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Advances in color matching

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There have been a number of recent technologic and materials advances that offer the potential to improve color-matching skills in prosthetic and restorative dentistry. Although the dental profession has been aware of shortcomings in shade guides and corresponding materials for decades, it is probably the current media-driven emphasis on appearance and an "esthetic standard" that is primarily responsible for pushing product development forward. Significant advances in dental porcelains, resins, bonding chemistry, and cements have accompanied developments in color measurement optics to create a marketplace that is exciting and at times overwhelming.

Continued research on the human visual system has given us greater insight into how color discrimination is affected by our environment and by disease, drug therapy, and normal aging. Over the last two decades, a number of laboratory and clinical investigations of instrumental color measurement have been published [1–9], and visual thresholds of color difference perceptibility and acceptability have been established [10–12].

The clinical focus of color matching in prosthodontics is the beginning and the end (ie, shade selection and evaluation of the final result), but the overall color replication process is more complicated than these isolated procedures suggest. The shade duplication phase encompasses many variables that can have isolated or cumulative negative effects on the final outcome. Variables that have been investigated include restoration thickness, type of crown substrate and veneer material choice, firing temperature and frequency, and technical skill [13–19]. An accurate initial shade selection does not necessarily lead to an acceptably matched final restoration.

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Nature of color

Color is all about light. For color to be seen, light is reflected from an object and stimulates the neural sensors in the eye's retina to send a signal that is interpreted in the visual cortex of the brain. There are numerous possibilities along this pathway for altering the final registration.

Light

Natural white light—daylight—is sunlight reflected back from the sky. It falls between 380 and 770 nm along the electromagnetic spectrum and is a mixture of component bands containing a continuous contribution from radiation of each wavelength between these limits. The component bands produce six different sensations (red, orange, yellow, green, blue, violet), but there are an infinite number of gradations, and the boundaries between component bands are not exact; rather, the colors merge into one another [20]. Light sources, or illuminants, may be deficient in some wavelengths and therefore be colored themselves.

Object color is dependent on the illuminant in which it is viewed. If incident light does not contain a particular wavelength segment, the object cannot reflect it. In the achromatic range there are an infinite number of grays that are "produced" by objects that are nonselective in their reflectance. Colorants, either pigments or dyes, are responsible for chromatic reflection of light. The chemical composition of a colorant makes it selectively absorb more of one part of the visible spectrum than another. When a particular wavelength segment of light is reflected and enters the eye, the sensation of color is produced.

Perception

As light enters the eye through the cornea and lens, an image is focused on the retina. The amount of light entering the eye is controlled by the iris, which dilates or constricts depending on the level of illumination. Retinal sensors are positioned to take advantage of this focusing of light. Rods outnumber cones approximately 19 to 1, are scattered broadly throughout the retina, and respond to very low light intensity. These sensors are for registering lightness only. There are three types of cones, sensitive to red, green, or blue wavelength bands. The distribution of cones is limited primarily to the fovea centralis, a small area in the center of the retina where there are no rods. In the area immediately surrounding the fovea, there is a mixture of both sensors. It is thought that this mixture, unique to each individual, is responsible for differences in color discrimination among observers with normal color vision [20]. The accuracy of color perception depends on the area of retinal field stimulated by light. In high illumination, the pupil narrows, directing light to that small area of the retina where the cones are located. When light is dim, the pupil widens, and much more of the retina is exposed, stimulating sensors that are less accurate. As a regulator of pupil diameter, light intensity is therefore a critical factor in color perception and shade matching [21,22].

As the eyes scan a ''scene'' during normal observation, there is a rapid and continuous change in chromatic sensitivity that influences color perception. The most important of these phenomena that come into play during color matching are successive contrast, simultaneous contrast, and color constancy. Successive contrast is the projection of a negative after image (complementary color) that occurs after staring at a colored object. Simultaneous contrast is an instantaneous change in chromatic sensitivity characterized by a change in appearance of hue due to surrounding colors. Color constancy occurs because we think of objects themselves as being colored, so that an object seems to be the same color even if the light received by the eye varies considerably [23–25].

Color vision confusion

There are two general categories of color vision confusion (CVC): genetic and acquired. Genetic CVC is commonly referred to as ''color blindness'' and affects approximately 8% of males and up to 2% of females. The genetic defect can be an absence of cone type(s), a shift in spectral sensitivity, or a loss of color-difference signals [22,24]. These individuals suffer from a reduction in or absence of discrimination of the reddish-greenish or bluish-yellowish contents of colors. Absence of all color discrimination is rare.

