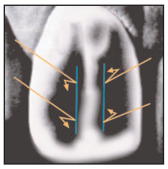
Shade Matching in Restorative Dentistry: The Science and Strategies



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Closely matching natural teeth with an artificial restoration can be one of the most challenging procedures in restorative dentistry. Natural teeth vary greatly in color and shape. They reveal ample information about patients' background and personality. Dentistry provides the opportunity to restore unique patient characteristics or replace them with alternatives. Whether one tooth or many is restored, the ability to assess and properly communicate information to the laboratory can be greatly improved by learning the language of color and light characteristics. It is only possible to duplicate in ceramic what has been distinguished, understood, and communicated in the shade-matching process of the natural dentition. This article will give the reader a better understanding of what happens when incident light hits the surface of a tooth and give strategies for best assessing and communicating this to the dental laboratory. (Int J Periodontics Restorative Dent 2003;23:xxx–xxx.)

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When light rays of different colors are added together to form a mixture, the eye perceives it as lighter than the original colors that were combined to create it (additive coloration). Mixing colors of light is very different from mixing colors of opaque pigments. Colorants like pigments, dye, and lacquer deal with reflected light. When an artist or dental ceramist works with pigments or dental porcelains of varying opacities, the amount of light reflected is decreased with the addition of different colors. Opaque pigments absorb or subtract the light waves of all colors except those perceived by the eye. Each subtractive mixture is darker than the original colors combined to create it. Each pigment absorbs different wavelengths and increases the absorptive ability of the mixture, decreasing the reflectance. The three primary colors of opaque pigments act differently when mixed, blending to gray or black. The primary colors of light (additive) are red, green, and blue-violet. The primary colors of opaque pigments (subtractive) are red, yellow, and blue. The additive primaries when combined yield white. The subtractive primaries when combined yield black.

Every opaque object is receiving light, the three primary light colors in some ratio. Some objects reflect all of the light they receive, and others absorb it almost totally.[1] Most "opaque" objects absorb partially and reflect the rest. The dominant wavelength/s reflected back to the eye is the perceived color of the object. White paper reflects almost all visible light rays; black objects absorb most of the light so nothing is reflected back to the eyes. A perfectly black body is basically unchanged by shining light on it. A yellow object when illuminated by the three primary colors will actually absorb the blue-violet and reflect back the red and green, which, when mixed, will appear as yellow.

Munsell's color theory

Albert Munsell described color as a three-dimensional phenomenon . He described the three dimensions as hue, value (brightness), and chroma (saturation).

Hue

Hue is the quality that distinguishes one family of colors from another. It is specified as the dominant range of wavelengths in the visible spectrum that yields the perceived color, even though the exact wavelength of the perceived color may not be present.[2] Hue is a physiologic and psychologic interpretation of a sum of wavelengths. In dental terms, hue is represented by A, B, C, or D on the commonly used Vita Classic shade guide.

Value

Value, or brightness, is the amount of light returned from an object. Munsell described value as a white-to-black gray scale. Bright objects have lower amounts of gray, and low-value objects have larger amounts of gray and will appear darker. The brightness of a crown is usually increased in two ways: by using lighter porcelain (lowering chroma), or by increasing the reflectivity of the surface. Lowering value means diminished light returns from the object illuminated; more light is being absorbed, scattered elsewhere, or transmitted through.

Chroma

Chroma is the saturation, intensity, or strength of the hue. Envision placing red food dye into a glass of water. Each time more of the same color dye is added, the intensity increases, but it is the same red color (hue). As more dye is added, the mixture also appears darker, so the increase in chroma has a corresponding change in value. As chroma is increased, the value is decreased; chroma and value are inversely related. Higher numbers on the Vita Classic shade guide represent increased chroma.

Other optical properties

Translucency

Dental ceramics try to imitate the appearance of the tooth as a sum of its visual dimensions. Human teeth are characterized by varying degrees of translucency, which can be defined as the gradient between transparent and opaque. Pieces of frosted glass or ice can have the same chroma, hue, and value but not look the same. Generally, increasing the translucency of a crown lowers its value because less light returns to the eye. With increased translucency, light is able to pass the surface and is scattered within the body of porcelain. When light enters enamel, it gets bounced around the enamel. If one side of a tooth is illuminated with a curing light, the entire crown is lighted. Enamel is an optically dense material bordered on either side by air or dentin, both with significantly lower optical densities. Normally, increasing opacity or reflectivity increases value. By increasing the optical density of dental ceramics, the fiberoptic properties of natural enamel can be replicated and the prosthetic crown can be bright and translucent at the same time. With the translucent enamel layer, the ceramist achieves color depth and the illusion of a vital natural tooth. The translucency of enamel is a function of wavelength. The longer the wavelength, the higher the translucency. Therefore, enamel is more translucent in light rich in yellow and red (eg, incandescent light) and will

