



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



available at www.sciencedirect.com



journal homepage: www.intl.elsevierhealth.com/journals/dema



Color related to ceramic and zirconia restorations: A review

Alessandro Vichi^{a,*}, Chris Louca^b, Gabriele Corciolani^a, Marco Ferrari^a

^a Department of Dental Materials and Fixed Prosthodontics, School of Dentistry, University of Siena, Siena, Italy

^b Eastman CPD, UCL Eastman Dental Institute, London, United Kingdom

ARTICLE INFO

Article history:

Received 7 October 2010

Accepted 22 October 2010

Keywords:

Color

Aesthetics

Spectrophotometer

Porcelain

PFM

Zirconia

ABSTRACT

The requirement to achieve natural looking restorations is one of the most challenging aspects of dentistry, and the shade matching of dental restorations with the natural dentition is a difficult task due to the complex optical characteristics of natural teeth. Dental porcelain is considered the reference material for prosthetic rehabilitation, but it is not easy to handle and aesthetic excellence is quite difficult to obtain. For these reasons, shade matching with dental porcelain is often considered to be more artistic than scientific. Shade matching is considered unpredictable due to several variables that may influence the final appearance of a restoration. In order to improve this situation, over the last decade new shade guides and instruments have been developed and the aesthetic aspects of dental porcelain have been further investigated. In this review some aspects of color selection and color reproduction have been examined. Color selection has advanced through the development of new shade guides and electronic shade taking devices, although visual assessment has still not been entirely replaced by electronic instruments. Color reproduction with dental porcelain has improved thanks to advances in the performance and knowledge of dental porcelain, but is still not easy to achieve. The difficulties of achieving good aesthetics with PFM restorations and the desire for metal free solutions have resulted in the increased use of zirconia. The unique optical properties of zirconia have introduced new opportunities for achieving superior aesthetics, however further research is required with this material.

© 2010 Academy of Dental Materials. Published by Elsevier Ltd. All rights reserved.

1. Introduction

Due to the complex optical characteristics of tooth color, achieving a close shade match with an artificial restoration of the natural dentition is a difficult process. Successful aesthetic restorations require the integration of several critical factors, including an individual's perception of color, the light source used for color evaluation, the surface and structural characteristics of both the tooth and of the restorative materials used and a knowledge of some basic principles of color perception. To be successful, clinicians require the understanding of color, light and related characteristics of porcelain and resin, as well as the ability to clearly communicate instructions with technicians when an indirect procedure is performed. Den-

tal porcelain, combining wear resistance, strength, toughness and excellent aesthetics is considered to be the reference material for prosthetic rehabilitation. However porcelain is not easy to handle and aesthetic excellence is quite difficult to obtain. In order to achieve a natural looking restoration it is necessary to perform two different steps: (i) to select the best possible shade, using a shade guide and/or an electronic shade taking instrument and (ii) to reproduce this shade with an appropriate dental material.

2. Color measurement

Since Newton's experiments during the 18th century, it has been difficult to explain the scientific basis of color. The con-

* Corresponding author.

E-mail address: vichialessandro@virgilio.it (A. Vichi).

0109-5641/\$ – see front matter © 2010 Academy of Dental Materials. Published by Elsevier Ltd. All rights reserved.

doi:[10.1016/j.dental.2010.10.018](https://doi.org/10.1016/j.dental.2010.10.018)

cept of color is difficult to understand, not easy to define, and is often related more to art than science. Within dentistry, color matching between natural teeth and restorative materials, is often a misunderstood and unpredictable procedure. Many authors have tried in the past to address this issue. The paper from Clark of 1933 [1], based mainly on the Munsell color scale of 1905, was the first attempt to organize dental colors. In the same period, the Commission Internationale de l'Eclairage published the first standards for color matching, establishing some scientific parameters for color evaluation [2]. However the absence of valid scientific instruments for color measurement did not allow significant improvements at that time. In the 1950s, the first dental shade guides based on a rational arrangement of shade tabs were introduced to the dental profession and, even if still based on individual perception rather than on strict scientific criteria, they were rapidly adopted by clinicians. Sproull in the early 1970s [3–5] published a series of articles in which the three dimensional nature of color and its relationship with dental shades was studied, and a series of theoretical and practical indications were given in order to improve color matching in dentistry. These articles, that represented for a long time the “state of the art” for dental color matching, pointed out how the procedure for shade taking was negatively influenced by several factors, among which shade guides that were regarded as poor and inadequate in relation to the complexity of the appearance of the teeth. Meanwhile, the developing science of color, which was led by the needs of industry, defined colors, measured them and calculated differences in order to allow proper color control in industrial processes. Since the Munsell system as well as the CIE specification of 1931 had an irregular space distribution, this resulted in differences between calculated and perceived color differences, and for this reason it was clear that a new system for color measurement was required. In 1976 and 1978 the CIE developed a new system, called CIELab* [6,7], in which for the first time it was possible to express color by numbers and calculate the differences between two colors in a way that corresponded to visual perception. In this system, which is regarded as the benchmark for scientific purposes, color is expressed by three coordinates: L^* value is the degree of lightness of an object, a^* value is the degree of redness/greenness, and b^* value is the degree of yellowness/blueness [7].

