference between two colors using the following equation (1):

$$\Delta E = \sqrt{\Delta l^2 + \Delta a^2 + \Delta b^2}$$

where ΔL*, Δa*, and Δb* are the respective differences in the L*, a* and b* color parameters between two colors.

The key elements of color perception according to CIE system (5)***:***

1- Standard illuminant: D65 illuminant which corresponds to average northern sky daylight.
2- Standard illuminating and viewing geometries: CIE recommended four types of illumination and viewing geometries, shown in figure (1):

a) Normal/diffuse (0/d)
b) Diffuse/normal (d/0)
c) 45/normal (45/0)
d) Normal/45 (0/45)

The 45/0 illumination/observation geometry is the most widely used in spectrophotometers.

•

Figure (1) schematic diagram of the four CIE standard illuminating and viewing geometries

3- Standard observer:

Depending on the relative size of the area being viewed, the perception of color can change. In 1931, CIE defined color matching functions for a 2◦ view. Then in 1964 they published color matching functions for a 10◦ field of view (5).

Color measurement is mostly evaluated using spectrophotometers and colorimeters.

1.1. Colorimeters

The **colorimeters** are compact, hand-held, simple and cheaper instruments than spectrophotometers.

In colorimeters, objects are illuminated with a specific light source that simulates the standard illuminant. The reflected light passes through the primary filters: ***red, green, and blue***, which simulate the spectral sensitivity curve, and reaches the detector where it provides a response proportional to the tristimulus value. Therefore, colorimeters provide information on the **amount of red, green, and blue light reflected by the object**. This colorimetric information is useful for color evaluations that do not require complexity or precision (6).

1.2. Spectrophotometers:

A spectrophotometer is an analytical instrument used for the objective calculation of **reflected or transmitted radiation in the entire visible spectrum therefore, it is more accurate than colorimeters.** Spectrophotometers measure intensity as a function of the wavelength of the light source (7). Figure (2) is a schematic diagram showing the difference between colorimeter and spectrophotometer, where colorimeter quantifies color by measuring the three primary color components of light (red, green and blue), while spectrophotometer has a monochromator (prism) to enable it to scan the entire visible spectrum of light.

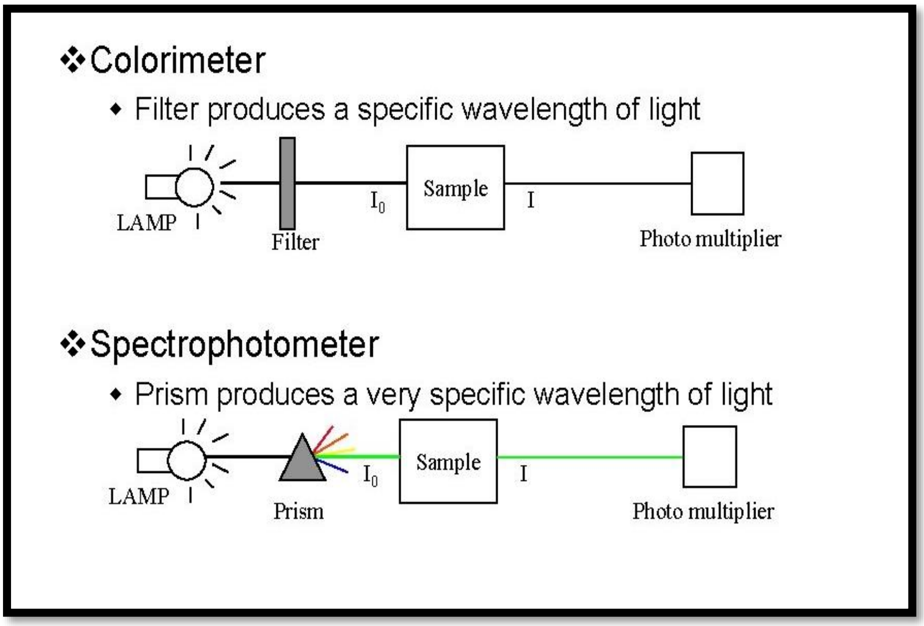

Figure (2) schematic diagram showing colorimeter versus spectrophotometer

Spectrophotometers are available in portable and bench-top instruments. The portable ones are used in color measurements of solid samples (teeth and dental restorations), while the bench-top type is mainly used for liquid samples.

