The Nature of Color

Part 1 of 2

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Fig. 1: Smile showing bright, high value healthy teeth.

Color is an essential ingredient in our environment and is associated with certain feelings, emotions and meanings. These associations are defined by the culture we live in as well as our personal experiences. Color communicates emotion, creates emotional and affects energy; color has an emotional impact that can delight or distress. It is almost impossible to separate the seeing of color from the “feeling of color” because so much of what is seen is based on what is felt.

Not surprisingly, these factors and influences have infiltrated into the oral healthcare environment with patients having a high expectation of a natural aesthetic result, both in the anterior and posterior dentition.

Although color as an entity should be regarded as only one of the many building blocks necessary in the achievement of an aesthetic result, nevertheless, a discordant color scheme can probably be more devastating to the overall effect than many of the other factors present. It is for this reason that so much time, research and expense has gone into the “color matching” properties of contemporary aesthetic restorative materials.

Color matching and shade taking continues to provide oral health clinicians and technicians with one of the great and important challenges of their respective professions. Yet, despite the importance of color matching, this area still remains largely and universally untaught in most teaching institutions (Figure 1). A viable reason for color matching not to be part of a healthcare curriculum could well be the fact that all areas involved in healthcare, it occupies the unique position of requiring three equal elements for understanding and implementation. These elements could be defined and classified as scientific aspects, objective reasoning and subjective response.

Scientific aspects would involve understanding of the basic properties and nature of light and color, and an understanding of the physical and chemical properties of natural color as well as those of the object being studied. In dental healthcare this would involve the understanding of the anatomy and physiology of the various structures that make up the oral environment. A knowledge of the anatomy and physiology of the eye would be required, as well as a thorough understanding of color and image interpretation by the brain (Figures 2 & 4).

Objective reasoning would involve the understanding of the effects that various colors have on society generally and the individual specifically. There would be a scientific basis in that such an objective reasoning forms a part of psychophysics, psychology, philosophy and the morays and ethics of our contemporary religions.

Although these aspects can be culturally and socially diverse, a unified pattern could nevertheless be established and reasoned, predictable “findings” applied. Subjective response is probably the least scientific of the three elements, yet possibly occupies the most dominant position. In order to achieve as near perfect color matching as possible, the subjective response needs to be disciplined in a positive and constructive fashion. In the fabrication of a single ceramic crown for example, three individuals are involved: the clinician, ceramist and the patient. Each individual will interpret color differently and success will be determined by achieving a consensus of approval for a particular shade. Attaining this consensus can often be a difficult and painstaking procedure, with possible remakes of the restoration commonplace. The scientific literature describes sexual and age differences in response to color stimulation, as well as cultural and ethnic differences. The manufacturer of aesthetic restorative materials have also inadvertently added to the challenge of accurate color matching. Although producing wonderful aesthetic materials, there still remains a lack of total standardization within the productive process and separate batches of the same material often display completely different color properties. The shade guide remains the traditional method of recording color matching, and for the most part this is totally inadequate as the guide is not unique to the chosen material.

The objective of this article is to present an understanding of the nature of color and to provide a simple road map technique that hopefully eliminates much of the uncertainty of color matching (Figures 4 & 5).

The Color of Light

One way colors in sunlight are discovered is that Isaac Newton, in the 1600s, white light through a prism. Because each of the colors has a different wavelength, each is bent by a different amount.

Rainbows are formed when water droplets in the sky act as natural prisms. As sunlight passes through the droplets, each of the different rays is bent by a different amount, creating a rainbow. The rainbow colors form one “octave” of light and are known as the “true hues”. Red is the longest wavelength we can see and it has the slowest frequency of vibration. Its magnetic energy is warming and stimulating. Violet has the shortest wavelength and the quickest vibration. It is cooling and cleansing (Figure 6).

Beyond the Visible Spectrum

At either end of the visible spectrum and of any wave lengths we cannot see. Ultraviolet light is just beyond violet, and farther beyond this are electromagnetic rays with increasing frequencies as the wavelengths get progressively shorter; these include X-rays and gamma rays.

Infrared light is found just beyond red light. Like red it has warming qualities although it gives off more concentrated heat; these
Fig. 11: Value scale and chart graduated from 0 to 10. A black or low value is represented by 0.10 represents a white or high value with the mid-tones being grey.

Fig. 12: Chromatic scale, extending from weakly saturated on the left to densely saturated chroma on the right.

Fig. 13: Munsell Color Space. Vertical axis represents value extending from black on the bottom to white on top, with grey in the middle. The color wheel, arranged around the axis, represents the hues and chroma increases outwards and perpendicular to the vertical axis. Thus, hue, chroma and value can be observed at various combinations.

Fig. 14: CIE L* a* b* scale. Lightness is calculated on the vertical or L scale and hue chroma on the ab axis.

Fig. 15, 16 & 17: Variations in value in natural teeth. Low value giving a grey appearance, mid-value giving a cream appearance and high value giving a white appearance.