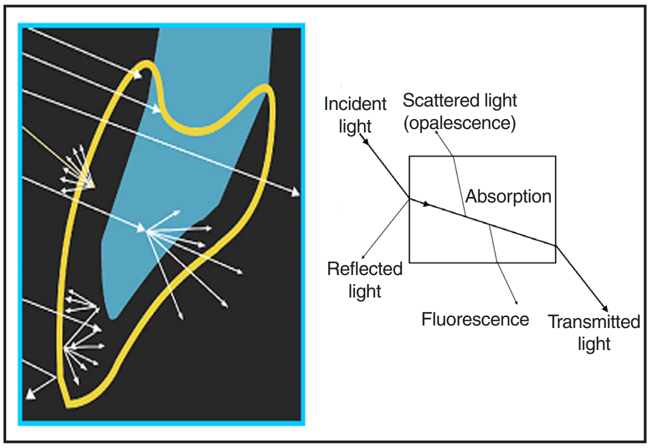


Fig 1 *Appearance of a tooth is the summation of reflected, transmitted, and opalesced light.*[12]

show more dentin, making the tooth appear redder, with a higher chroma and lower value than it actually has.[3]

Fluorescence

Ultraviolet (UV) light can have a dramatic effect on the level of vitality exhibited by restorations. With the characteristic of fluorescence, they look brighter and more alive. Fluorescence is the absorption of light by a material and the spontaneous emission of light in a longer wavelength.[4] In a natural tooth, it primarily occurs in the dentin because of the higher amount of organic material present.[1,5–7] Ambient near-UV light is absorbed and fluoresced back as light primarily in the blue end of the spectrum, but it will occur at all wavelengths. The more the dentin fluoresces, the lower the chroma.[1,8] Fluorescent powders are added to crowns to increase the quantity of light returned back to the viewer, block out discolorations, and decrease chroma.[8] This is especially beneficial in high-value shades, as it can raise value without negatively affecting translucency when placed within the dentin porcelain layers.

Opalescence

Opalescence is the phenomenon in which a material appears to be one color when light is reflected from it and another color when light is transmitted through it.[9] A natural opal is an aqueous disilicate that breaks transilluminated light down into its component spectrum by refraction. Opals act like prisms and refract (bend) different wavelengths to varying degrees. The shorter wavelengths bend more and require a higher critical angle to escape an optically dense material than the reds and yellows. The hydroxyapatite (HA) crystals of enamel also act as prisms. Wavelengths of light have different degrees of translucency through teeth and dental materials. When illuminated, opals and enamel will transilluminate the reds and scatter the blues within; thus, enamel appears bluish even though it is colorless.[1,5,10] The opalescent effects of enamel brighten the tooth and give it optical depth and vitality[11] (Fig 1).

Contrast and glare

Contrast is caused by a difference between the brightness or color of an object and its immediate background. Object forms with high contrast are easier to pick out than objects with low contrast. While some contrast is helpful, excessive contrast causes glare. An extremely bright object against a dark background or significantly differently colored objects cause discomfort and can interfere with perception.[1,13,14] This interference is generically called glare. The illumination of the teeth should not be significantly brighter than the ambient environment.[15] With dental photography, the use of a black background increases impact, but it will cause glare.

Color perception

Color perception depends largely on human physiology. Humans have three types of cone-shaped receptor cells, each sensitive to one primary color. Impulses from the three types of receptor cones are thought to combine into a coded signal prior to transmission from the eye to higher visual centers in the brain. The combination takes place in the ganglion cells in the retina. Changes in the color stimulus change the patterns of the coded signals.[13] The eye cannot distinguish the component wavelengths in a color sample. Two lights of different colors when mixed produce a third color, and no human eye can detect its composite nature. Ultimately, the perceived hue is the dominant or average wavelength. The ability to perceive color differences varies from person to person.

Afterimage and visual distortion

Afterimages are frequent physiologic effects of the cone receptors with normal function that cause alterations in perceptions. One type of afterimage that commonly affects clinicians is the spreading effect that occurs when light is removed from the retina; the receptors continue for a short time to be active and send a signal to the brain.[1] Under normal circumstances, the eyes do not stare fixedly at a single spot, but rather roam the visual field continuously. Thus, one constantly creates weak, overlapping afterimages of which one is totally unaware. If presented simultaneously with two adjacent areas of different color, the eyes will flick back and forth between them involuntarily. The color seen for each is a combination of the true color of the area and the afterimage of the adjacent area. When holding a shade guide close to a tooth, it is important to decide within seconds because the two will soon begin to appear more and more alike.

A negative afterimage occurs because of fatigue of the receptors, which become less sensitive to further stimulation. Strong red lipstick next to the tooth being evaluated will fatigue the red receptors in the roaming eyes, while the blue and green receptors remain fresh and can be fully stimulated. This can yield a perception of the tooth that is too blue-green. Give the eyes a break with neutral gray backgrounds. Kulzer's small intraoral gray shields screen background color glare; 18% reflective gray cards are the photographic industry standard achromatic background.[16] Blue backgrounds are not appropriate because they cause afterimages and will bias perception to its complementary color, orange. Some advocate use of a blue background[17–20] to make the eyes more sensitive to yellow-orange, but this selectively fatigues one type of cone and does not make the others any more sensitive. An 18% reflective gray card is an excellent background for photographic evaluation of hue and chroma.[21]

Proper environment for color rendering

The ability to perform shade selection depends on how well the eyes perceive the details of teeth. Factors determining the visibility of these details include ambient light quality, luminance (light quantity), size, contrast, and glare. Establishing the proper environment for evaluation requires an understanding of these "seeability" factors. Dental-unit lights are commonly used for color rendering. Most are incandescent and emit light high in the red-yellow spectrum and low at the blue end. Therefore, illuminating opaque samples of red, yellow, and blue under an incandescent light source shows that red and yellow are quite strong, or highly saturated, while blue is weaker and more difficult to see. Under an ordinary cool white fluorescent source, which is high in the green-yellow spectrum with some strong but narrow blue-spectrum spikes, the reds and violets are less apparent. Some fluorescent bulbs have full color content and render color more accurately. The ambient light quality of the operatory must be maintained with artificial lighting (natural light conditions vary); it is commonly measured by the color temperature and Color Rendering Index (CRI).

Color temperature

When black iron is heated gradually, it will begin to glow, first with a red hue, then yellow, white, and blue.

Plotting the temperature increase of this black iron radiator relates temperature with color change and establishes a color temperature scale. This scale is commonly used to index color of light sources; the ideal color temperature for color rendering is 5,500 K. Light at this temperature can be described as having a medium-temperature feel and is considered "white" light. Color temperature is the mean wavelength of the ambient light. Because color temperature is an average, not all wavelengths are present, nor in equal amounts.

Color Rendering Index

Not all wavelengths need be represented to produce white light; it can be simply produced by mixing the three primary light colors. Ambient light is a varying assembly of many different wavelengths. Artificial lighting can approach white light (5,500 K), but the full spectrum of wavelengths is not necessarily present. The reflected colors (wavelengths) of a tooth cannot be seen if those wavelengths are not present in the ambient light spectrum.[2,18] If ambient conditions have only a small range of the spectrum of light wavelengths, all that is reflected back are the wavelengths present. If red light is not fairly represented in the spectrum, the reds in the object to be matched will not be visible.

CRI is the measure of the completeness of the light spectrum. A measure of 100 indicates that the entire visible and near-UV light spectrum is present. Although the close-to-visible UV spectrum cannot be seen, it is commonly absorbed and fluoresced out at wavelengths in the visible spectrum. Fluorescent bulbs tend to be at 3,000 to 4,200 K. The average incandescent dental-unit lamp has a CRI of 75 and averages 3,800 K.[13,20,22] Theoretically, the ideal light to take a shade has an equal energy mixture of light—a balanced, equal mixture of all the visible wavelengths. A CRI greater than 93 is preferred. Ideally, both the clinician and laboratory technician should have balanced full-spectrum lighting conditions.

Metamerism

Metamerism occurs when restorations match in one light but display a different color in other light conditions.[16] One object may have the ability to reflect more red than another. However, if there is no red range in the light source, they will appear the same; when viewed under a light source containing red, they will appear different. The color seen depends on the nature of the light source illuminating the object. The color of an opaque object is the sum of the wavelengths that reflect off it. Light spectrum reflectance graphs measure the percentage of reflectance of all the near-UV and visible-light spectrum off of a material. Porcelain might reflect light off its surface exactly as enamel in one part of the spectrum, but under different illumination the two objects that previously looked identical might look different. The closer the curves of the two materials to be matched, the more successful the color match will be.[23] Use of opaque surface stains to correct mismatches will increase metamerism. When reconstructing a tooth with dental porcelain, mimicking the layers of the tooth employing materials with the same optical properties (spectral reflectance curves) will minimize metamerism.

Light intensity

The intensity of the light conditions is also important. If the amount of light (measured in foot-candles or lumens per foot^2) is too small, fine details are missed and the eye has difficulty perceiving hue. Usually, the ceiling lighting in the dental operatory is not intense enough to see everything. With teeth that have subtle color variations, proper intensity is needed. Too great an intensity and glare decrease the accuracy of color rendering. Dental-unit lights should not be used for color rendering; they are too bright and cause glare. Glare fatigues the eyes; rendering shades immediately after using a dental-unit light is also contraindicated.

The ideal luminosity for dental shade matching is 75 to 250 foot-candles.[15,17,20,24–26] To have 175 foot-candle intensity at the level of the dental chair, ten to twelve 4-foot bulbs would be needed in a 10 ft × 10 ft room with 8-foot ceilings.[1,14,15,25] The diffusion panels covering fluorescent bulbs are also

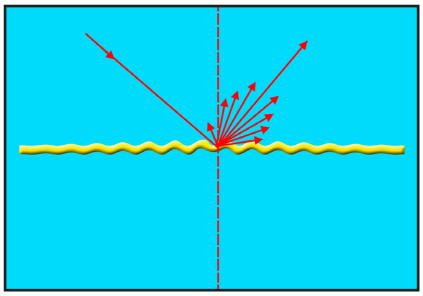
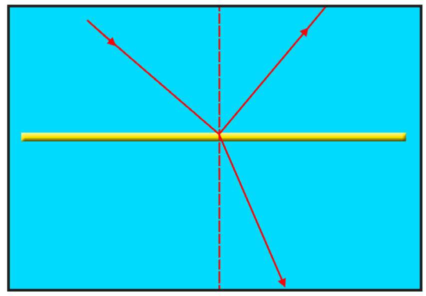


Fig 2 (left) *Roughened surface diffuses light.*[33]

Fig 3 (right) *Smooth, polished surface produces a well-defined image and can be more translucent.*[33]



important because they screen out wavelengths. As they age, the panels change what wavelengths they absorb. The best diffusers, preferably the egg-crate type, do not filter out any wavelengths of the spectrum. Using 10 to 12 color-corrected bulbs on the ceiling will yield more light in the operatory than would be considered comfortable. Portable high-quality light units, such as the Vident light, are ideal. Shade matching with photography lessens, but does not obviate, the need for special lighting. The proper shade tabs still need to be selected.

Reflections of light

It is important to realize that hue and chroma are fifth or sixth in importance on the list of things to match when constructing a prosthetic replacement. One must be fairly close to someone to detect subtle differences in hue; yet shape, surface morphology, value, and translucency disparities can be seen from 4 or 5 feet or more. Violating conformity of the unique characteristics of the natural dentition will cause unwanted prominence of the restoration.[18,27–29] These characteristics determine how light is reflected, transmitted, or scattered, affecting its hue, chroma, value, and translucency.[18,30,31] The appearance of teeth is mostly determined by how light interacts with the curved and varied surfaces. Attractive prosthodontic replacement starts with a consistent silhouette and shape of the buccal surface because these factors determine how the majority of light will be reflected.

An observer only sees an object when light comes from that object. Surfaces perpendicular to the viewer send the most light back. The reflective surfaces of a tooth will not return as much light to the eyes if they are not perpendicular to them. Because a viewer mainly sees the surfaces of a tooth perpendicular to him or her, the perceived width and length can be manipulated by bending or flattening surfaces. The practitioner can make a tooth look narrower or shorter by decreasing the width or length of the direct buccal reflective surface.[32] Another example is a maxillary incisor tipped lingually: It will not reflect light directly back and will appear darker. The smile can be made to appear more uniform even without realigning the tooth simply by brightening it.

Reflection from a smooth, mirror-like surface results in a clear, well-defined image. Such a "specular reflection" returns a high percentage of direct, nondiffused light, and if strongly illuminated, will be brighter and stand out (Figs 2 and 3). Smoothing the texture of the buccal surface will make teeth appear lighter and brighter and is therefore a primary determinant of value. **[AU: Correct as edited?]** The more reflective the surface, the more wavelengths return to the eyes; the additive combination of more wavelengths yields whiter light (hue change). Brighter objects appear closer to the viewer, so a restoration that is too light appears to "jump out at you." Lowering the value makes objects appear further away. Roughening texturally the specular highlights of a too-bright crown will make it blend better. Most teeth have irregular surfaces with convexities and concavities. The convexities tend to wear and become smooth, with specular reflective characteristics. The visual impact of a tooth comes from these specular highlights that give the tooth its visual shape. Concavities tend to be unpolished and collect light by reflecting inward, diffusing the light and return-

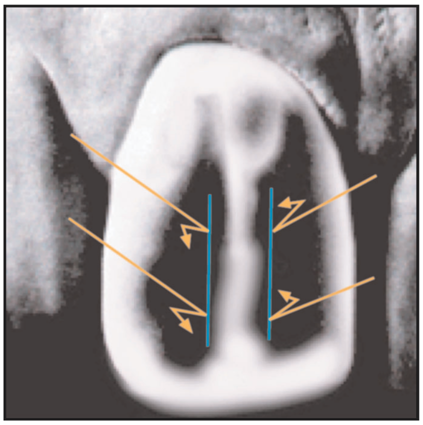


Fig 4 (left) *Double reflection and absorption of light in the fissures and concavities cause diminution of light coming out of these areas.*

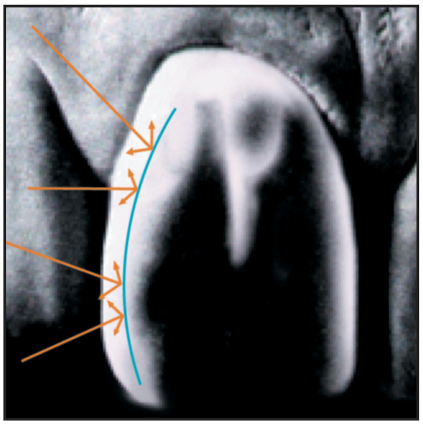


Fig 5 (right) *Light is reflected more in bulging and curved areas, which are generally more worn and polished.*

Fig 6 (left) *Heavy vertical surface textures highlighted by specular reflections off the heights of contour.*

Fig 7 (right) *Heavy horizontal surface textures sit on top of the vertical textures and thus follow in and out of the concavities.*

ing less to the eyes[33] (Figs 4 and 5).

Surface texture

After shape and contour, surface texture and luster are the next most important factors affecting how light interplays with the tooth surface. A roughened surface texture will not yield as well-defined an image and will scatter the light; the individual wavelengths bend differently, yielding a substantially different spectrum returning to the eye.[34] Texture can be broken down into subgroups: vertical, horizontal, and malformations (Aiba N, personal communication, June 2001). **[AU: Personal communications (originally refs 35, 38, and 60) moved into text; subsequent refs renumbered.]** Vertical surface textures are primarily composed of the heights of contour of the developmental lobes and marginal ridges (Fig 6). The specular highlights reflecting off these heights tend to form the visual outline of the tooth.

Perichymata, the fine, transverse, wavelike grooves believed to be external manifestations of the striae of retzius,[7,35] are horizontal textures. The striae, or lines, of retzius are the result of the layering manner in which the deposition of enamel takes place (Fig 7). Perichymata can be abraded with age, often resulting in horizontal grooves separated by distances much greater than the original perichymata traversing the tooth. These grooves can be convexities and/or concavities, and they stretch in a flat to U shape (bottom of U toward gingiva) across the buccal surfaces of the maxillary incisors. These horizontal undulations get flatter and closer together going gingivally (Aiba N, personal communication, June 2001); they never cross, and they go circumferentially. There tends to be more stippling of these textures gingivally. The concentrations of dechromatized white enamel so often found in younger, more superficial layers of enamel are often associated with horizontal textures. Horizontal textures are formed on top of vertical textures; the horizontal patterns follow into the concavities formed by the vertical textures, but the vertical are not affected by the horizontal. When texturizing restorations, carve the vertical textures first and then overlay the horizontal ones.

Malformations are the third textural group and can be from cracks, chips, and other surface aberrations. Surface texture can be generalized as being heavy, medium, or light. A rough, or heavy, surface texture will have a lower value because it tends to diffuse light by reflecting it in many directions, and less light returns to the viewer. A light surface texture has a higher value beause of the increased specular reflection. At eruption, teeth have their roughest surface texture. With age, these surface features gradually wear. As the wear process continues, all signs of the perichymata are usually lost, and even the definition of the developmental lobes is obliterated.

Luster

There is an order of magnitude or more size difference between luster and texture. Reducing the surface luster of a piece of clear window glass by wet sanding or etching will produce a frosty white look. As light hits the surface of the etched glass, it scatters irregularly, causing an increase in opacity. The light is not carried off and away from the surface, but rather reflected. As the glass becomes less translucent, the value goes up. The net effect is that more light returns to the viewer as the luster goes down. A decrease in luster creates a similar change in enamel opacity as dehydration and bleaching. It is important to note that surface texture, not luster, determines specular reflection. Young teeth tend to have a much lower luster but still have flat areas that allow for specular reflections. Polishing the rough glaze off a porcelain restoration is a subtle way to lower value by making the porcelain clearer and more translucent.[36] Super-polished flat surfaces can appear bright because of the specular reflection, but they also have more translucency because the light is not scattered at the surface. When a surface defect is polished down approaching the wavelength of light, it disappears.

A surface can have different combinations of texture and luster. A heavy surface texture will produce a lower value by redirecting reflections away from the viewer or with double inward reflections, and a high surface luster also makes a tooth or crown darker and more translucent. Because of the impact they have on the optical properties of the tooth, the prudent practitioner will note these properties in the lab prescription.

Tooth color characteristics

In a newly erupted tooth, the superficial layers of enamel are the most opaque. These layers frequently appear as though they have a white frost. This enamel may have a higher organic component (Eubank J, personal communication, 2001; and Boyde[37]), is less mineralized, and has more empty space between the enamel crystals, all causing increased opacity.[10,37] It has a very low luster caused by the pronounced rod endings from enamel deposition. As these top layers wear off, the underlying enamel is less opaque. The chroma of a tooth, which primarily comes from dentin, will be lower in a young tooth because of the masking effect of the enamel. The natural thickness of enamel is greatest at the incisal and lowest at the cervical aspect; therefore, chroma is greatest at the cervical and decreases toward the incisal aspect.[38] As the enamel gets thinner with age, the dentin becomes more obvious and the tooth becomes less monochromatic. Young enamel is also more permeable and will dehydrate quickly. The deeper layers of enamel have fewer air spaces and are more highly mineralized. This deeper enamel is more translucent.[36]

When light enters a tooth, it may reflect off many surfaces within the tooth before it exits, substantially changing its character. The more scattering in the enamel, the higher the value.[6,10] Enamel rods and the surrounding interprismatic substances are positioned perpendicular to the dentin layer. Light tends to travel easily down the rods but not as well laterally. This directionally dependent light transmission is called anisotrophy.[39,40] A highly pigmented area can sometimes be seen from one angle but not another. The translucency of enamel varies with the angle of incidence, surface luster, wavelength, and dehydration.

The hues of natural teeth tend to be in the yellow to yellow-orange range. If one were to place the rainbow on a line, the A shade is more toward the red end of the yellow spectrum, and the B shade is more to the green end of the yellow spectrum. Most teeth are closer to A on the Vita Classic shade guide, but there is a much wider spectrum of natural hues than most shade guides provide.[17,41–46] The thickness of dentin, size of the pulp chamber, and vitality of the pulp tissue differ during different stages of tooth development. Teenagers generally have a larger pulp chamber that adds red. With secondary dentin formation, the pulp chamber decreases in size, causing the dentin to appear less red.[47] Older or sclerotic dentin is darker (higher chroma, lower value) and has more green and blue. Young dentin is more red-yellow.[38,48] (CIE Lab color spaces[49] a* and b* go negative with age.) There is a positive linear correlation between age and chroma of the roots.[50] Although the dentin undergoes a color shift from red-yellow toward yellow, the overall color of older teeth is redder[48];less bright enamel covers the red dentin because of wear. Different teeth in the arch can belong to different hue families.[48] a* (red-to-green gradient) is highest (most red) in canines, then central, then lateral incisors.[47] b* (yellow-to-blue gradient) is highest (most yellow) in canines, then lateral, then central incisors.[47] The cervical hues are always redder than the middle or incisal ones.[48]

Value is mainly determined by qualities of the enamel layer in the form of reflectivity and opacity. As the superficial layers of the enamel surface are worn, the translucency goes up and the dentin becomes more visible and dentinal chroma begins to influence value more. To raise the value in a restoration that needs to be highly translucent (translucency normally drops value), the brightness needs to be built into the dentin instead of the enamel. Value is typically lowest at the cervical, then at the incisal, and highest in the middle third of the tooth.[38] Value increases going medially from the maxillary canines to the central incisors.[47,48]

Translucency is greatest in lateral incisors; therefore, opalescence (primarily in translucent enamel) is most evident in them. The mammelons and interproximal contact areas usually show the most blue opalescence because there is no opaque dentin behind them to reflect back the red and yellow wavelengths. Canines show very little translucency. Remember that the maxillary canines are often one to two full chroma steps higher than the maxillary incisors and will sometimes give a better clue to the average hue family. The hue and chroma of natural teeth are not constant. If a laboratory uses the same porcelain for all of the teeth in an arch, the mouth will look flat.[36] A natural three dimensionality can be developed with chroma gradients getting darker from the central incisors tothe posterior.[51]

Bleached teeth

Bleaching teeth will cause a change in hue, chroma, value, and translucency. Bleaching causes dehydration and the brightening or removal of pigmented organic material from between the HA crystals, which significantly changes how light interacts with the enamel and, with prolonged beaching, the dentin. Common clear glass is relatively transparent. When crushed into smaller pieces, the glass that remains becomes opaque. If water is added to the pile of broken glass, it becomes more translucent again. Dehydration increases the opacity of the enamel. Light no longer can go from HA crystal to crystal. Less translucency causes more reflection, so the tooth is brighter.[6] The hue changes because of a change in the reflectance spectrum of the enamel.[52] Recently bleached teeth are not color stable; shade matching should be delayed for at least 1 month. The rebound of bleaching is mostly due to the rehydration of enamel. Bleached teeth dehydrate much faster than other teeth, so shade rendering should be completed prior to any treatment.

Surface staining

There are several very good uses for porcelain surface stains. The best use is to help communicate the look of a difficult-to-match tooth to the lab. Painting the surface of a shade tab or a mismatched, already completed crown is very helpful to the lab and can be a great complement to photography. Tanaka Dental Products makes a good porcelain stain that can be painted onto the surface of anything. It can also be used for enhancing the beauty of provisional restorations; stains can be sealed on with Palaseal (Heraeus Kulzer), a light-cured methyl methacrylate. Painting shade tabs is a great way to convey hue and chroma, but ultimately it can encourage the lab to use surface stains on the restoration, increasing metamerism.

Stains can be used for characterization and modification of a mismatched restoration. When trying to cover an unwanted color, one can use subtractive laws of color mixing and add the complementary color. The two colors will cancel each other out, blending to gray.[53] Caution: This will lower value. Chroma can be increased easily with surface stain (subtractive darkening), and to a limited extent it can be decreased with bright stains, but these will decrease the light coming out of the tooth. Lowering the chroma with surface stains will limit vitality and depth of color.

Laboratories commonly lower the value of a restoration gingivally by adding surface stains. Surface stains are less preferable than internal staining for permanent restorations because they are more opaque and a light barrier, which prevents seeing the color from the internal body of ceramic,[54] of the restoration. They also wear off with time. Stains increase light absorption, alter reflectivity, and decrease translucency and opalescence.[54] Opaque surface stains increase the likelihood of metamerism.[23,41] Grays attained by mixing complementary colors are "complex" grays, with erratic spectral reflectance curves that increase metameric problems.[23]

Labs should lower value primarily within the dentin layers, not with superficial stains. Translucent porcelains are less metameric than the more opaque body porcelains. The addition of proximal and lingual stains can reduce a monochromatic appearance of a restoration without directly visible stains. Visual form can also be altered by the use of stains. Long restorations can be "shortened" by the use of darker stains cervically. Stains can be used in many ways to darken (deemphasize) or highlight contours.

Guidelines for matching

Clinicians can create circumstances to allow for better viewing of the teeth. If the quality of a match is judged by shape, surface morphology, value, translucency, hue, and chroma, finding superior ways to assess these is imperative. The chromatic portion of value and the hue and chroma require the freshest eyes and should be evaluated first. Remember that value or brightness comes from two sources, the chroma of the tooth and the surface reflectivity. The chromatic portion is evaluated with a value guide in subdued light conditions.[20,30] The rods in the eyes are sensitive to lightness/darkness, or the value scale, even with small amounts of light. The cones only become activated with higher light levels. When the cones are functioning, the hue and chroma seen will confuse value discrimination. Once the chromatic portion of value is measured, raise the light levels to normal light conditions. This light level is still too low for hue determination but is perfect for further value evaluations. Now view teeth with the lips relaxed (indirect light) and reflected (with direct light at 90 degrees). If there is a great value drop when shadows are cast on teeth by the upper lip, or with a polarized light filter, the predominant brightness source is superficial, caused by high surface reflectivity. After value is determined, hue and chroma are selected.

Environmental conditions are critical to the proper selection of hue and chroma. Create a neutral-colored environment. Extraorally, bright clothing and the color of the walls in the operatory and lab can alter color perception. Peri- and intraorally, lipstick and the red oral tissue background fatigue the cones, yielding complementary afterimages. The best extra- and intraoral backgrounds for hue and chroma selection are neutral gray.[55,56] Neutral gray has no complementary color and is restful to the cones. This is even more critical with aged teeth that have a glossy surface that reflects the shade of any color placed in close proximity.[15,22,35,56] Use a gray bib or towel to cover the patient's clothes,[57] and remove, retract, or cover any lipstick.

Provide the ideal lighting conditions while hue rendering. No matter what technique is used, without a light source that approaches 5,500 K and has a CRI of 93 and the proper luminosity, a superior match is difficult for the clinician and lab. **[AU: Correct?]** Viewing teeth under diffuse illumination will minimize the distortion of the reflected light. Reflection from the specular surfaces of a tooth reveals more of the color of the illuminating light than the color of the tooth.[3] Consider using a portable Vident light with a rheostat that can control the light intensity and give a diffuse illumination.

Miller[44] has suggested arranging the Vita Classic shade guide by hue with the A and B hues at opposite ends and C and D in the middle.[42] C and D have hues in between A and B[43] on the linear rainbow (chroma and value are manipulated to yield different looks). When choosing the hue family, use the A-4 and B-4 or A-2 and B-2 tabs, which facilitates the process of elimination by using tabs with the greatest hue spreads.[20] The chroma is very low for shades A1 and B1; it can be difficult to distinguish the proper hue family using these tabs. Compare the highest chroma tab in each hue family with the maxillary canines. If in doubt as to the hue family, choose A (Miller L, personal communication, Feb 2001; and Smith and Wilson[58]). Most natural teeth have more red than the B family. Perhaps as much as 80% of natural teeth are a closer match to the A hue family.[59]

Hold the shade tab incisal edge to the incisal edges of the teeth. This effectively isolates the shade tabs from the teeth so they do not reflect onto each other (Aiba N, personal communication, June 2001; and Ray[22]), reducing afterimages. When choosing the hue with a shade tab, look to the midbuccal aspect of the tooth. Differences between the shade tabs and the natural color of the teeth increase near the root. Compared to the Vita shade guide, natural teeth exhibit increased redness and lower translucency at the cervical aspect,[22,38] and this must be noted in the prescription. Because of later eye fatigue, first impressions are the best. To prevent hue accommodation, do not stare at the teeth for more than a few seconds.[20] Most humans have eye dominance, and one eye will preferentially perceive shade.[51] In addition, difficulties can arise where the tooth being examined differs considerably in size from the specimen on the shade guide. A variation in color perception can occur, with the larger area appearing brighter and more vivid.[60]

Different light wavelengths reflect off a rough surface in different ways. Shades should be evaluated by looking at the tooth at different angles, or vectoring.[16,27,51] It is wise to hold the shade guide on both sides of the tooth at different vectors (Aiba N, personal communication, June 2001). Because of the curved translucent surfaces found on teeth, the anisotrophic properties of enamel, and the complex layering of the tooth structure, vectoring will allow the operator to identify colorations within the layers of the tooth and better visualize the translucent areas. Sometimes, the value of the gingival and incisal thirds of a tooth is seen as lower than it actually is because of the natural curvature of the tooth.[56] These are all limitations of the new mechanical shade-taking devices that register reflected light predominantly from surfaces perpendicular to them.

Translucency is best evaluated with a black background. The best way to evaluate translucent areas is to look for the opalescent blues. The translucent enamel transmits reds and yellows and holds in blues. A black background prevents the reds from the back of the mouth from remixing with the blues. When drawing proximal translucence, ask the patient to turn from right to left, which allows a better analysis.

Shade map in a 3-D drawing all that is seen. Use multiple views (eg, 90-degree straight buccal, straight incisal/occlusal). Break the labial face of the crown into zones. Describe the surface texture as vertical, horizontal, or with malformations, and whether it is heavy or light. The preoperative models will help duplicate these contours, although the luster and texture can be better documented photographically. Be specific when describing the reflectance pattern and heights of contour on the prescription form. These surface features determine the character and amount of light reflected[35] and the amount of light that enters the tooth. The surface morphology of a crown should be designed to simulate the contralateral tooth.

All shade guide selection should be done *before* turning on the dental-unit light. This light is too bright and causes eye fatigue.[51] Another reason to do shade selection before treatment is dehydration.

Fig 8 *For chroma and hue, take shots at 60 to 70 degrees from surface with incisal edge of tooth down and away from camera; keep tabs at uniform distance from tooth surface; vector shots; use 18% reflective gray background; include occlusal and incisal shots; and bracket F stops.*

Fig 9 *Shade guides perpendicular to the flash have reflections rendering them useless for hue and chroma evaluation. One never knows what reflections will appear in a slide until later, so take pictures at many angles.*

Photos for shade rendering

Many methods have been described to facilitate the transfer of shade information to the lab. It is difficult to accurately describe a complex, multilayered, multitextured, 3-D color scheme of varying opacities with a 2-D shade guide system.[43] In addition, 9.3% of male dentists have a color vision defect, and most of them do not receive help with matching from someone trained in color science.[61]

The best way to communicate to a laboratory is with color-accurate 35-mm slides. Use a color-corrected professional-quality film (eg, Kodak EPN-100, E100-S, or EPP; Eastman Kodak), and use a good photo lab for developing. An accurate clinical photograph can document numerous details that would be missed by the eyes. Use a color-corrected flash.

The teeth should be dry when evaluating value, translucency, and surface geography to allow unrestricted observation of surface. Surface geography and value shots should be taken at 90 degrees from the surface. The teeth can be wetted for hue and chroma evaluation to limit the influence of surface morphology (Fig 8).

Arrange the matching tab in the middle and use the tabs one chroma stop higher on the right and one stop lower on the left. Note that shade guides are being used not to measure sum total color, but rather the color of each layer of the tooth. Use as many tabs as there are colors in the tooth. If more than one hue family in a tooth/arch is visible, photo all the tabs that seem to match. Suggest ratios to the lab in the prescription. Vector shots. Try to keep the tabs at the same distance as the teeth from the camera; if brought closer, they will appear brighter.

The reflections produced at 90 degrees reduce the ability to color render the tooth and/or shade tab (Fig 9). A ring flash surrounds the camera lens and increases the amount of reflection back at almost any angle. Note that if the pictures are taken below the incisal edge, the flash will light the back of the mouth, making it difficult to evaluate hue, chroma, and translucency without a background.[62] An 18% reflective gray card is a helpful background while selecting hue and chroma.[16,21] It has no complementary colors (thus, no afterimages are produced), and it is bright enough to limit the contrast of brightness between the teeth and background. The cardboard Pensler Shields should be kept 5 to 15 mm from the teeth (Fig 10).

It is easier to identify the translucent areas of a tooth with a black background behind the incisors (Fig 11). This will stop any light reflected from inside the mouth from reentering the enamel (thus adding itself back in), which would lessen the visual impact of the bluing in translucent areas.[63] Bracket the camera F stops. Closing down the lens increases contrast and allows better visualization of the internal structures. Lower light helps identify the coloration within the different layers of the tooth and better viewing of translucent areas.[64] A black background is not useful in hue and chroma selection, as it increases glare.[13] Because of the confusing influence of hue and chroma in the shade tabs, value can be more easily evaluated in low light or with black-and-white film.[63]

Remember to take incisal or occlusal shots. The older the patient, the higher the chroma of these areas. Also take photos with shoulder and incisal porcelain tabs. Although the media image of teeth has a limited chroma gradient going gingivally, if one wants the single central to disappear, this information is needed.

Distinguishing the source of value can be challenging. Use of a polarized light filter will cancel the reflected light, making it easier to determine if the brightness is from low chroma or surface reflectivity.[65] If an all-ceramic restoration is to be used, photograph the prepared teeth. Keep the prepared teeth wet for these pictures.

An extension tube allows for more magnification of the characterizations. Take photos at 1:1 scale. The technician can then use calipers to measure exactly where to place characterizations. Always document the shade tabs visible in the slide by including the tab number in the photograph or writing it down on the slide border. If the crown does not match, rephoto with the mismatched crown in the mouth.

Fig 10 *Gray background is too far behind the teeth; it appears to be black, which increases contrast and glare. Gingival necks are also partially copped, not allowing total view of the teeth.*

Fig 11 *For translucency, use a black background; underexpose shots; take shots from 60 degrees to surface (from above); and vector shots.*

Conclusion

Knowing how light interplays with the surface and internal layers of teeth is beneficial in the creation of an artificial replacement of tooth structure. Faithfully matching the optical properties of each layer increases the likelihood of a good match and decreases the problem of metamerism. What the practitioner sees is very difficult to communicate to the laboratory technician without the proper language. Both clinician and technician need to understand the nomenclature of visual effects. Clinicians should create the optimal environmental circumstances in the shade-matching process so that all that there is to see can be seen without distortion. When matching teeth, the shape, surface geography, value, translucency, chroma, and hue are all important characteristics. Intraoral photography is the best device to communicate these factors to the laboratory.

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