A spectrophotometer is made up of two instruments: a spectrometer and a photometer. The spectrometer is to produce light of any wavelength, while the photometer is to measure the intensity of light. The spectrophotometer is designed in a way that the liquid or a sample is placed between spectrometer and photometer. The photometer (colorimeter and spectrophotometer) measures the amount of light that passes through the sample and delivers a voltage signal to the display. If the absorbing of light changes, the voltage signal also changes (7).

1.2.1. Basic principle of spectrophotometers:

Spectrophotometry is a procedure for determining how much light is reflected or transmitted by a sample by measuring the strength of light as a light beam travel through the sample. The fundamental theory is that light is absorbed or emitted over a certain wavelength spectrum by each compound (7).

1.2.2. Working parts of spectrophotometers (8):

All spectrophotometers contain four elements as shown in figure (3):

1. A source of radiation.

2. An optical system, or monochromator, to isolate a narrow band of wavelengths from the whole spectrum emitted by the source.

3. The sample (and its cell if it is liquid or gaseous).

4. A detector of radiation and its auxiliary equipment.

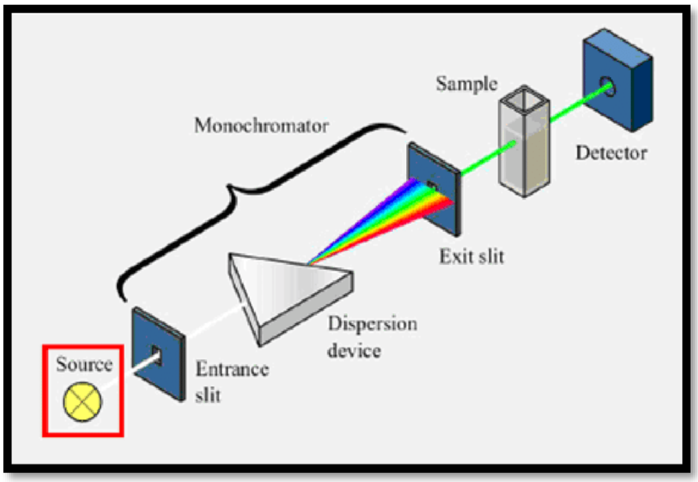

Figure (3) schematic diagram for spectrophotometer instrumentation

1.2.3. Working technique of spectrophotometer (8):

1. A sample solution is placed inside the spectrophotometer.

2. A light source shines light toward the sample.

3.A monochromator splits the light into each color, or rather, individual wavelengths. An adjustable slit allows only one specific wavelength of light through to the sample solution.

4. The wavelength of light hits the sample, which is held in a little container called a cuvette.

5. Whatever light passes through the sample is read and displayed on the output screen.

Both colorimeters and spectrophotometers must be calibrated each time before use.

1.2.4. Data obtained from spectrophotometers and its interpretation:

A spectrophotometer provides immediate spectral data.

ΔL (lightness) = $L_{reference}$ - $L_{experiment}$, Δa (green - red) = $a_{reference}$ - $a_{experiment}$, and Δb (yellow - blue) = $b_{reference}$ - $b_{experiment}$.

$$\Delta E = \sqrt{\Delta l^2 + \Delta a^2 + \Delta b^2}$$

Figure (4) is an example for data obtained from a spectrophotometer of tooth color before and after bleaching. The instrument scans parts of the tooth (cervical, middle, and incisal) then provide quantitative data about each parameter.