Acquired CVC affects everyone and is not necessarily constant. There are many causes. Emotion affects papillary diameter, and with aging comes a yellowing of the cornea that affects blue and purple discrimination. Environmental exposure to cigarette smoke, sun, and lasers can have adverse affects. There are a number of chronic diseases that can have significant affects on color perception as well. Diabetes, glaucoma, leukemia, Addison disease, pernicious anemia, sickle cell anemia, multiple sclerosis, Parkinson disease, liver disease, and alcoholism have been shown to compromise color vision [21].

Some of the medications used to treat the above conditions affect some part of the visual system, leading to CVC. There are many common drugs that can significantly affect one's ability to distinguish colors, including analgesics, antibiotics antihypertensives, sildenafil citrate (Viagra), and oral contraceptives. Because of the number and variety of over-the-counter and prescription drugs, the risk of medication-related CVC is widespread [21,22].

Color organization and specification

Its three-dimensional nature makes it possible to pinpoint a specific color in a coordinate system that defines a color solid, and there are many systems designed for the specification of color. How a person is involved in the use of color determines which system is preferred. There are two such systems that are widely used in dentistry. In the Munsell System, the three-color attributes are Hue, Chroma, and Value. Hue is the attribute of color perception by means of which an object is judged to be red, yellow, green, etc. and is tied to a specific spectral wavelength band. Chroma refers to the depth or purity of the hue and is commonly referred to as saturation. It can be thought of as a measure of how different the color is from gray [25]. Value is the luminous dimension referred to as "lightness" of an object appearance and is completely separate from the chromatic attributes of hue and saturation.

Although these attributes can be designated numerically and the ranges for tooth color have been well established, they are more often referred to in descriptive and relative terms. We refer to Hue nominally (ie, red, green, blue, etc.). When comparing a target color to a standard (tooth to shade tab), a shift toward another Hue is described. Natural teeth lie in the yellow-red area of the color solids, so the shifts are generally "toward" red or yellow, or the Hue is described as more yellowish or more reddish. Chroma is either higher or lower, or more or less, because it is descriptive of intensity. Value can be higher or lower, or lighter or darker, because it is an achromatic quality and can be thought of as the amount of light that is reflected to the eye.

When color is measured and specific color differences are identified, the CIELAB system is frequently used. It is a nearly uniform color space whose three coordinates define lightness, red-green chromaticity, and yellow-blue chromaticity. This is the most popular means of defining the color of solid objects and is based on the Commission Internationale de l'Eclairage (CIE) 1976 L*a*b* uniform color space. In 1931 the CIE defined a "standard observer" by a set of three functions $x(\lambda)y(\lambda),z(\lambda)$. These were carefully prescribed spectral sensitivity curves designed to model the blue-, green-, and red-sensitive cone receptors of the eye, respectively. These functions are key to the transformation of spectral energy data into meaningful color data [26].

Visual shade-matching environment

Recommended environmental conditions for color matching have changed little since the early 1970s, except perhaps with regard to illuminants. The light source is critically important because of its influence on the quality and intensity of light reaching the teeth to be matched. Although we traditionally have sought natural daylight as the best color-matching light source, it is not dependable because of its variable color temperature, which influences its spectral composition, and its inconsistent intensity due to varying cloud cover and atmospheric pollutants.

The benefits of performing color matching under controlled standard full-spectrum illumination have been reported [27]. Controlled lighting sources in the dental operatory and laboratory should be spectrally balanced in the visible range (380–780 nm) and should have a color temperature of approximately 5500°K and a Color Rendering Index of >90 [28]. A number of lighting manufacturers supply bulbs that meet these requirements.

The quantity of light is important for optimum comfort and work efficiency. However, the intensity of the dental operatory lighting may not be critical for color matching [29]. Nonetheless, traditional recommendations for ambient lighting are a reasonable guide for establishing a comfortable environment: 200 to 300 footcandles (fc) in the operatory and 300 fc in the dental laboratory [30].

It may be helpful to use an auxiliary light source that provides the appropriate spectral balance and diffuse illumination and is bright enough to overcome the effects of ambient illumination. A 3:1 ratio of task-to-ambient light has been recommended [28]. The intensity should be comfortable to the eyes; too much compromises the ability to discriminate small color differences. A number of hand-held lights are available, including the Shade Wand (Authentic Products, San Antonio, Texas) and the Hand Held (Greatlakeslighting, Bay City, Michigan). A prototype, the Shademat Visual, has recently been evaluated and was found to improve visual shade matching [31]. The operatory ceiling, walls, counter tops, and cabinets are reflectors that contribute to the intensity and color of the ambient lighting and therefore should have a high Munsell Value and low Chroma [28]. Pastels and neutral grays have been suggested for walls, staff clothing, and patient napkin or drape.

Certain practical guidelines should be followed when selecting shades visually [32]. The patient should be in an upright position with the mouth at the dentist's eye level. Lipstick should be removed, and a neutral patient drape should cover colorful clothing. The teeth should be slightly apart and the tongue retracted. The shade tab should be in the same plane as the tooth. Shade selection should take place before any intraoral procedure that dehydrates the teeth, significantly altering their appearance. The value dimension should be selected first, so it is helpful to have a guide whose tabs are arranged from light to dark for an initial quick scanning. This can be done with squinted eyes to decrease the amount of light entering the eye so that the rods are activated for light-dark discrimination. Rapid chromatic comparisons of less than 5 seconds help avoid cone fatigue. Although it may help to look away at an achromatic surface (eg, neutral gray) to replenish the photopigments of the cones, gazing at a blue surface does not heighten yellow sensitivity as was once thought but distorts it [33].

If having trouble determining Hue, one should reference the natural canine, which is of higher chroma so the dominant hue is more apparent. Once a choice has been made, it should be verified under other lighting conditions, with the patient standing, at different viewing angles, and with the lip retracted and draped naturally. It is helpful to have a second observer stand about 3 feet behind the primary observer to verify that the value dimension is appropriate. If the tab ''stands out,'' it is most likely too high in value (ie, too bright).

These procedures can be done at multiple appointments to confirm one's choice. Provided one has normal color vision, shade selection can be learned and improved with practice.

Shade guides

Shade guides that are the most widely used today have not changed much in the last 50 years, except for the addition of a few more tab colors. In the early 1970s, Sproull [34–36] published a series of articles examining color matching in dentistry and made sound suggestions to the profession and manufacturers for the direction of research and product development. In the approximately 25 years that followed, numerous studies identified additional limitations of available shade guides and porcelain formulations, and many lecturers and authors called upon dental manufacturers to invest in reformulation, quality control in porcelain production, and development of logically ordered shade guides that would allow for proper orientation within the color space of natural teeth. By identifying the color attributes of natural tooth and shade guide colors, it was possible to determine that manufacturers' shade guides did not adequately cover the color space occupied by natural teeth [37–39].

Significant advances in shade guide organization and coverage of natural tooth color space are coming to the marketplace. An example is the Vitapan 3D-Master Shade System (Vita Zahnfabrik, Bad Sackingen, Germany). According to the manufacturer, this shade system provides a systematic arrangement of ''virtually all existing natural tooth shades,'' and it has been determined that the order of color dimensions in this guide is adequate [40]. Based on spectrophotometric measurements of natural teeth, the shade guide is organized so that it covers the three-dimensional natural tooth color space in logical, visually equidistant order. Rather than grouping the shades by Hue, as in the Vita Classical (Vita Zahnfabrik) and Chromascop (Ivoclar Vivodent, Amherst, New York) guides, the tabs are arranged in five clearly discernible value levels (Figs. 1–3). Within each level are tabs that represent different chromas and hues. The five levels cover that area of the CIELAB color solid occupied by natural teeth, with approximately 50% of natural tooth shades occupying the middle value level. The lightest value level has only two chroma steps of a single hue, and the darkest value level has three chroma steps of one hue. About 2% of natural teeth occupy these outer levels. Groups 2, 3, and 4 have three chroma levels of the middle and orange hue, and two chroma levels in each hue shift toward yellow or red. The sequence of shade selection is value, then chroma, followed by hue. The way

Fig. 1. Vitapan 3D-Master shade guide.

the shades are formulated allows for one visually perceptible step between value levels. Unique to this system is the possibility of selecting this in-between shade; powders can be mixed to achieve it with predictability. There are no visually perceptible steps between chroma levels of each hue.

Shade-taking devices

These devices have been designed to aid clinicians and technicians in the specification and control of tooth color. The earliest color-measuring device

Fig. 2. Vita Lumin shade guide.

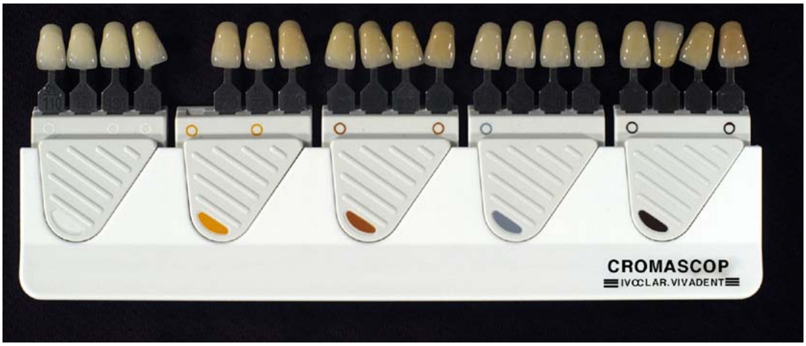

Fig. 3. Chomascop shade guide.

designed specifically for clinical dental use was a filter colorimeter. The Chromascan (Sterngold, Stamford, Connecticut) was introduced in the early 1980s but enjoyed limited success due to its inadequate design and accuracy [41,42]. Further development was hindered primarily by lack of resources and commitment on industry's side—the market was too small. Now, with esthetics as a major focus of dental marketing and with the availability of improved color-measuring optics, companies are willing to make the investment required to apply advanced technology to the challenge of shade control.

Basic design

All color-measuring devices consist of a detector, signal conditioner, and software that process the signal in a manner that makes the data usable in the dental operatory or laboratory. Because of the complex relationship between these elements, accurate colorimetric analysis is difficult at best.

Colorimeters

Filter colorimeters generally use three or four silicon photodiodes that have spectral correction filters that closely simulate the standard observer functions. These filters act as analog function generators that limit the spectral characteristics of the light that strikes the detector surface. The inability to exactly match the standard observer functions with filters while retaining adequate sensitivity for low light levels is the reason that the absolute accuracy of filter colorimeters is considered inferior to scanning devices such as spectrophotometers and spectroradiometers. However, because of their consistent and rapid sensing nature, these devices can be precise with differential measurements. This is why they often are used for quality control.

Digital cameras as filter colorimeters

The newest devices used for dental shade matching are based on digital camera technology. Instead of focusing light upon film to create a chemical reaction, digital cameras capture images using CCDs, which contain many thousands or even millions of microscopically small light-sensitive elements (photosites). Like the photodiodes, each photosite responds only to the total light intensity that strikes its surface. To get a full color image, most sensors use filtering to look at the light in its three primary colors in a manner analogous to the filtered colorimeter described previously. There are several ways of recording the three colors in a digital camera. The highest-quality cameras use three separate sensors, each with a different filter over it. Light is directed to the different filter/sensor combinations by placing a beam splitter in the camera. The beam splitter allows each detector to see the image simultaneously. The advantage of this method is that the camera records each of the three colors at each pixel location.

Spectrophotometers and spectroradiometers

Spectrophotometers and spectroradiometers are instruments designed to produce the most accurate color measurements. Spectrophotometers differ from spectroradiometers primarily because they include a stable light source. There are two types of basic designs commonly used for these instruments. The traditional scanning instrument consists of a single photodiode detector that records the amount of light at each wavelength. The light is divided into small wavelength intervals by passing through a monochromator. A more recent design uses a diode array with a dedicated element for each wavelength. This design allows for the simultaneous integration of all wavelengths. Both designs are considerably slower than filter colorimeters but remain the tools that are required to examine and develop accurate color-measuring devices.

Currently available devices

There are at least six commercially available systems, ranging from simple to complicated, with capabilities and prices to match. The devices are generally one of three types—colorimeters, spectrophotometers, or digital color analyzers—and use various measuring geometries (Table 1).

Shofu's Shade NCC (Natural Color Concept) Chroma Meter (Shofu Dental, Menlo Park, California) has been available since the 1990s (Fig. 4). It consists of a freestanding, hand-held contact probe that is about 3 mm in diameter. The probe is placed against the tooth, and an activation button is pushed. This sends a flash of light to the tooth, from the periphery of the probe, and the reflected light is transported through the center of the probe to the detector where the collected light is evenly distributed through color filters that closely match the three standard observer functions. Data are

Table 1
Shade-taking devices

System	Manufacturer	Type	Approximate cost
ShadeEye	Shofu Dental Corp., San Marcos, CA	Colorimeter	$7000
EasyShade	Vident, Brea, CA	Spectrophotometer	$5500
ShadeScan	Cynovad Inc., Montreal, Quebec, Canada	Digital color imaging/colorimeter	$6000
ShadeVision	X-Rite Inc., Grand Rapids, MI	Digital color imaging/colorimeter	$6000
SpectroShade	MHT, Niederhasli, Switzerland	Digital color imaging/spectrophotometer	$15,000
ClearMatch	Smart Technology, Hood River, OR	Software only (to be used with digital camera)	$3000

transmitted to the docking unit via an infrared signal. There is a database of porcelain samples stored in memory, and the closest match of the target with the stored data is presented. A readout is generated that includes the tooth number; the closest Vita Lumin shade guide designation; and specific opaque, body, and enamel powders. Although the ShadeEye was developed for use with the Vintage Halo Porcelain system (Shofu Dental), updated software versions reference other popular porcelains as well.

The Vita Easyshade (Vident, Brea, California) is a hand-held spectrophotometer that consists of a handpiece connected to a base unit by

Fig. 4. Shade Eye NCC.

Fig. 5. Vita Easyshade.

a monocoil fiberoptic cable assembly (Fig. 5). The contact probe tip is approximately 5 mm in diameter. It contains 19 1-mm-diameter fiberoptic bundles. During the measurement process, the tooth is illuminated by the periphery of the tip, directing the light from a halogen bulb in the base unit into the tooth surface. There are several spectrometers in the hand piece that monitor the light source and measure the internally scattered light. A combination of various filters and photodiode arrays receive the light as it is directed through the return fibers located in the center of the probe tip. Through this arrangement, spectral reflectance of the scattered light is essentially measured in 25 nm bandwidths. Before measurement, it is necessary to select a measurement mode (tooth, crown, or shade tab). The display presents the closest Vita shade in the classical or 3D shade guide designation.

The first system to combine digital color imaging with colorimetric analysis was introduced by Cynovad (Saint-Laurent, Canada). The ShadeScan is a hand-held device with a color LCD screen to aid in image location and focus (Fig. 6). Through a fiberoptic cable, a halogen light source illuminates the tooth surface at a 45° angle and collects the reflected light at 0°. Light intensity and calibration to gray and color standards are continuously monitored and adjusted to provide consistent color reproduction. The image is recorded on a flashcard, obviating the need for a computer in the operatory. The transmitted data can be downloaded to a computer with the ShadeScan software. Shade and translucency mapping can therefore be transmitted to the dental laboratory by e-mail or by including a printout or flashcard with the clinical items required for restoration fabrication. Surface shade mapping with the standard software

Fig. 6. ShadeScan.

is in basic Vita Lumin shade designations. Higher-resolution shade mapping, additional shade guide designation conversions, and Hue/Value Chroma values are possible with additional software for dental laboratories.

Another instrument that combines digital color analysis with colorimetric analysis is the ShadeRite Dental Vision System (X-Rite Inc., Grand Rapids, Michigan). It consists of a hand-held device with its own light source, and an LCD screen facilitates positioning on the tooth (Fig. 7). To focus and align the camera, a ''glare spot'' must be located at the junction of the gingival and middle thirds of the tooth. Measurements are taken through a series of rotating filters that simulate the CIE standard observer functions. The device is freestanding and is placed in its docking station for calibration and data transmission to the computer. Shade and translucency mapping are possible, and colorimetric data (CIE L*a*b* values) can be downloaded from the computer. The laboratory must have the required software.

The SpectroShade (MHT, Niederhasli, Switzerland) is the dental shade-taking device most complex in design and is the most cumbersome in terms of hardware. It offers the most flexibility in terms of color analysis and colorimetric data and is by far the most expensive (Fig. 8). It is the only one that combines digital color imaging with spectrophotometric analysis. The handpiece is relatively large compared with the contact probe designs, and positioning can be tricky. Calibration is a two-step process involving positioning the handpiece against white and green tiles. Light from a halogen source is delivered through fiber optic bundles and lenses to the tooth surface at 45°. The image of the tooth is displayed on the computer screen so that positioning can be verified. The incident light is monochromated as it strikes the tooth, and as it is reflected back the spectral scanning process is completed at 10-nm bandwidths by a black and white and a color-filtered CCD. Because there is a spectral curve associated with each pixel of the CCD, a significant amount of data are generated for analysis. Color differences can be calculated between compared images, and shade maps of

Fig. 7. ShadeRite Dental Vision System.

increasing complexity and one for translucency are possible. The software contains shade guide references for most porcelain systems, and more can be added. The closest shade and the magnitude of the color difference from that reference are specified. A digital image of the tooth, the shade mapping, and the colorimetric data can be transmitted to the laboratory electronically or by printout.

A different approach to digital color matching is achieved with the ClearMatch System (Smart Technology, Hood River, Oregon). This is a software system that requires a Window platform PC and a digital camera. To properly calibrate the digital color signal, a black and white standard and a shade tab must be included in each photograph. Detailed shade mapping is provided in shade guide designations, and standard and custom shade tab information can be entered into the system database. Because this system is software only, it is the most reasonably priced.

Limitations

There are a number of limitations common to all of these systems, and for the most part they stem from the nature of what is being measured (ie, translucent structures). Accuracy of color measurement is affected by the

Fig. 8. Spactroshade.

phenomenon of edge loss, which occurs because of light ‘‘lost’’ primarily through the translucent tooth and ceramic enamel layers. Although algorithms are incorporated into the software to accommodate for the different light scattering properties in teeth, crowns, and shade tabs, it is difficult to compensate totally, and this can be a significant source of error.

Translucency mapping is inadequate with all of the systems. The replication of tooth translucency remains the most challenging aspect of matching the appearance of a natural tooth. The transfer of this three-dimensional quality to a two-dimensional map provides little benefit. Systems that incorporate digital imaging have the best chance because a high-quality ‘‘visual’’ is the best that is currently available.

Positioning of the probe or mouthpiece seems to be critical to the repeatability of the measurement. In addition, any device that uses a small-diameter contact probe is limited because it cannot give detailed mapping of color on the surface; only a general base shade of the limited area measured. The larger mouthpieces are limited to measurements of anterior teeth because of access.

The accuracy of the target shade obtained from the measurement is only as good as the database and its distribution of references shades. The readout provides the shade closest to the measured surface, and if the tooth to be matched is not close in color space to a designated shade, then a mismatched restoration results. None of the above instruments are sophisticated enough to function in a formulation mode (ie, specifying powders and layering to achieve the actual color designation of any tooth color or translucency distribution measured).

For this approach to be efficient, the laboratory must have the system as well, and indeed many commercial laboratories provide a shade-taking service. The quality control aspect is a real advantage. The technician can verify that the color replication process was accurate for the shade requested, and, with the more sophisticated systems, a "virtual try-in" can be accomplished. However, the research examining whether or not this instrumental approach provides a final result superior to conventional shade-matching techniques is lacking. Investigations are ongoing, but there are only a few published studies available [43–47].

Shade communication

Tooth appearance information beyond a basic single-shade designation is required when the restoration is in an esthetically prominent location. Shade mapping, which can be accomplished visually and instrumentally, is becoming a basic component of the work authorization. Characterization can be located on a drawing but may be more helpful if drawn on a cast that duplicates the size, shape, and contours of the requested restoration. Appropriate length and incisal edge position is best communicated in this way. An image of the selected shade tab(s) near the tooth to be restored or matched should accompany the written order and casts. Although the color of the image cannot be relied upon for accurate assessment or matching, the visual appearance of translucency, characterization, and color blending is far superior to that of a drawing. Digital images can be sent electronically or on a CD. Discussing with the technician the preferred methods of documenting and communicating information enhances the shade duplication process.

Summary

Media emphasis on an "esthetic standard" is probably responsible for driving the most recent advances in dental imaging and shade matching. Although we tend to focus on color matching, it is an appearance match that we are after, so the optical properties of translucency, light scattering, surface texture, and gloss and the basic principles of esthetics, including tooth size and proportion, symmetry, outline form, and overall harmony are just as important, if not more so, to a successful restorative match. With more research and development it should be possible to achieve a higher percentage of successful matches than the approximately 50% experienced today [48–51], but even with the acceleration of progress in color matching technology, the success of a restorative effort remains dependent on adequate tooth preparation, tissue management, and treatment planning.

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