Describing Color
Color can be described in at least three different ways:
• Spectrophotometry describes the physical characteristics of a color (eg, the spectral reflectance of a surface at different wavelengths).
• Colorimetry describes what a color matches with.
• The Munsell system describes what the color looks like.

The Munsell Color System
This system was proposed by the American AH Munsell in 1905 and revised in 1945. The system defines three attributes of color: H (hue), C (chroma), and V (value). Color matching in dentistry is based on this system. Munsell established numerical scales with visually uniform steps for each of these attributes.

Hue is that attribute of a color by which we distinguish red from green, blue from yellow etc.

Munsell called red, yellow, green, blue and purple principal hues and placed them at equal intervals around a circle. He inserted five intermediate hues:
• Yellow-red
• Green-yellow
• Blue-green
• Purple-blue
• Red-purple

This makes ten hues in all.

Value indicates the lightness of a color. The scale of value ranges from 0 for pure black to 10 for pure white. Black, white and the greys between them are called neutral colors. They have no hue.

Colors of low chroma are sometimes called weak, while those of high chroma are said to be highly saturated, strong or vivid (Figure 12).

Munsell Color Space
Hue, value and chroma can be varied independently and the colors can be arranged in a three-dimensional space. The neutral colors are arranged in the vertical plane called the neutral axis. Black is at the bottom, white at the top and all greys are in between. Hues are displayed at various angles around the neutral axis and chroma arranged perpendicular to the axis increasing outward (Figure 15).

CIE XYZ
In 1951 the CIE developed the XYZ color system, also called the “norm color system”. Red components of a color are placed along the X (horizontal) axis and green components along the Y (vertical) axis. Every color is assigned a particular point and the spectral purity of colors decreases as you move left along the coordinate plane. What is not taken into consideration in this model is brightness.

CIE L* a* b*
A three-dimensional model with the color differences perceived corresponding to distances when measured colorimetrically. The a-axis extends from green (-a) to red (+a); b axis from blue (-b) to yellow (+b). Brightness (L) increases from the bottom to top (Figure 14).

Chromatic & Achromatic colors
Achromatic colors are white, black and grey in between. They lack the attributes of hue and saturation. Chromatic colors are everything else. We refer to them as having "color"; anything other than white, black or grey.

Color of the Natural Tooth
In describing the color of a natural tooth we find there are two additional attributes. In addition to hue, chroma and value, we discover the attributes of opalescence and fluorescence.

The definitions of the first three attributes are identical to those defined by Munsell, but each can be qualified further:

Hue: The primary source of color is dentine and the hue of a vital, healthy tooth is in the yellow to yellow-red range.

Chroma: In natural teeth the chroma is dictated primarily by dentine but is influenced by the translucency and thickness of enamel. The thinner the enamel, the less the effect on the chroma. Thus, in the cervical area the thin enamel, the chroma appears densely saturated. The thicker the enamel, the greater the optical effects resulting in a higher value. Thick, dense, opaque dentine has the effect of lowering the enamel value (Figures 15, 16 & 17).

Opalescence: In a natural tooth, this is an effect produced in enamel and is due to different scattering indices of the various organic and inorganic components of enamel as well as the ability of hydroxyapatite crystal to scatter incident light. The result is that the long wavelengths are transmitted through the tooth whilst the short wavelengths are reflected, producing a blue or white appearance. (Figure 18).

Fluorescence: This effect occurs when a body absorbs luminescent energy and then diffuses it back to the visible spectrum. In nature this is caused by ultraviolet light striking pigments in the dentine enamel interface resulting in light emission range.
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It would be prudent at this stage to dispel one of the great myths of color matching in the natural tooth. Translucency is currently one of the “buzzwords” in aesthetic restorative dentistry and clinicians, in their search for the invisible restoration, demand more and more translucency from their ceramists. Understanding of the previous paragraph would surely indicate that the desire is not for more semi-transparency but rather for more glow and vitality effects, i.e., opalescence. A small point, but once grasped, the author submits that use of the term “opalescence” as opposed to “translucency” would convey a greater understanding (with significantly less confusion) as to the requirements of a particular restoration.

Physiology of Natural Tooth Color

The observed color of a tooth results from the combined effects of the interaction of light with dentine and enamel. The macro- and micro-anatomical structure of the dentine produces areas of high and low saturation of opaque color resulting in dentine being primarily responsible for the hue and chroma of the tooth. The scientific literature describes the predominant hue as being in the yellow-red range, but varies in quantification of this as being between 76% to 86%, with the remaining percentage leaning towards the yellow range. Using the Vitapan standard this would describe the hue of teeth as being predominately in the A range with a small percentage of B shades.