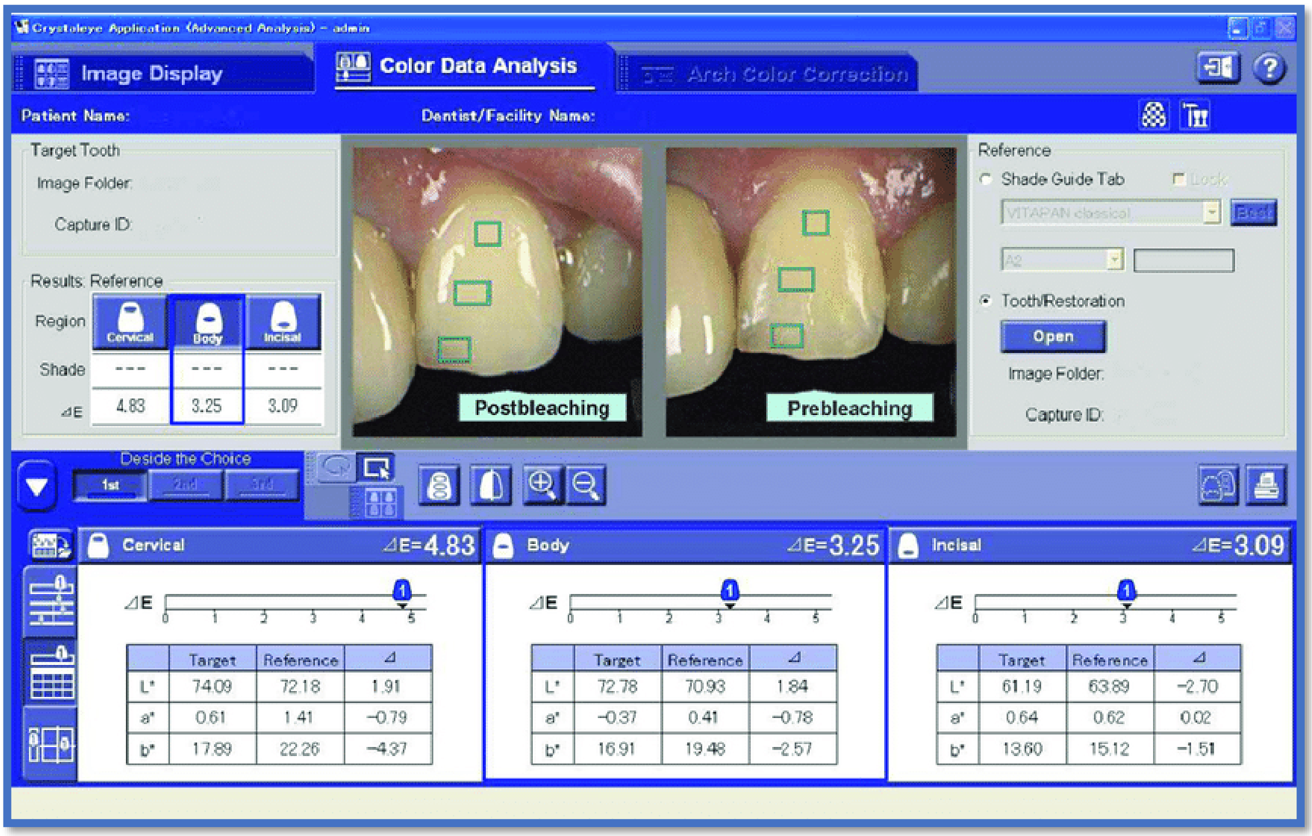

Figure (4) example from digital data obtained from a spectrophotometer

1.2.5. Data interpretation:

Interpretation of the data obtained from a spectrophotometer relies on the acceptability and perceptibility thresholds. **Perceptibility threshold (PT)** refers to the smallest color difference that can be detected by an observer. **Acceptability threshold (AT)** is the difference in color that is acceptable for 50% of observers corresponds to a 50:50%. The latest reported 50:50% PT/AT: ΔE_{00} = 0.8/1.8; ΔE_{ab} = 1.2/2.7 (9).

1.2.6. Measuring the color of liquid samples:

The color of liquid samples is evaluated using bench-top spectrophotometers.

a) <u>Opaque Liquids:</u>

To measure the color of opaque liquids, a reflectance spectrophotometer can be used. A glass test tube holder is mounted on the front of the device to hold the opaque liquid in the right location for color measurement. The measurement device shines light onto the sample and captures the illumination that reflects into the optics to quantify the color data (10).

b) <u>Translucent Liquids:</u>

A reflectance measurement will not work for clear liquids, which have color but are usually translucent. The wavelengths of light will go right through the sample instead of bouncing back. To measure translucent liquids, a spectrophotometer must be used in transmission mode (10).

Transmission spectrophotometers allow to put a liquid sample inside the instrument in glass test tubes or cuvettes. The device shines visible spectrum illumination through the sample and receivers on the other side capture the percentage of light that passes through at numerous wavelengths. A relatively transparent liquid will absorb some components of white light, while allowing other components to pass through. This data is used to quantify the color of the sample. Many benchtop spectrophotometers are capable of measuring in both reflectance and transmission modes (10).