The CIELab* system was scientifically based and useful for calculating color differences, but not amenable to easy color communication. For color communication, the HSB/HSV (Hue; Saturation or Chroma; Brightness or Lightness or Value) system is most commonly used, even in dentistry. In this system, H (Hue) is defined as the radial component of the cylindrical coordinates CIELab* and calculated according to the formula $h_{ab} = \arctan(b^*/a^*)$; S (Saturation or Chroma) is defined as the radial component of the cylindrical coordinates CIELab* and calculated according to the formula $C_{ab} = [(a^*)^2 + (b^*)^2]^{1/2}$; L (Lightness or Brightness or Value), corresponds to the L^* of the CIELab* system and represents the lightness-darkness of a color [7]. Color can be measured in these two systems, as well as in other systems such as CIELuv, XYZ, Lch and RGB. All these systems differ mathematically, but may be correlated to each other by the use of conversion formulae.

In the CIELab* system a formula is used to calculate color differences:

$$\Delta E_{ab} = [(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2]^{1/2}$$

This “ ΔE ” value became pivotal in color science, for both industry and dentistry [8]. Following this new fundamental approach to dental color science, instruments like colorimeters and spectrophotometers were quickly developed and improved to measure color and color differences. Unfortunately, color matching in dental practice did not benefit immediately from these developments and visual assessment was still considered to be the best approach. This was mainly due to the fact that the appearance of an object is not only related to the color attributes of the CIELab* system but is also heavily influenced by the geometric attributes of appearance such as gloss, opacity, transparency, translucency, and optical phenomena such as metamerism, opalescence and fluorescence [9] (Table 1). As the tooth is affected by all these different aspects of color perception, the optical characteristics of a tooth were considered too difficult and obtaining a proper aesthetic result was considered an art form and not a completely standardized and predictable procedure. Dental color matching then developed so that errors in visual color selection were minimized and instructions for dental porcelain fabrication were introduced [10–13].

In 2004 the specification for measurement of color differences was upgraded by the CIE [14] and an improvement of the ΔE_{ab} formula was proposed. This new formula is defined as ΔE_{00} :

$$\Delta E_{00} = \{[\Delta L'/(k_L S_L)]^2 + [\Delta C'/(k_C S_C)]^2 + [\Delta H'/(k_H S_H)]^2 + RT[\Delta C'/(k_C S_C) \times \Delta H'/(k_H S_C)]\}^{1/2}$$

This new formula has been developed in order to introduce weighing functions (S_L , S_C and S_H) and parametric factors (k_L , k_C and k_H) to allow for differences in texture, background, separations, etc for the lightness, chroma and hue components, respectively. The aim was to improve the correlation between visually perceived differences and calculated differences. Lee [15] reported that the two color formulae can be used interchangeably for the evaluation of color differences, even if the ΔE_{00} formula should be considered for the evaluation of changes in separate color parameters such as Lightness, Chroma and Hue. Perez Mdel et al. [16] reported a significant correlation between ΔE_{ab} and ΔE_{00} , even if a significant involvement of weighing functions for lightness, chroma and hue components was observed, thus recommending the use of ΔE_{00} . Wee et al. [17] reported that the ΔE_{00} color difference formula provides a better fit to the calculated color differences, thereby providing better indicators of human perceptibility and acceptability of color differences between tooth colors. Johnston in 2009 [18] reported that it can be expected that the revised color difference formula will be used in dental research and other dental applications. Ghinea et al. in 2010 [19] reported that the CIEDE2000 color difference formula provided a better fit than the CIELAB formula in the evaluation of color difference threshold of dental ceramics. Notwithstanding the possible beneficial use of this improved formula, most of the papers recently published in the dental literature still

Table 1 – Main definitions for appearance related to tooth [9].

Color attributes	
L^* (Lightness, Brightness, Value)	Perception by which white objects are distinguished from gray objects and light from dark colored objects
a^*	In CIELAB opponent-color scale, the degree of redness/greeness
b^*	In CIELAB opponent-color scale, the degree of blueness/yellowness
C (Chroma, Saturation)	The attribute of color perception that espresse the degree of departure from the gray of the same lightness
H (Hue)	The attribute of color perception by means of which an object is judged to be red, yellow, green, blue, purple and so forth
Geometric attributes	
Scattering	The process by which light passing through granular, fibrous or rough surface matter is redirected throughout a range of angles
Opacity	The property of a material to hide what is behind it
Transparency	The property of a material by which a negligible portion of the transmitted light undergoes scattering
Translucency	The property of a material by which a major portion of the transmitted light undergoes scattering
Optical phenomena	
Opalescence	The process by which a material appears yellowish-red in transmitted light and blue in the scattered light perpendicular to the transmitted light. The phenomenon is named after the appearance of opal stone
Fluorescence	The process by which electromagnetic radiation of one spectral region is absorbed and reradiated at other, usually longer, wavelengths
Metamerism	The phenomenon whereby the color of specimens match when illuminated by light of one spectral composition despite differences in spectral reflectance of the specimens, and that consequently may not match in light of some other spectral composition
Gloss	The property of a surface which involves specular reflection and is responsible for lustrous or mirror-like appearance

refer to ΔE_{ab} . This is probably due to the relative complexity of the ΔE_{00} formula, as well as to the ease of comparison with earlier studies, even if the transformation of $L^*a^*b^*$ into $L'a'b'$ is just a matter of arithmetics [20].

3. Threshold

Since spectrophotometers can detect small differences in color at a level that is not appreciable by the human eye, an important issue of color science in dentistry is to establish a reference value for the evaluation of study results in terms of ΔE . In other words, if in a study a certain difference in terms of ΔE has been measured, it is important to understand whether this difference can be perceived by the human eye and, if so, whether this difference can be considered clinically relevant. This value is subjective and is therefore difficult to establish. Sim et al. [21], in a study performed by matching the shade tabs of the Vita Lumin shade guide reported that perception varies between different groups of dental personnel and thereby established the individuality of color perception. A quite old but frequently cited article is a study by Kuehni et al. [22]. In this study experienced industrial color matchers were examined and the average ΔE CIELab for perceiving color difference was $\Delta E = 1$. Seghi et al. [23] in a study performed with translucent color porcelain disks, and dental professionals reported a color difference of $\Delta E = 2$. Ragain et al. [24] also evaluated color difference acceptability in translucent porcelain disks and reported an average acceptability threshold of $\Delta E = 2.72$. Johnston et al. [25] in 1989 published in the Journal of Dental Research a study which established this limit as $\Delta E = 3.7$ despite indicating the importance of other factors such as translucency and effects of the surroundings, in appearance matching. The value reported in this study has been referenced for many years. Later, it was focused that one single value was probably not completely representative of

the problem, and that a differentiation between perceptibility (the difference that can be identified by the human eye) and acceptability (the difference that is considered tolerable) was proposed. Douglas and Brewer [26] found that the thresholds for perceptibility (mean 0.4 ΔE units) were significantly lower than thresholds for acceptability (1.7 ΔE units) for metal ceramic crowns differing in their chroma. Vichi et al. [27] proposed 3 different intervals for distinguishing color differences. In this paper, considering that the ability of the human eye to appreciate differences in color differs between individuals, since it is a combination of eye characteristics and skill of the operator [28], ΔE values of less than 1 unit were regarded as not appreciable by the human eye; ΔE values greater than 1 and less than 3.3 units were considered appreciable by skilled operators, but clinically acceptable; ΔE values greater than 3.3 were considered perceivable by untrained observers (e.g. patients), and for that reason were regarded as not acceptable [29–31]. Douglas et al. [32], in a study on denture teeth, reported the 50/50 perceptibility to be $\Delta E = 2.6$ and acceptability as 5.5 ΔE , confirming that tolerances for perceptibility were significantly lower than tolerances for acceptability for shade mismatch. Conversely, Lindsey et al. [33] in a study on computer simulated teeth, reported that no differences between thresholds for acceptability versus perceptibility were found. More recently, Ishikawa-Nagai et al. in 2009 [34] reported in a study on all-ceramic crowns that a $\Delta E = 1.6$ represents the color difference that could not be detected by the human eye. Ghinea et al. [19], using the calculation for both ΔE_{ab} and the new ΔE_{00} formula, reported a significant difference between perceptibility and acceptability thresholds for dental ceramics. In their paper, different values of ΔE were reported with the same data set depending on the ΔE formula, ΔE_{ab} and ΔE_{00} , and of the fitting method, S-shaped curve and TSK Fuzzy Approximation, used for calculation.

Despite much effort, the identification of a ΔE value for the “clinically acceptable differences” is a very difficult task and

the establishment of a widely accepted limit is still controversial.

4. Color selection

4.1. Shade guides

Tooth shade matching is most frequently performed visually using dental shade guides. The first large-diffusion shade guide was introduced onto the market in 1956 by Vita Zahnfabrik for the measurement of the color of ceramic systems, and it introduced some visual parameters that with some minor modifications are still routinely used by dental practitioners. The shade guide proposed in 1956 established a widely adopted reference and remained almost unmodified until today. This shade guide, now called Vitapan Classical consists of 16 tabs arranged into four groups (A–D) of different Hue. Within each group, Lightness and Chroma are identified by a number. As number increases, Lightness decreases and Chroma increases [35]. This worldwide diffused shade guide has the advantage of ease of use but it lacks a logical and adequate distribution in the color space as defined by CIELab* specifications. This is not surprising as it was developed more than 20 years before the CIELab* specification was introduced. Another quite popular shade guide is the Ivoclar-Vivadent Chromascop. Similarly to the Vitapan Classical, the Chromascop shade guide is arranged in groups based on 5 different color definitions mostly based on Hue, and according to increasing Chroma and decreasing Lightness within each group. It additionally shows an irregular distribution of the shade in the CIELab* color space [36]. In the late 1990s the CIELab* system was first incorporated into dental shade guides with the development of the Vitapan 3D-Master Toothguide. This shade guide is based on a color classification principle in which the three dimensions of color, i.e. Lightness, Chroma and Hue, are considered equally so that the determination of shade can be easily carried out using systematic, consistent criteria [35,37–39]. The shade guide consists of 29 tooth-shaped tabs built up with cervical, dentinal and incisal powders and made of feldspar nepheline and high-temperature ceramic pigments from the VITA family of ceramic porcelains. Tabs are arranged in groups of two or three to form six sets (numbered 0–5). The Group “0”, originally not present, was added later for the shade matching of bleached teeth [40,41]. These “numbers” express the degree of Lightness, that remains constant within each group. Chroma is expressed in different degrees within each Lightness group and Hue is expressed as a variation of the basic one (M) to a more yellowish (L) or reddish (R). The distance between each of the pairs of adjacent colors is approximately 2 ΔE units. Each of the six Lightness levels differs from the next by a ΔE of approximately 5. Each Chroma level differs from the next by a ΔE of approximately 6 [42].

The VITA 3D-Master Shade Guide addressed the most important deficiency of the other shade guides, i.e. a more ordered color distribution [37,40,43], based on scientific criteria, within the natural tooth color space and an objective, numerical measure of color, according to the colorimetric

CIELab* order principle, rather than on the mere observation of the natural tissue aspects. From a procedural viewpoint, the sequence of shade selection involves the sequential selection of Lightness, Chroma and Hue. From a complete set of tabs, the tabs placed on top are used for selecting the Lightness. Then, the selected lightness group can be extracted from the shade guide and Chroma (up-down) and Hue (left-right) have to be selected in sequence from a three-dimensional simulated arrangement. This approach reinforces the importance of Lightness selection, which is particularly important since Lightness is the parameter most perceptible to the human eye, due to a greater number of rods (photoreceptor cells involved in the transduction of monochromatic light into nerve signals to the brain via the optic nerve) than cones (photoreceptor cells that detect different colors), in the human retina. Another reported advantage of this shade guide is the ease with which the color can be corrected. After the try-in it is now possible to communicate the need for color correction referring to one color parameter at a time instead of two simultaneously as with the Vitapan Classical or Chromascop shade guides.

Despite the fact that the Vitapan 3D-Master shade guide was scientifically based and systematically arranged in the color space, its adoption in dentistry was initially limited. One of the possible reasons was that its use introduced the need for a different approach to “3D” color selection, that required some additional education in terms of color knowledge. In order to facilitate routine clinical work, the manufacturer recently introduced the Linearguide 3D-Master. This is not a new shade guide, but a different arrangement of the same shade tabs from the Vitapan 3D-Master shade guide. Shade selection is now performed by selecting Lightness with a reduced set of 6 tabs which contain only the 6 different Lightness levels linearly arranged. After the Lightness selection, 6 reduced sets of tabs each containing only the tabs of the same Lightness but with different Chroma and Hue linearly arranged are provided. This new arrangement seems to better meet the needs of clinicians in terms of ease of use, thereby leaving the traditional 3D color distribution in the color space unmodified [35,44].

4.2. Shade taking devices

The traditional clinical procedure of visually matching shade tabs with teeth might be negatively influenced by several factors, including variations in the type and quality of light [45,46], the presence of color blindness and/or color perception defects [47,48], differences in gender [49,50] and variations in experience of the evaluators [51–53]. In order to minimize color mismatch due to visual estimation and improve the color selection procedure, shade taking devices were developed. Two main categories of electronic instruments for general color measurement are available: colorimeters and spectrophotometers [9]. The colorimeter is generally a relatively simple and low-cost instrument that is designed to measure color on the basis of three axes or stimuli by using a filter that simulates the human eye. The spectrophotometer is a more sophisticated instrument, built to measure by reflection or transmission an observed object, giving the entire spectral curve and is limited for color measurement to the visible

Table 2 – Shade taking devices commercially available.

Shade taking devices		
Instrument	Company	Type
Shade Eye	Shofu	Colorimeter
Easyshade	Vita	Spectrophotometer
Easy Shade Compact	Vita	Spectrophotometer
Shade Scan	Cynovad	Digital color imaging/colorimeter
Shade Vision	X-Rite	Digital color imaging/colorimeter
SpectroShade Micro	MHT/Degussa	Digital color imaging/spectrophotometer
Clear Match	Clarity Dental	Software (requires a digital camera)
Color Scanner 2006	Nuova Franco Suisse	Software (requires a digital camera)
DVS11	DV	Spectrophotometer
Crystal Eye	Olympus	Digital color imaging/spectrophotometer
Shade X	X-Rite	Spectrophotometer
ShadeStar	Degussa/Dentsply	Spectrophotometer

frequency range (usually 350–800 nm). Significant advantages with spectrophotometric measurements include the ability to analyze the principal components of a series of spectra and the ability to convert data to various color measuring systems. Although the first spectrophotometers were already very accurate, they were quite complex instruments, difficult to manage or correctly calibrate and their use in dentistry was limited to research purposes. In the last decade, advances in electronics, more sophisticated CCDs and better fiber optic technology have all resulted in the development of clinical dental shade taking devices. These devices range from software that can be used in conjunction with images taken with a digital camera, to colorimeters and spectrophotometers, in some cases combined with an imaging system (Table 2). The SpectroShade Micro (MHT, Niederhasli, Switzerland) combines digital color imaging with a spectrophotometer and is one of the most representative of the various instruments. This device acquires images with a 45/45° geometry and a polarized filter is used to avoid specular reflection from the tooth surface which can influence color evaluation. The polarized images are then used for color analysis and calculation, and for comparison with a data set of several shade guides stored in the instrument. Its software can perform several functions including both coarse and fine color shade mapping, it can send data via e-mail to the laboratory and it can overlay the clinical image with the images taken of the porcelain manufacturer to perform a virtual try-in. Another benchmark instrument is the Easyshade Compact (Vita Zahnfabrik, Bad Sackingen, Germany), released in 2009 as an evolution of the former Easyshade. In order to avoid specular reflected light, that contains little or no color information and that can negatively affect color measurement, the Easyshade is engineered relying on large diameter fiber optics arranged in a specific pattern in a stainless steel probe that can both illuminate a tooth and receive light that is internally scattered by the enamel layer and reflected from the dentin layer of the tooth. In this way, light can penetrate a tooth reaching the dentin layer through the enamel, and then exiting by reflection some distance away, in order to obtain the proper degree of absorption and dispersion inside the tooth structure. Due to the array of light fibers, it is possible to select two different reading areas that differ in the distance from the tip of the probe of the instrument. The reading at a longer distance (“Tooth” mode) is

indicated for measuring the color of the tooth, as the reading area is ideally positioned at the dentin level; while the closer one (“Restoration” mode) is designed to measure the color of a dental ceramic. The instrument's software is programmed to give absolute CIELab* color values only for natural teeth. When assessing the color of a ceramic, the spectrophotometer provides the differences (Δ values) from color value presets in the instrument's database [54]. The shade matching performance of electronic instruments has been compared with visual assessment especially from a repeatability viewpoint. Firstly, the use of the instruments is quite simple, and possible errors due to improper use are minimal. Intra-examiner reliability was reported as acceptable [55]. In the traditional procedure for shade selection, where shade tabs are visually compared to the natural tissues, repeatability has always been considered low. Okubo et al. [56] in 1998 reported that the repeatability of selecting the same shade when evaluating the same shade tab twice at different times was about 50%. Tung et al. [57] found that clinicians agreed with each other with 73% of the color selections, while the colorimeter agreed with itself 82% of the time. Paul et al. [58] reported that visual shade selections matched 26.6% of the time while spectrophotometric shade selection matched 83.3% of the time. Kim-Pusateri et al. [59] reported for an intra-oral shade taking device repeated readings occurred 95% of the time with Vita Classical and 91.2% with Vita 3D-Master. The same author, in another study [60], reported values for four different instruments ranging between 99% (ShadeVision) and 87.4% (Shade Scan) in reliability and between 93% (Easyshade) and 67% (Shade Scan) for accuracy. Derdilopoulou et al. [61], evaluating visual and spectrophotometric shade analysis of 3758 teeth reported that spectrophotometric shade determination seems to be significantly more reproducible than the visual procedure. Browning et al. [62] reported that the Easyshade device, when compared for accuracy and consistency to three experienced clinicians, was at least comparable if not better than the dentist. In particular, the degree of matching was 91% for Easyshade and 69%, 85% and 79% for the three clinicians, respectively. It should be noted that the results seemed to improve with time. Despite this high repeatability of readings, Hugo et al. [63] reported that computer-aided color shade determination of natural teeth seems to not reflect human perception. Fani et al. [64] reported that visual assessment

performed by experienced clinicians and spectrophotometer shade selection provided similar results. Paul et al. [65] reported in a study on the fabrication of PFM crowns for incisors, that in 9 of 10 cases the crowns fabricated on the basis of the spectrophotometric indications were preferred over crowns fabricated on visual assessment color selection. Da Silva et al. [66] reported in a clinical study that crowns fabricated using a spectrophotometer had a significantly better color match and a lower rate of rejection due to shade mismatch compared to crowns fabricated with a conventional shade-matching method. Yoshida et al. [67] reported in a spectrophotometric analysis of tooth color reproduction on anterior all-ceramic crowns that the precise color measurement systems lead to an accurate verification of color reproduction and its transfer. It should be noted that the advantages of spectrophotometers can be appreciated even for other aspects of color reproduction, such as communication with technicians. Gerhke et al. [68] reported in 2009 that spectrophotometric shade determination is more reproducible compared to conventional visual shade assessment, enhancing shade analysis, communication and fabrication of dental restorations. Yoshida et al. [67] reported that the use of a dedicated dental spectrophotometer during the fabrication of all-ceramic crowns allows the dentist and the laboratory technician to accurately communicate important information about the shade, thereby allowing the technician better control over the outcome of their tooth color matching efforts and the final color match of an all-ceramic restoration. The spectrophotometer is also of value for evaluating the effect of tooth bleaching. Kielbassa et al. [69] in a comparison of visual and computer aided shade determination after using various home bleaching procedures, reported that spectrophotometry was reproducible and objective. Ishigawa-Nagai et al. in 2010 [70] reported that the use of a dedicated spectrophotometer allows the evaluation and measurement of the color of a bleached tooth. This may be useful for evaluating the effect of bleaching as well as to understand when the bleached tooth color has become stable. Recently, these instruments have been used for research purposes. Lehmann et al. [71] reported in a comparison between one spectrophotometric reference system and 4 clinical spectrophotometers that the electronic dental color-measuring devices showed excellent repeatability, but some devices showed substantial deviation in color coordinate values from the spectrophotometric reference system. Notwithstanding this possible limitation, the use of these devices for research purposes has become quite extensive. These instruments have also shown a great potential for educational purposes as they allow an improved understanding of color perception and its correlation with clinical aspects, helping to achieve the Sproull aim to teach color science to under- and post-graduate students.

Shade taking spectrophotometers are at present sufficiently developed to help clinicians make shade related decisions even if they are not yet able to entirely substitute visual assessment. This has been recently reported also by Chu et al. [72] in a review, that even if these instruments are useful tools in color analysis, communication, verification of shade, whenever possible, both instrumental and visual color matching methods should be used, as they complement each other and can lead towards predictable aesthetic outcome.