Dentinal tubular architecture, exhibiting varying diameter, frequency and an S-shaped distribution produces areas of dense and sparse mineralization. The various micro-anatomical structures, tubular architecture, combined with the overall gross anatomy of dentin result in areas of differing reflective indices resulting in a non-homogeneous reflection and scattering of light rays. This results in areas of dense opacity and saturation of color giving dentine...
a polychromatic effect. Vanini (1996) studied this effect and defined and applied the term “chromatic banding” to the polychromatic effects (Figure 19). Traditionally, chromatic banding has been described at the gross level as consisting of three broad areas:

- The cervical third
- Middle third
- Incisal third

The chroma is most saturated in the cervical area, gradually decreasing through the middle third into the incisal third which exhibits the lowest chroma. Vanini demonstrated that even within the three broad bands there are areas of dense opacity and saturated chroma mixed with areas of less saturation, giving rise to a true polychromatic appearance. These areas can be organized in a definite pattern resembling bands of differing chroma, or there might be a random scattering of differing chromas. Organic pigments present within the microstructure of dentine are responsible for fluorescent effects giving undetectable areas of white or blue.

**Enamel Effect**

The inorganic organized arrangement of the enamel prisms, the varying thickness of enamel over the dentine contours and the presence of organic protein pigments allows light to be reflected, refracted and transmitted. The translucent and opalescent characteristics of enamel impart value as well as areas of intense color and/or opalescent effects to the underlying dentine giving sparkle and vitality to the tooth. The thicker the enamel, the more light is refracted and reflected, thus increasing the luminosity and hence the value giving a whiter appearance.

**Combined Effects of Enamel & Dentine**

The observed color of a tooth is achieved through the combined optical effects of enamel and dentine. Therefore, it is imperative to understand the influence that each component makes on the tooth’s basic properties. The opaque dentine, exhibiting the attributes of hue and chroma, has the tendency to decrease the value of enamel, thus moving the overall color towards the grey. If the enamel is very thin and the dentine very saturated (such as the cervical area) then the hue of the dentine dominates the overall perception. By dividing the thickness and the dentine decreases in density (mid third) so does the value of the enamel increase, leading to a whiter effect. Careful observation of the tooth will show that the polychromatic nature of dentine will exert similar effects on the value, giving rise to a pattern of variance of the value of enamel that matches the polychromatic pattern of dentine (Figure 20).

**Opalescent, Translucent & Intensive Effects**

Opalescence in a tooth is caused by minute particles in the translucent enamel reflecting and refracting light. This particular matter is so minute that only the shortest wavelengths are reflected, thus creating a blue gleam. In the natural tooth this occurs usually at the edges of the incisal third where the tooth is devoid of dentine, causing the familiar blue halo. As the dentine thickness increases, more wavelengths are reflected leading from grey to white opalescent effects (Figure 21).

Vanini (ca. 2001/2) in an as-yet unpublished study demonstrates that there appears to be a definitive pattern to the translucent effects of enamel. This pattern can be classified into categories and further divided into effect elements. Vanini’s work and study still requires universal acceptance and scientific verification. Nevertheless, it’s sheer pragmatism and practicality make it an exquisite diagnostic tool in tooth color matching and provides a wonderful communication tool between clinicians, manufacturers and laboratory technologists. Vanini postulates that the sum total of all opalescent, translucent or enamel effects fall into one of three categories:

- **Intensive effects**
- **Opalescent effects**
- **Characterization**

**Intensive Effects**

Intensive effects present discrete but intensive areas in the enamel surface, usually of a milky/white nature. A typical example of an intensive effect is the stain associated with hypermineralization (flourous) of the enamel structure. The opalescent category attempts to classify the distribution and appearance of typical enamel opalescence. The presence of the blue halo in many teeth, both anterior and posterior, is typical of opalescent effects. This halo can actually be classified by describing its physical appearance, such as mamelon, split mamelon, window or comb. A fifth division will occur in the elderly patient where a large part of the incisal edge has occurred, enamel has thinned and extrinsic stain mixes with the opalescent area producing an opalescent stain usually of a white/amber color. The final category, characterization, describes the two most common examples of character effects, the stain and crack as well as the areas of definitive effects that can surround the areas of opalescent or intensive effects.

As an example, immediately below and above the opalescent halo there is usually an area of solid enamel effect accentuating the halo and thus would be defined in the characterization category as mamelon or marginal effect. Therefore, by subdividing the opalescent, translucent or enamel effects into three broad categories, and further dividing each category into four or five elements, a predictable, repeatable and easily describable roadmap for color matching can be recorded and charted (Figure 22).

**Aging Effects in the Natural Tooth**

Young teeth are generally characterized by white, bright opalescence (Figure 23) whereas aged teeth are usually dark opaque and worn (Figure 24).

What has happened to the thickness of dentine allows light to pass through the translucent effects of the dentine. The thick intact enamel masks the effects of the opaque effects of the dentine. The young enamel shows marked opalescent effects and in the incisa area the halo effects are obvious. With aged teeth, the dentine blood vessels diminishes and the tubules become sclerotic. Although sclerotic dentine is slightly more translucent, the overall chroma increases and the dentine becomes darker. The enamels wears and thins with resulting reduced value as well as allowing more of the opaque dentine to show through. The thinnest enamel shows reduced opalescent effects, particularly at the incisal edge, the loss of enamel due to functional wear, Accumulated stains also darken the tooth.

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