1.2.7. Possible measurement errors:

a) Accuracy and repeatability of color measurements:

The two separate aspects of measurement error involve a lack of accuracy or validity and a lack of precision. Precision may be described with the repeatability of only the measuring device over time or the reproducibility of the entire measurement process, including specimen positioning. Accuracy of a color measuring device may be assessed by comparing a test instrument to a reference instrument which is considered to be correct (calibration), and precision assessed by comparing repeated measures of the same specimen or standard (7).

b) Edge loss:

Edge-loss has also been demonstrated for translucent pigmented maxillofacial materials, demonstrating that edge-loss may occur in either spectrophotometric or colorimetric measurement of translucent materials, depending on its inherent optical properties and the sizes of both the illumining light beam and the specimen port opening. In effect, edge-loss is caused by a shadow from the edge of the specimen opening within the translucent material, which allows the shadow to influence the intensity of the observation. Edge-loss can be avoided by avoiding a measurement system which uses an opening or aperture to position the specimen relative to the illumination and observation components. Such non-contact systems have been described which utilize a 45/0 illumination/observation geometry (7).

1.2.8. Advantages of spectrophotometers (1):

- **Comprehensive:** A spectrophotometer has more advanced hardware and can measure qualities that a colorimeter can’t, including metamerism and reflectance.
- **Adaptability:** You can typically adjust illuminance and observer settings to get just the right options on a spectrophotometer.
- **Powerful software:** By integrating with software, spectrophotometers offer a new, comprehensive way to review and analyze data outside of a built-in display.
- **They come in a variety of styles.** Spectrophotometers are available for a wide array of sample types, including powders, liquids, and transparent materials.

1.2.9. Disadvantages of spectrophotometers (1):

- **They are more complex:** With complexity comes sensitivity, and they may not be as suited for factory environments.
- **They can be more expensive than colorimeters:** Though price varies by model, spectrophotometers and their precise, broad range of information typically cost more than a colorimeter.

- **They may have more technology than necessary:** If you only need simple color measurements that a colorimeter can provide, a spectrophotometer may be more than you need.

2. Translucency

The translucency of a sample is determined by two parameters: the contrast ratio (CR) and the translucency parameter (TP) (11).

Contrast ratio *is defined as the ratio of the luminous reflectance of a translucent material on a black backing to the luminous reflectance of the same material on a white backing* (11).

In this definition, it is important to note that luminous reflectance is the Y

tristimulus value in reflectance as defined by the CIE. From this definition, it is obvious that when the two luminous reflectance values are identical, the material is completely masking the backings and CR is one, which is as high as possible for this measure. When the material is completely transparent, the luminous reflectance values are the values of the backings, respectively, and in this case, CR has the lower limit of the ratio of the luminous reflectance of the black backing to that of the white backing (11).

Translucency parameter *is defined as the color difference found for the material at a specified thickness, where the color difference was between the material when in optical contact with ideal black and white backings* (12).

TP and CR are also based on CIE colorimetry and therefore the illumination, the observer, and the color difference formula used for the color difference calculations must also be presented.

Both CR and TP are measured by ***a spectrophotometer*** like color, therefore all the key elements of CIE colorimetry are identified just as mentioned in color measurement.

$\mathbf{CR = Y_B/Y_W}$, where (YB) is the luminance of black and (YW) is the luminance of white.

$\mathbf{TP = [(L^*B - L^*W)^2 + (a^*B - a^*W)^2 + (b^*B - b^*W)^2]^{1/2}}$**,** where B and W refer to color coordinates over a black and a white background, respectively.

- ***The working principle of spectrophotometers, its advantages and disadvantages are the same for measuring translucency***

3. Gloss

Gloss is defined as '*The attribute of surfaces that causes them to have shiny or lustrous, metallic appearance.'* It is an important parameter affecting the appearance and quality of the products. We can find the gloss difference through our naked eye; however, this is subjective therefor it must be measured quantitatively for readily comparisons of different products (13).

The perception of gloss also relates to finish (the magnitude, frequency, randomness, and scale of curvatures), texture (changes in reflecting properties over the surface) and how a sample is illuminated and viewed (13).

A **glossmeter,** shown in figure (5) is an instrument which is used to measure specular reflection gloss of a surface (Figure 6). Gloss is determined by projecting a beam of light at a fixed intensity and angle onto a surface and measuring the amount of reflected light at an equal but opposite angle (14).