4.3. Shade reproduction: porcelain fused to metal restorations

Dental porcelain, with its properties of wear resistance, strength, toughness and aesthetics is the preferred material to replace natural tooth tissue in prosthetic dentistry [73]. However, the reproduction of a selected shade with dental porcelain is not an easy task because many factors may influence the outcome. Wee et al. [74] found that reliable delivery of a properly matched restoration to existing porcelain restorations cannot be ensured regardless of the shade assessment method used (visual or computer-generated). Douglas et al. [75] found that the ability to reproduce the color of the target shade tab differed among laboratories and most crowns fabricated by the laboratories in their study, when compared to the prescribed shade tab, were above the clinical threshold for an acceptable shade match. This is probably due to the long list of factors that are relevant in influencing the final color of the porcelain restorations. In traditional porcelain-fused-to-metal restorations, one of the reported manipulatable variables is the metal substrate. Many alloys are available [76] and different alloys may influence the final color of the restoration [77–85]. This is due to the different color of the metal substructure but also to the fact that different metal alloys produce slightly different metal oxides which may influence the color observed [86]. Kourtis et al. [87] reported that Au and Co–Cr alloys were found to be brighter (higher L^* values) than the Ni–Cr and the Pd alloys. Ceramco porcelain was found to be the most red (higher a^* values) of all tested alloys. Gold and Pd alloys caused a yellow shift to the metal–ceramic color compared to the Ni–Cr and the Co–Cr alloys. The authors concluded that the final color of the metal ceramic was influenced by the type of alloy substructure. Stevenson et al. in a recent review [86] reported that high gold-backed samples were lighter (higher L^*) than samples backed by nickel chrome and silver–palladium alloys. Gold-backed samples were found to be more yellow (higher b^*) than base metals. The effect of silver–palladium on yellowness (b^*) was reported to be controversial. In general, the differences (ΔE) induced by the use of different alloys were perceptible but at the limits for clinical acceptability. In order to minimize the effect of the metal substrate on the color of the restoration, an Opaque layer is generally applied as the first ceramic layer. Even when variations of this layer, particularly of thickness, were reported to influence the final aesthetic results [81,88,89], the color differences measured were reported to be within the range of clinical acceptability [84]. Opaque can be applied in different modalities, such as paste, premixed paste mixed with a water base liquid, airbrush spray gun and pre-packaged aerosol spray. Jorn at al. in a recent paper [90] reported that no visible color differences were found between the different application methods. Another predominant manipulatable variable is the number of firing cycles. The Opaque itself can be influenced by repeated firings; Yilmaz et al. in 2009 [91] reported that subsequent firings significantly affected the color of a 0.1-mm-thick layer of opaque porcelain but color shifts were below the limits for perception and clinically acceptable. After the Opaque layer, the porcelain layers are applied in various degrees of opacity in order to imitate the natural effect of the tooth structure. The effect of repeated firings on the color of the various

porcelain layers has been the subject of several investigations and it appears that this factor is able to produce modification in color to a clinically relevant extent [92–100]. Several studies demonstrated that the layering ratio between the various opaque and translucent shades greatly influences the final results of the restoration. Omar et al. [101] reported that even if a correct shade selection is performed, by itself it is not enough if not correlated with thickness and layering of the restoration. Fazi et al. [102] analyzed whether the indications coming from the manufacturers in terms of porcelain layering were sufficient in order to achieve the intended shade. They concluded that guidance given by the manufacturer to help the technician to obtain the color match between the selected shade and the final restoration is very limited, and not sufficient to avoid color mismatch, in particular because of the problems connected with the layering patterns. Corciolani et al. [103] evaluated the ability of one ceramic system to correctly reproduce the selected shade with reference to two available shade guides. They reported that specimens layered in the Vita 3D-Master shade guide exhibited a closer match in color than a specimen of the same ceramic system in the Vitapan Classical shade guide, concluding that higher color correspondence can be considered shade guide dependant. In another paper [104] the same author reported that two different ceramic systems, both in VITA 3D-Master Toothguide, performed differently in terms of shade matching, thus concluding that the scheme followed for layering the porcelain upon the metal had a predominant role in achieving the selected color for PFM restorations. Since the layering scheme related to thickness is a key-factor for color match, the effect of single layers on the final color have been reported to be critical. Jarad et al. [105] in an in vitro study found that a change in enamel porcelain thickness had a greater effect on higher chromatic shades than those with lower chroma, and the reduction of the enamel thickness produced three-dimensional color changes (lightness, hue angle and metric chroma). Corciolani et al. in a recent paper [106] analyzed the behavior of a specific ceramic system with different total thicknesses of the restoration. They reported that the individual thickness of each layer and the ratio between the layers play an important role in achieving the best color match. In addition the authors reported that the effect of the variation in thickness for each single layer for the ceramic system tested might be useful for technicians in porcelain layering as well as for color adjusting after try-in. Other factors are reported to influence the final color of the porcelain restorations such as glazing [107], mixing ratio between powder and liquid [108], batch [98,109], temperature of ceramic firing [92,110] and metal surface treatment [111].

As a result of this series of variables, the color matching of PFM restorations to the selected shade is quite a difficult task, and it is understandable why this procedure might be at least partially unsuccessful in routine dental practice. It should be noted that most of the published literature referring to PFM restorations is quite old, and despite the high degree of validity of these studies as basic references, most of these materials tested have been replaced by newer ones, hopefully with improved features. It looks like there is a lack of knowledge between the available literature and the PFM materials actually used.

4.4. Shade reproduction: zirconia framework restorations

Even though PFM materials still represent the majority of the restorations made, metal-free restorations are gaining popularity. In particular, the progressive introduction of zirconia frameworks has noticeably increased the use of metal-free restorations in dental practice, thanks to its peculiar mechanical and physical properties, and optimal biocompatibility [112–118].

From an aesthetic viewpoint, zirconia differs completely from dental alloys. As natural zirconia is white, an immediate advantage over PFM restorations is the absence of the metallic collar usually placed on the margin, and identified by patients as a “black line” as seen with gingival recession [119]. The other optical property of zirconia that differs from traditional alloys, is its relative translucency. Translucency is considered one of the important factors responsible for matching color of natural teeth with restorative materials [120–122]. Translucency is defined as the property of a material by which a major portion of the transmitted light undergoes scattering [9]. The translucency of dental porcelain is largely dependent on light scattering [120]. If the majority of light passing through a ceramic is intensely scattered and diffusely reflected, the material will appear more opaque. If only part of the light is scattered and most is diffusely transmitted, the material will appear more translucent. The amount of light that is absorbed, reflected, and transmitted depends on the crystal content within the core, its chemical nature, and the size of the particles [120]. An increased crystalline content in order to achieve high strength cores will generally result in greater opacity [73,123]. In metal-free restorations the translucency is affected by the thickness of the core [124,125]. As soon as the thickness of the core decreases, this results in an increase of translucency even if at the same time this decreases the strength. Few data are available on the translucency of different zirconia core materials at the required clinical thickness. Heffernan et al. [125] reported in 2002 an opacity (contrast ratio) of 1.00 (completely opaque) for a 0.5 mm thick In-Ceram Zirconia core, and these data have been confirmed by Chen et al. [126], but In-Ceram Zirconia is structurally different from Y-TZP zirconia as it is a glass-infiltrated material. Chen et al. [126] reported an opacity value of 1.00 also for Cercon Base Zirconia at 0.5 mm thickness. This brand of zirconia has been reported to be a highly opaque one by Baldissara et al. [127] who in a recent study reported different translucency values for different zirconia materials with the direct transmission method and light flow instead of the contrast ratio. In this study, Lava Frame of 0.3 and 0.5 resulted in the most translucent material among the tested ones. The authors reported that all of the materials evaluated may be considered translucent to a certain degree, although the quantity of transmitted light is not remarkable when compared to the value of the positive control flow. This supports the current definition of zirconia as a “semi-translucent” core material. It should be considered that the translucency of the core is not always considered to have a positive effect. The presence of discolored tooth remnants, amalgam or other heavily colored restorative materials, metallic post and cores or carbon fiber posts can all interfere with the desired aesthetic result [128–131]. In these

clinical situations, a highly masking material would be preferable [132] and this reinforces the fact that there is no evidence to support the use of a single ceramic material and system for all clinical situations, as reported by Conrad et al. [133] It should be taken into consideration that the translucency measurements for zirconia cores are carried out on core material in the absence of veneering material and are not representative of usual clinical conditions, in which the presence of veneering porcelain can reduce the translucency, as a function of thickness, opacity and of the veneering material itself [128,134].

The final color of the translucent cores is influenced by the color of the cement [135] and it is possible that this could affect the zirconia core as well. Only one paper could be found on this subject, in which an influence of the opacity of the cement for thin Lava Frame zirconia frames was reported [136]. The white color of zirconia does not allow an optimal aesthetic integration to be achieved per se, therefore a veneering material must be used. In order to compensate for the possible negative effect of the white color of the zirconia on the final color of the restoration the use of liners has been proposed [137,138]. These liners have been advocated to reduce the zirconia-veneer bond strength and might be a factor (or a co-factor) responsible for one of the reported problems of zirconia framed restorations that is the de-lamination between the zirconia core and the veneering porcelain [139]. As an alternative to the use of liners, more recently staining solutions for the zirconia have been used before sintering and/or the use of pre-colored zirconia has been proposed, but their advantages are controversial. Aboushelib et al. [139] reported that the application of the required veneer ceramic over the natural zirconia framework resulted in an accurate reproduction of the required color; while for colored zirconia application of liner material or deep chroma dentin was necessary to reproduce the required color. The author concluded that using pre-colored zirconia frameworks did not offer any direct advantages over the standard natural zirconia. Moreover, Hjerppe et al. [140] reported a decrease in strength of zirconia that had been color shaded with zirconia coloring liquids. Very little data are available on the shade reproduction with veneering ceramic systems for zirconia cores [86,141]. Since the differences between veneering ceramics for zirconia cores and veneering ceramics for PFM, alumina, glass infiltrated and PFM restorations are mainly related to CTE, it is reasonable to state that most of the factors influencing the color of these more widely investigated ceramic systems [138,142,143] may affect veneering ceramics for zirconia cores as well. For example, the firing procedure has been reported to influence the final color of zirconia restorations. Celik et al. [144] reported that the color of the all-ceramic zirconia core with different veneering porcelain shades is influenced by repeated firings, and this was confirmed by Ozturk et al. [145] who reported significant changes in *Lab** color data as the number of firings increased. With respect to layering, Lee et al. [138] reported that the brand of core material used may influence the final color of sample equally veneered. Ho-Jung et al. [141] in a recent paper, in which the effect of veneer ceramic on zirconia substrate (Lava) was reported, observed that color changes of the layered ceramics varied by brand, shade and dentin porcelain thickness. The authors concluded that the

final appearance of zirconia core ceramic restorations can be manipulated by varying the dentin porcelain thickness.

As a final consideration, it has to be underlined that very few scientific papers are available at present on the color of zirconia core restorations and that the subject requires to be more widely investigated.

5. Conclusions

Achieving a natural looking restoration which satisfactorily integrates with the biological tissues requires the skill of both the clinician and technician. The desire to have a scientific basis to a clinical procedure that has always been considered an art form represents one of the greatest challenges in modern dentistry.

Achieving a correct color match between natural dentition and restoration or prosthesis is a complex process which consists of two specific procedures: color selection and color reproduction.

The traditional shade guides with their irregular distribution of shades in the color space, even if still widely used, are no longer adequate for the increasing demands of aesthetic dentistry. The VITA 3D-Master Toothguide seems to be more useful even if its use is still not yet widespread, perhaps due to its complexity of use. The recent introduction of a linearly arranged 3D master shade guide should simplify clinical use.

The clinical spectrophotometers look promising for helping clinicians with shade selection. Despite the reported positive indications from the literature, their use should still be considered to be an adjunct to and not a replacement for, visual assessment. These instruments have the capability to become routinely used in clinical dentistry. They can be used to help less experienced clinicians in color matching procedures in order to avoid or at least reduce color mismatch. Clinical studies are necessary to support laboratory data, in order to provide evidence that instrumental color detection may be as efficient as a human and more reliable.

The instructions given by ceramic manufacturers to help technicians to obtain the desired color match between the selected shade and the final restoration are very limited, and not sufficient to avoid color mismatch.

Layering plays a determinant role in achieving the color match with the intended shade. Depending on the final thickness of the metal ceramic restoration, the individual thickness of each layer and the ratio between the layers both play an important role in achieving the best color match. The technician has to be able to individually adjust color parameters in order to achieve a certain shade. Ceramic manufacturers should provide specific schemes on how to layer their porcelain material relative to the final thickness of the restoration in order to obtain the desired shade.

The use of a zirconia framework has not shown at present, to greatly improve the aesthetic appearance of the restoration. The white color of the zirconia and its low translucency still limit the possibility of imitating the natural appearance of a tooth and requires layering with feldspathic ceramic. Only few data are available in the literature on the aesthetic performance of layering over zirconia frameworks.

REFERENCES

- [1] Clark EB. Tooth color selection. *J Am Dent Assoc* 1933;20:1065–73.
- [2] 2CM CIE (Commission Internationale de l'Eclairage). Standard Colorimetric Observer x2 (λ), y2 (λ), z2 (λ). Vienna, Austria: Bureau Central de la CIE; 1931.
- [3] Sproull RC. Color matching in dentistry. I. The three-dimensional nature of color. *J Prosthet Dent* 1973;29:416–24.
- [4] Sproull RC. Color matching in dentistry. II. Practical applications for the organisation of color. *J Prosthet Dent* 1973;29:556–66.
- [5] Sproull RC. Color matching in dentistry. Part III. Color control. *J Prosthet Dent* 1974;31:146–54.
- [6] CIE (Commission Internationale de l'Eclairage). Light as a True Visual Quantity: Principles of Measurement. CIE Pub. No.41, Vienna, Austria: Bureau Central de la CIE; 1978.
- [7] CIE (Commission Internationale de l'Eclairage). Colorimetry—technical report. CIE pub. no.15, 2nd ed. Vienna, Austria: Bureau Central de la CIE; 1986. p. 35–6 (corrected reprint 1996).
- [8] Clarke FJJ. Measurement of the color of the human teeth, Dental ceramics. In: Proceedings of the first international symposium on ceramics. 1983. p. 441–88.
- [9] Hunter RS. The measurement of appearance. 2nd ed. New York: John Wiley and Sons, Inc.; 1987.
- [10] Miller L. Organizing color in dentistry. *J Am Dent Assoc* 1987. S.I.:26E-40E.
- [11] Miller LL, Shade, Matching. *J Esthet Dent* 1993;4:143–53.
- [12] Miller LL. Shade selection. *J Esthet Dent* 1994;2:47–60.
- [13] Preston JD. Current status of shade selection and color matching. *Quintessence Int* 1985;16:47–58.
- [14] CIE (Commission Internationale de l'Eclairage). Colorimetry—technical report. CIE pub. no. 15:2004. 3rd ed. Vienna: Bureau Central de la CIE; 2004. p. 18.
- [15] Lee YK. Comparison of CIELAB ΔE^* and CIEDE2000 color-differences after polymerization and thermocycling of resin composites. *Dent Mater* 2005;21:678–82.
- [16] Pérez Mdel M, Saleh A, Yebra A, Pulgar R. Study of the variation between CIELAB ΔE^* and CIEDE2000 color-differences of resin composites. *Dent Mater J* 2007;26:21–8.
- [17] Wee AG, Lindsey DT, Shroyer KM, Johnston WM. Use of a porcelain color discrimination test to evaluate color difference formulas. *J Prosthet Dent* 2007;98:101–9.
- [18] Johnston WM. Color measurement in dentistry. *J Dent* 2009;37(Suppl. 1):e2–6.
- [19] Ghinea R, Pérez MM, Herrera LJ, Rivas MJ, Yebra A, Paravina RD. Colour difference thresholds in dental ceramics. *J Dent* 2010. July 27 [Epub ahead of print].
- [20] Luo MR, Cui G, Rigg B. The development of the CIE 2000 color difference formula:CIEDE2000. *Color Res Appl* 2001;26:21–8.
- [21] Sim CP, Yap AU, Teo J. Color perception among different dental personnel. *Oper Dent* 2001;26:435–9.
- [22] Kuehni FG, Marcus RT. An experiment in visual scaling of small color differences. *Color Res Appl* 1979;4:83–91.
- [23] Seghi RR, Johnston WM, O'Brien WJ. Performance assessment of colorimetric devices on dental porcelains. *J Dent Res* 1989;68:1755–9.
- [24] Ragain Jr JC, Johnston WM. