1. Introduction

The interest in color research in dentistry has increased significantly over the past several decades. When keywords color and dentistry were used for Medline search, only 107 papers were found by 1970. In subsequent decades, the number of references increased as follows: 409 (1980), 1134 (1990), 2259 (2000) and 4062 (April 2010). Advancements in technology, computers, the Internet, and communication systems have greatly affected and shaped modern society. Commensurate with these strides are the advancements in contemporary dentistry. During the past half decade, the dental profession has experienced the growth of a new generation of technologies devoted to the analysis, communication and verification of shade. Shade determination for direct and indirect restorations has always been a challenge for the esthetic dentist. Clark in 1931 described this in the Color Problems in Dentistry.1 As opposed to subjective visual shade selection with not always quite controlled conditions and methods, and shade guides that exhibited significant shortcomings, several authors tried to objectively quantify tooth color in the past. This was done through identifying color problems in dentistry2; the importance of the quantity and quality of light required to properly analyse shade3

**References**

2. **Objective:** To review current status of hand held systems for tooth color matching in vivo and corresponding research.
3. **Sources:** "Medline" database from 1981 to 2010 were searched electronically with key words tooth, teeth, color and dentistry.
4. **Conclusion:** Spectrophotometers, colorimeters and imaging systems are useful and relevant tools for tooth color measurement and analysis, and for quality control of color reproduction. Different measurement devices either measure the complete tooth surface providing a "color map" or an "average" color of the limited area [3-5 mm] on the tooth surface. These instruments are useful tools in color analysis for direct or indirect restorations, communication for indirect restorations, reproduction and verification of shade. Whenever possible, both instrumental and visual color matching method should be used, as they complement each other and can lead towards predictable esthetic outcome.

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through studying correlation between extracted teeth and shade guides or the development of the early shade measuring instruments and shade guides.

The late 1990s marked the birth of a new industry in dentistry, commercially available instrument-based color measurement systems, with the development of the ShadeScan system (Cortex Machina, Montreal, Canada). This was the first effort toward a shade analysis system for complete tooth surface measurement. Prior literature published by several authors described limited area measurement instruments, with an optical diameter of 3–5 mm, in the analysis of shade. Another study evaluated clinical application of the ShadeScan prototype which employed digital camera technology, in a case report comparing visual vs. instrument-based shade information in the restoration of a single maxillary central incisor.

Today’s shade-matching technologies have been developed in an effort to increase the success of color matching, communication, reproduction and verification in clinical dentistry, and, ultimately, to increase the efficiency of esthetic restorative work within any practice. The aim of this paper is to provide a comprehensive review of the current state of shade-matching technologies and instrumentation, and their clinical and research application.

### 2. Rationale

Dental shade-matching instruments have been brought to market to reduce or overcome imperfections and inconsistencies of traditional shade matching. The most commonly used shade-matching method is the visual method, whilst Vitapan Classical (Vita Zahnfabrik, Bad Säckingen, Germany) and its derivations are probably the most commonly used shade guides. The colored tabs of distinctive shades organize the empiric-based Vita chart. In addition, unequivocal findings were reported on color consistency amongst shade guides from the same manufacturer. Introduction of evidence-based Vitapan 3D-Master shade guides, Toothguide, Bleachedguide and particularly Linearguide by the same manufacturer correspond to color of human teeth and therefore increase chances for successful shade matching.

Historically, assessing shade visually has been characterized by several innate difficulties: metamerism, suboptimal color matching conditions, tools and method as well as the receiver’s age fatigue, mood and drugs/medications. Despite these difficulties, the human eye can discern very small differences in color. However, the ability to communicate the degree and nature of these differences is lacking.

The final color of an all-ceramic restoration is a merging of the underlying tooth structure or core and the ceramic material. The color of the final restoration cannot match the shade selected from a shade guide unless this modification is taken into account. Therefore, a stump or base tooth preparation shade needs to be obtained and transmitted to the technician.

### 3. Overview

Instruments for clinical shade-matching encompass spectrophotometers, colorimeters and imaging systems. As with any device, benefits and limitations exist, and the clinician must consider how the technology relates to expectations and needs. Intra-oral color measuring devices have been designed to primarily fit the needs of clinical dentistry, such as information on the corresponding shade tabs, tooth translucency, or information associated with color communication, reproduction and verification. This, together with price limitation dictated by the dental market, resulted in having scientific aspects, such as providing reflectance values or color formulation, less emphasized. Another significant difference compared to other, non-dental applications, are optical properties of human teeth—they are small, curved, multi-layered, translucent and exhibit color transitions in all directions (gingival to incisal, mesial to distal and labial to lingual). This is why the accurate repositioning (measurement of the same area) is frequently of critical importance for either clinical and research use of dental color matching devices. The list of instruments and software for in vivo color matching and their properties is given in Table 1.

In addition to the instruments listed in Table 1, there are numerous dental color matching products that are presently withdrawn from the market, of limited availability, or undergoing major redesigning. The list includes Chromascan (Sterngold, Stamford, CT, USA), Dental Color Analyzer (Wolf Industries, Vancouver, Canada), Identacolor II (Identa, Holbaek, Denmark), Digital Shade Guide DSG4 (A. Reith, Schornhof, Germany), Ikam (Metalor Technologies, Atteboro, MA, USA), ShadeEye NCC Chroma Meter (Shofu Dental, Menlo Park, CA, USA), Beyond Insight Shade Taking Device (Beyond Dental & Health, Beijing, China), Shadescan (Cynovad, Montreal, Canada) and Vita Easyshade (Vita Zahnfabrik, Bad Säckingen, Germany).

### Table 1 – Instruments and software for color matching in dentistry: types, measurement area and relative cost ($1000–$7500).

<table>
<thead>
<tr>
<th>Product</th>
<th>Manufacturer</th>
<th>Device type</th>
<th>Measurement area</th>
<th>Relative cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ClearMatch</td>
<td>Clarity Dental, Salt Lake City, UT</td>
<td>Software, digital image analysis</td>
<td>Complete tooth image</td>
<td>Low</td>
</tr>
<tr>
<td>CrystalEye</td>
<td>Olympus America, Center Valley, PA</td>
<td>Imaging Spectrophotometer</td>
<td>Complete tooth image</td>
<td>High</td>
</tr>
<tr>
<td>Easyshade Compact</td>
<td>Vident, Brea, CA</td>
<td>Spectrophotometer</td>
<td>5-mm probe diameter</td>
<td>Low</td>
</tr>
<tr>
<td>Shade-X</td>
<td>X-Rite, Grandville, MI</td>
<td>Spectrophotometer</td>
<td>3-mm probe diameter</td>
<td>Low</td>
</tr>
<tr>
<td>ShadeVision</td>
<td>X-Rite, Grandville, MI</td>
<td>Imaging colorimeter</td>
<td>Complete tooth image</td>
<td>Moderate</td>
</tr>
<tr>
<td>SpectroShade Micro</td>
<td>MHT, Niederhasli, Switzerland</td>
<td>Imaging Spectrophotometer</td>
<td>Complete tooth image</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
4. Characteristics and clinical application

4.1. Spectrophotometers

Spectrophotometers are amongst the most accurate, useful and flexible instruments for overall color matching and color matching in dentistry. They measure the amount of light energy reflected from an object at 1–25 nm intervals along the visible spectrum. A spectrophotometer contains a source of optical radiation, a means of dispersing light, an optical system for measuring, a detector and a means of converting light obtained to a signal that can be analysed. The data obtained from spectrophotometers must be manipulated and translated into a form useful for dental professionals. The measurements obtained by the instruments are frequently keyed to dental shade guides and converted to shade tab equivalent. Compared with observations by the human eye, or conventional techniques, it was found that spectrophotometers offered a 33% increase in accuracy and a more objective match in 93.3% of cases.

Crystaleye (Olympus, Tokyo, Japan) combines the benefits of a traditional spectrophotometer with digital photography. Through the development of optical and image processing technology, this product allows the practitioner to match tooth shade and color more accurately and simply compared with the traditional spectrophotometer.

The significant benefit of this system is that ‘virtual shade tabs’ in the computers database can be cross-referenced and superimposed visually onto the natural tooth image to be matched giving the technician the ability to visualize the correct shade tabs. The digital image produced by the Crystaleye uses a 7-band LED light source, which results in a more precise depiction of color than the conventional systems used with digital cameras. Moreover, the image produced by the Crystaleye is taken from inside the oral cavity and consequently is devoid of the external light that can cause discrepancies.

Vita Easyshade Compact (Vita Zahnfabrik, Bad Säckingen, Germany) is cordless, small, portable, cost efficient, battery operated, contact-type spectrophotometer that provides enough shade information to help aid in the color analysis process. Different measurement modes are possible with Easyshade Compact: tooth single mode, tooth area mode (cervical, middle and incisal shades), restoration color verification (includes lightness, chroma and hue comparison) and shade tab mode (practice/training mode).

Shade-X (X-Rite, Grandville, MI) is also compact and cordless “spot” measurement” spectrophotometer with 3-mm probe diameter, and keyed to the majority of popular shade guides. Shade-X have two databases to match the color of the dentin (more opaque) and the incisal tooth regions (more translucent).

SpectroShade Micro (MHT Optic Research, Niederhasli, Switzerland) is an imaging spectrophotometer. It uses a digital camera/LED spectrophotometer combination. It has an internal computer with the analytical software. The tooth positioning guidance system, shown on the LCD touch screen, is used during color measurement. Images and spectral data can be saved on the internal memory and transferred to a computer.

4.2. Colorimeters

Colorimeters measure tristimulus values and filter light in red, green and blue areas of the visible spectrum. Colorimeters are not registering spectral reflectance and can be less accurate than spectrophotometers (aging of the filters can additionally affect accuracy). ShadeVision (X-Rite, Grandville, MI) is an imaging colorimeter. Complete tooth image is provided through the use of three separate databases: for gingival, middle and incisal third. Virtual try-in feature enables virtual testing of color reproduction during fabrication.

4.3. Digital cameras and imaging systems

Digital Cameras. Most consumer video or digital still cameras acquire red, green and blue image information that is utilized to create a color image. The RGB color model is an additive model in which red, green and blue light are added together in various ways to reproduce a broad array of colors. Digital cameras represent the most basic approach to electronic shade taking, still requiring a certain degree of subjective shade selection with the human eye. Various approaches have been used to translate this data into useful dental color information.

ClearMatch (Smart Technology, Hood River, OR) is a software system that uses high-resolution digital images and compares shades over the entire tooth with known reference shades. Similar to the software associated with color measuring devices, ClearMatch contains the color database of industry-standard shade guides.

4.4. Interpretation and application of shade analysis data

Complete tooth surface measurement [CTSM] devices give a color map of the gingival, body and incisal shades for the fabrication of direct or indirect restorations. These systems give a virtual shade overlay of the proposed tab onto the digital image on the computer screen of the tooth measured for visual reference and assessment by the clinician and/or technician. CTSM spectrophotometers, such as Crystaleye and SpectroShade, provide shade tab designation and the respective \( \Delta E^* \) values compared to shade tab values in the memory. However, these mappings are two dimensional and they do not necessarily take into account the shape, texture, thickness of the restoration, type of abutment and different core material (metal or ceramic). In addition, they ‘average out’ color data over the complete tooth surface or larger defined areas which can lead to inaccurate shade information.

Limited area measurement devices provide 3–5 mm diameter areas of the tooth being measured. Therefore several areas of the tooth should be considered to obtain a representative evaluation of tooth shade. At a minimum, a limited area measurement of the gingival, body and incisal areas of the tooth [total of 3 measurements] should be assessed and recorded for the technician if an indirect restoration is prescribed. It was found that decreasing the window size when examining extracted teeth with a spectrophotometer and spectroradiometer resulted in lower CIE \( L^*a^*b^* \) values. Small-window tooth color measurement may cause edge loss of the light due to a tooth’s translucency.
Once the technology-based information is analysed, the information must be communicated to the technician for indirect restorations. The aforementioned instruments and technologies are predominantly intended for shade analysis, however, this information alone may be insufficient for the technician to adequately interpret the shade information provided. Subsequent reference photography is highly recommended for communication on tooth color. Digital photographs are an important adjunct to the laboratory technician and together with the shade or “color map” should be sufficient communication material to construct an acceptable restoration.

Clinicians and technicians are frequently located in different areas. A digital camera permits the transfer of images from the clinician to the technician. The best way to reference shade information is by using shade tabs to communicate shade. A systematic protocol to referencing shade information as well as changes in shade between tabs is required. Shades identified in the digital map are arranged by gingival (G), middle (M) and incisal third (I). The shade tabs should be selected and photographs should be taken with each tab in its proper orientation in reference to the tooth.

Camera and light settings and image format must be kept constant at all times for consistent shade color communication. In addition to the three basic shade tabs representing the respective G, M and I shades, two additional reference shade tab photographs should be included to graduate and calibrate shifts in hue, chroma and value between physical tabs visually in the laboratory, in the photographs and between the photos. One selected tab should be lighter in shade and one darker in shade in respect to the selected basic shades. The combination of accurate digital shade analysis information coupled with standardized reference shade communication photography can ensure a predictable esthetic restorative outcome of the final direct or indirect restoration.

Indirect restorations can and should be verified visually and with the instrument system in the laboratory prior to being returned to the clinician. This verification process can streamline wasteful chair side time attributed to remakes due to incorrect shade. Clinical excellence backed with sound color science and its appropriate interpretation can probably make the critical difference between good to excellent. Examples of color matching, interpretation and application of shade analysis data are given in Figs. 1–6.

5. Research

Besides the clinical applications, dental color measuring instruments and systems are increasingly used in research. The most frequent research topics associated with these instruments and systems are associated with evaluation of measurement uncertainties, comparison between visual and instrumental findings, visual color thresholds and evaluation on color compatibility, stability and interactions of human hard and soft oral tissues, head and neck tissues and dental materials. Although non-dental, professional bench-top color measurement instruments were used in many research projects in dentistry, this paper will focus mainly on these conducted using hand held devices designed for dental application.

5.1. Measurement uncertainties

In color science, evaluation of measurement uncertainties of shade-matching instruments is performed through precision and accuracy testing. The uncertainties associated with precision are most frequently associated with random errors, whilst the uncertainties associated with accuracy usually originate from systematic errors. Precision is tested by evaluation of repeatability (same method, operator or instrument) and reproducibility (different method, operator and/or instrument). Based on time interval, we are talking about short term (measurements in succession), medium term (hours) and long term measurements (weeks or longer). Based on the specimen manipulation, measurement can be performed with- and without replacement. Evaluation of measurement uncertainties encompasses the use of referent instrument, preferably professional, non-dental, color measuring instrument.

In a study that compared five dental color measuring devices—ShadeScan, Easyshade, Ikam, IdentaColor II and ShadeEye, five group A Classical tabs were in vitro measured five times by two operators, whilst 25 upper right central incisors were measured in vivo by one operator. The best precision in vivo was recorded for Easyshade and Ikam, whilst performance of the other instruments was better in vitro than in vivo. In an another study, SpectroShade, ShadeVision, Vita Easyshade and ShadeScan were evaluated. High reliability (reproducibility?) and variability in accuracy was reported. One in vitro study found that repeatability and accuracy of a dental color measuring instrument (ShadeScan) was influenced by shade guide systems used for testing. When the precision of measurement of different tooth areas was evaluated, the middle third of each labial tooth surface exhibited the most consistent results.

Dental color matching instruments also provide the information on best matching tabs from different shade guides. This application-specific color information is also of importance and therefore requires proper attention of dental researches. When Vita EasyShade and ShadeEye NCC were tested on extracted human teeth, there were discrepancies in shade guide designations provided by the instruments. Higher inter-device agreement was recorded for Vitapan Classical than for Vitapan 3D-Master.

Digital imaging systems are becoming increasingly popular in determining the color of teeth. Precision and accuracy of these systems are influenced by the quality of camera and image processing method. Several studies reported that digital cameras, may be reliable instruments for determining the color of teeth and gingiva when combined with the appropriate calibration protocols.

Clinical imaging and conventional image processing methods such as Adobe Photoshop and Corel Photo-Paint are suitable for many purposes in dentistry: lab communication, documentation, patient education and others. However, scientific imaging, appropriate methods of data processing and color science terminology is preferred in dental research. This, together with lack of the referent instrument (the instrument that has already been validated, not necessary by the same authors), diminished the validity of some studies on precision and accuracy of dental color matching instruments.
Fig. 1 – Clinical application of CrystalEye spectrophotometer (Courtesy Dr. Shigemi Nagai). (a) Crystaley captures the spectral image of the tooth, abutment, arch and full face image. (b) Laboratory report can be sent to the lab as a quick color note. (c) Color analysis of the ceramic crown (after 1st bake try-in) placed on the abutment. Excellent color match was confirmed in the cervical and body areas. Minor modification may be required in the incisal area to increase the value and yellowness. (d) Color difference $\Delta E$s obtained in all 3 areas are considered to be excellent color match. $L^*$ value map indicates indistinguishable value distribution on #8 and #9.
5.2. Comparison between visual and instrumental findings

When the first dental color measuring instruments appeared, they exhibited slightly better accuracy compared to visual findings that were described as inconsistent. Since that time, the modernization of both visual and instrumental means for color matching in dentistry occurred. More recently, better results were reported with dental spectrophotometer than using the visual method in approximately 47% of the cases, which is in accordance with independent studies that documented the supremacy of spectrophotometric color matching compared to visual shade assessment. Another paper reported that the performance of Easychade was comparable or better than that of dentists, whilst the agreement between visual and instrumental findings was qualified as good to very good. In another paper, it was found that the agreement amongst the observer groups was significantly better than that of each device and that color matching instruments did not reflect human perception.

It was found that consensus amongst observers led to better shade-matching results with some shade guides, compared to results of individual observers, and that intraexaminer shade-matching agreement was mainly acceptable. Significantly higher visual-instrumental agreement was recorded for experienced dentists (compared to dental students and non-dental observers), regardless of shade guides and lighting conditions.

The comparison between visual and instrumental findings is a very attractive topic as it reveals pros and cons of both methods. Visual color matching is subjective and influenced by variety of factors. However, this method is not inferior and should not be underrated. Actually, the all “objective” color measuring instruments have been developed based on the visual response of the “standard observer” and they are good only if they match that response. In addition, the numerically smallest \( \Delta E^* \) value does not necessarily correspond to the best match because of the uneven eye sensitivity to hue, value and chroma differences. Therefore, the answer whether to use visual or instrumental method for color matching in dentistry is: whenever if possible, use both, as they complement each other and can lead towards predictable esthetic outcome.

5.3. Evaluation of visual color thresholds

Perceptibility and acceptability visual thresholds can be quantified only by combining visual and instrumental color measurement methods. Although majority of studies used professional (non-dental) color measuring devices in threshold evaluation, this topic is of exceptional importance in interpretation of color differences in clinical dentistry and dental research.

When the color difference between compared objects can be seen by 50% of observers (the other 50% will notice no difference), we are talking about the 50:50 perceptibility threshold. In dental literature, it is frequently interpreted that a \( \Delta E^* \) of 1 is the 50:50 perceptibility threshold under controlled conditions (50% of observers will notice the color difference and 50% will see no difference between compared objects), whereas a \( \Delta E^* \) of 2.7 and 3.3 were found to be 50:50 acceptability thresholds (50% of observers will accept the restoration and 50% will replace it because of color mismatch).
Several other studies, more or less controlled, reported the variability of findings on visual color thresholds. This, in addition to the introduction of new color difference formulae (CIEDE2000), suggests systematic approach and standardization of methods.

5.4. Color compatibility

Color compatibility studies encompass comparisons amongst teeth, shade guides and dental materials. Evaluation of color of natural teeth is important for clinical dentistry since knowledge on color ranges and color distribution of natural teeth can provide guidelines for designing of dental materials that will enable better and easier match to natural teeth. Databases encompassing spectral properties of teeth, regardless whether created using dental or non-dental color measuring devices, are of particular validity. Two independent studies, both performed using Vita Easyshade, reported almost the same color coordinate ranges of natural teeth: L* = 55.5–89.6, a* = 4.2–7.3 and a* = 3.6–7.0, and b* = 3.6–38.9 and b* = 3.7–37.3. Current shade guides exhibit moderate to pronounced discrepancy with results recorded for natural teeth. This discrepancy has been quantified by calculation of coverage error, the mean value of the minimal color differences amongst

Fig. 2 – Clinical application of EasyShade Compact spectrophotometer. (a) Instrument calibration. (b) Color measurement. (c) Color difference metric values as compared to the corresponding Vitapan Classical shade. (d) Color coordinate values and the corresponding Vitapan 3D-Master shade.

Fig. 3 – Clinical application of Shade-X spectrophotometer.
each tab in the shade guide and the database of human teeth.\textsuperscript{57, 73–76}

Although teeth exhibit color transitions in all directions, the correlation between colors of different regions on the labial tooth surface has been recorded. This study, performed using digital camera, suggested that color of a missing part of a tooth can be determined using the color of existing areas.\textsuperscript{77} The same team reported color correlation between maxillary incisors and canines, which may influence color matching of missing teeth.\textsuperscript{78}

As far as the compatibility amongst materials is concerned, different comparisons have been performed. An Easyshade comparison between Vitapan Classical shade guide and four different veneering porcelain systems for metal ceramic restorations, revealed that differences were shade-dependent: A2 porcelain disks exhibited better match to corresponding VITA shade, followed by A3 and A3.5 disks.\textsuperscript{79} The same instrument was used to test the ability of a ceramic system to correctly reproduce the shade selected using two shade guides. Toothguide 3D-Master outperformed VITA Classical.\textsuperscript{80} When the quality of color match of different shade guides and corresponding porcelains was evaluated, the highest percentage of clinically acceptable matches was recorded for Toothguide 3-D Master/Omega 900 combination.\textsuperscript{81} A study, conducted using Easyshade, reported that evaluated resin composites exhibited poor match compared to target Vitapan Classical tabs of the same shade designations.\textsuperscript{82} Similar conclusions were derived when various composites of corresponding shades were compared with a shade guide using a non-dental colorimeter,\textsuperscript{83} and with each other using a bench-top spectrophotometer.\textsuperscript{84}

5.5. Color stability

Color stability of teeth and dental restoration is one of the prerequisites for long-lasting esthetics of dental restorations. Dental materials can exhibit color shifting during fabrication or at placement, and after placement. The later type of color shifting is associated with aging and staining.

When nanofill composite specimens were immersed into coffee, yerba mate, grape juice or water (control solution) for one week and tested using Easyshade, perceivable color change was observed only for the group immersed into the grape juice.\textsuperscript{85} Another study used Easyshade to evaluate resin composites polished with two one-step polishing systems and exposed to coffee solution for seven days. Although all materials exhibited significant color changes, statistically significant polishing system-dependent differences were recorded ($p < 0.05$). Composite polymerized against Mylar
Fig. 5 – Clinical application SpectroShade Micro spectrophotometer. (a) Tooth #7 of a congenitally missing lateral incisor to be replaced with an implant [3i, Palm Beach, FL] and metal ceramic full coverage restoration. (b) The SpectroShade Micro system creates a color map which can be converted to several shade guide systems, this being the Classic Vita Shade Guide. It provides either an overall shade or the shade can be broken down into three distinct areas, cervical, middle and incisal, and provides detailed shade information in each of these areas and will provide a mathematical analysis resulting in a $\Delta E^*$ value. (c) Virtual shade verification can be formed with this system so that shades can be assured prior to time consuming patient visits. (d) Final restoration of tooth #7 with an implant and crown with an excellent aesthetic and functional outcome.
strip showed the most intense staining ($p < 0.05$) and authors concluded that removing the Mylar layer by polishing is essential to achieving a stain resistant, more color stable composite surface.86

Easyshade was also used in studying the effect of repeated firings (3, 5, 7, or 9 firings) on the color of an all-ceramic system with two different veneering porcelain shades (A1 and A3): The $L^*a^*b^*$ values of the ceramic system were affected by the
number of firings (3, 5, 7, or 9) \( (p < 0.001) \) and the veneering porcelain shade \( (p < 0.001) \). Although the color of the specimens was influenced by repeated firings, recorded changes in color were clinically acceptable.\(^87\) In another study by the same group, the effect of ceramic thickness and number of firings on the color of two all-ceramic systems was reported. The mean \( \Delta E^* \) value increased as the thicknesses increased for both types of all-ceramic specimens tested. However, the difference between materials was significant.\(^88\)

Color stability of 3 veneering ceramics for zirconia frameworks was evaluated using SpectroShade. All materials exhibited significant color deviation from the reference teeth, with \( \Delta E^* \) ranging from 5.6 to 6.8, but no significant differences were found between crowns and teeth for the 3 ceramics. The authors concluded that all 3 ceramics met the esthetic demands to a limited extent.\(^89\) In an evaluation of a standard shade guide for color change after disinfection using Easyshade, a statistically significant increase in lightness and chroma were observed after 2 and 3 years of simulated treatments. However, these changes were not perceptible to the clinician.\(^90\)

Color stability of esthetic brackets made of different materials was evaluated using the Easyshade. The brackets were immersed for 10 days at \( 37 \, ^\circ C \) in various solutions, or exposed to accelerated photo-aging (150 kJ/m\(^2\), 340 nm). It was found that the consumption of certain foods, such as red wine, tea, coffee and curry, greatly influenced the color changes of tooth-collared brackets.\(^91\)

5.6. Tooth whitening

Color measurement devices have been used for bleaching studies to document shade changes.\(^92\)–\(^94\) As indicated earlier, one of the problems with shade matching especially for bleaching studies is positioning of the shade taking device. A flat surface is required to enable accurate placement during the shade measurement procedure. In addition, measurement near the incisal edge introduces error due to the translucent enamel allowing more light to be transmitted and not reflected to the shade taking device. Nonetheless, some clinicians feel a spectrophotometer can provide better comparison of shade change compared to a shade guide as a shade guide is non-linear. However a new Vita Bleachguide 3D-Master provides a more uniform color distribution in a linear fashion.\(^95\) One study evaluated bleaching efficacy with and without supplementary light using Vitapan Classical and Bleachguide 3D-Master in visual evaluation, and Easyshade spectrophotometer for instrumental evaluation.\(^96\) A statistically significant difference between with- and without light treatment was registered using Bleachguide and Easyshade, and greater color differences were recorded for baseline versus with light whitening. However, the \( \Delta E^* \) values recorded in controlled conditions and by trained observers might not be perceivable in typical dental office conditions and by untrained observers. Clinical evaluation of different light-activated in-office bleaching systems revealed similar bleaching efficacy of four methods used: bleaching without light activation, diode laser activation, plasma arc lamp and a light emitting diode, with \( \Delta E^* \) ranging from 5.3 to 5.7 (Easyshade).\(^97\) Given the findings and less tooth and gingival sensitivity with diode laser, the authors suggested that this method might be the preferred in-office bleaching.

When two over the counter products, a 6% hydrogen peroxide (HP) bleaching gel delivered on polyethylene film and an 18% carbamide peroxide (CP) brush-applied liquid gel, were compared visually (Classical) and instrumentally (ShadeVision), both treatments caused significant tooth whitening. However, the HP-based product exhibited significantly greater efficacy.\(^98\) Evaluation of the effect of laser tooth whitening revealed that teeth belonging to Classical group A showed greater shade improvement than teeth belonging to groups C and D. Whilst the whitening response was better in younger individuals, this response was not affected by gender. It should be noted that measurements were performed immediately after removal of the whitening gel, using ShadeEye NCC Dental Chroma Meter.\(^99\) Another paper reported that Nd:YAG laser associated with hydrogen peroxide bleached the enamel, similarly to whitening efficacy obtained with the traditional method performed with halogen light.\(^100\)

Digital imaging has also been used for tooth whitening monitoring. In one study, digital imaging implied that 35% carbamide peroxide was more effective for darker teeth than 10% solution of the same agent.\(^101\) Several studies stated that their digital imaging system is reproducible and reliable in evaluating changes in whiteness of teeth\(^102\) and that clinical measurement of tooth color was highly reproducible with very high intra-class correlations for the image pairs.\(^53\) Using the imaging system tested in reference 53, it was found that: (a) twice-daily use of 6% hydrogen peroxide whitening strips resulted in teeth becoming lighter and less yellow compared to baseline during initial 2-week use\(^103\); (b) short-term color rebound after treatment may impact the utility of in-office tooth whitening with peroxide and light as a stand-alone...
esthet procedure\textsuperscript{104}, and (c) two professional at-home tooth whitening systems in a teenage population resulted in significant reduction in yellowness and increase in lightness after two weeks of treatment on each arch. No significant difference between groups was recorded.\textsuperscript{105}

5.7. Color interactions

Dental and professional color measurement devices have been used for quantifying of translucency-dependent color interactions. It was reported that different metal substructures and different porcelains significantly affected the final color of the restoration.\textsuperscript{106} Changing the enamel porcelain thickness was found to have a greater effect on elevated chromatic shades compared to those of a lower chroma,\textsuperscript{107} whereas semitranslucent all-ceramic materials achieved more accurate shade matches at reduced thickness of translucent porcelain than metal ceramic or semi-opaque all-ceramic crowns.\textsuperscript{108} It was found that composite cements created perceptible color differences with particular combinations of die material, cement and ceramic crown,\textsuperscript{109} and that final color of thinner specimens was significantly affected by the shade change and thickness of luting agent.\textsuperscript{110} Different backgrounds also influenced color of glass-infiltrated ceramic veneers,\textsuperscript{111} whilst In-Ceram Alumina ceramic veneers showed the greatest improvement in the color performance of discolored teeth.\textsuperscript{112}

In addition to layering, physical translucency can contribute to overall color shifting (color adjustment potential, blending) of restorative materials. Blending effect in the narrow sense is optical illusion, not measurable by any device, while more widely understood it also encompass the objective and measurable shifting caused by physical translucency. Blending effect was found to be material and shade dependent, and it increased with the decrease of restoration size.\textsuperscript{113} It increased with the decrease of initial color differences and the increase of translucency.\textsuperscript{114} Blending effect and double-layer effect were found to be directly proportional and highly correlated.\textsuperscript{115}

6. Conclusion

The blending of science and art is something the dental industry is primed for. Patients are demanding contemporary esthetic dentistry, which has prompted the industry to continuously raise the bar with regard to esthetic detail. Many factors can influence the perception of color; by taking advantage of today’s shade-matching technology, the subjectivity of color assessment can be minimized and accurate diagnosis of a restoration’s shade is more easily communicated.

Complete tooth surface and limited area tooth surface measurement devices exist and either measure the complete tooth surface providing a “color map” or a smaller diameter [3–5 mm] on the tooth surface, respectively. Complete tooth measurement devices average the color in a larger area versus limited area measurement devices which measure a smaller area. These instruments are all useful supplementary tools in color analysis for direct or indirect restorations, reproduction and verification of shade. Color communication is best performed using reference photography with reference shade tabs from current shade guide systems obtained using digital camera.

Besides the clinical applications, dental color measuring instruments and systems are increasingly used in research. This includes evaluation of measurement uncertainties, comparison between visual and instrumental findings, visual color thresholds and research on color compatibility, color stability including tooth whitening and color interactions of human teeth and dental materials.

Chances are that new affordable high-quality color matching instruments and technology will contribute to successful work with color and esthetic dentistry in general, particularly if complemented with better color-related education and training of dental professionals and advancement of dental materials. Whenever possible, both instrumental and visual color matching method should be used, as they complement each other and can lead towards predictable esthetic outcome.

Conflict of Interest

Dr. Paravina is a paid consultant for Vita Zahnfabrik.

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REFERENCES