Figure (5) A gloss meter

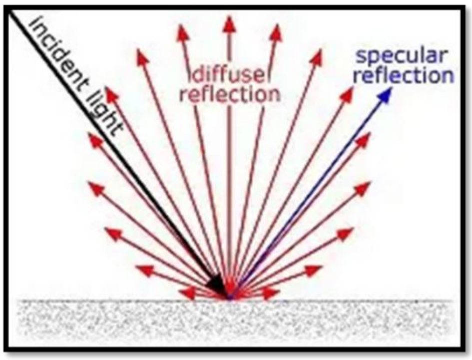

Figure (6) Diffuse Vs Specular reflection of light

3.1. Construction of gloss meter:

A typical glossmeter consists of a fixed mechanical assembly comprising a standardized light source that projects a parallel beam of light onto the test surface to be measured and a filtered detector located to receive the rays reflected from the surface (2), shown in figure (7).

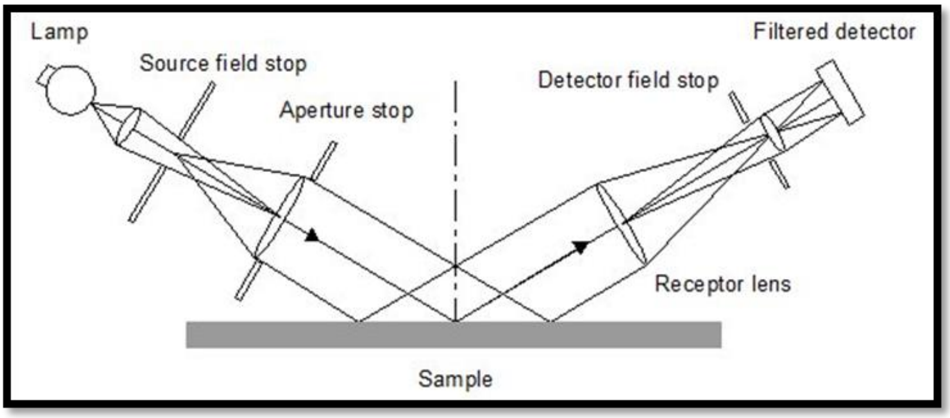

Figure (7) schematic diagram for a gloss meter

3.2. Instrument calibration:

The instruments are calibrated using reference standards that are usually made from highly polished, plane, black glass with a refractive index of 1.567 for the Sodium D line, and these are assigned a gloss value of 100 for each geometry (2).

3.3. Choosing the correct angle for gloss measurement

Measurement angle refers to the angle between the incident and reflected light. Three measurement angles (20°, 60°, and 85°) are specified to cover the majority of industrial coatings applications (15). The angle is selected based on the anticipated gloss range, as shown in the following table.

Gloss Range	**60° Value**	**Notes**
High Gloss	>70 GU	If measurement exceeds 70 GU, change test setup to 20°
Medium Gloss	10 – 70 GU	
Low Gloss	<10 GU	If measurement is less than 10 GU, change test setup to 85°

To determine the correct measurement, angle the surface should be assessed with the 60° geometry (15).

Matt surfaces which measure below 10 GU at 60°should be re-measured with the 85° angle (15).

High gloss surfaces which measure above 70 GU at 60° should be assessed using the 20° angle (15).

• The 60°degree angle is best employed on mid gloss samples 10-70 GU (15).

3.4. Understanding Gloss units

The measurement scale, Gloss Units (GU), of a glossmeter is a scaling based on a highly polished reference black glass standard with a defined refractive index having a specular reflectance of 100GU at the specified angle. This standard is used to establish an upper point calibration of 100 with the lower end point established at 0 on a perfectly matt surface. This scaling is suitable for most non-metallic coatings and materials (paints and plastics) as they generally fall within this range (16).

3.5. Advantages of Gloss meter (16):

Rapid measurement and instant reading.
Available in hand-held and bench-top types.
Wide varieties of materials can be tested.

3.6. Disadvantages of gloss meter (16):

It is not sensitive to common effects which reduce appearance quality such as haze and orange peel.

Haze is caused by microscopic surface structure which slightly changes the direction of a reflected light causing a bloom adjacent to the specular (gloss) angle. The surface has less reflective contrast and a shallow milky effect.

Orange peel is caused by an uneven surface formation of large surface structures distorting the reflected light.

Two high gloss surfaces can measure identically with a standard glossmeter but can be visually very different.

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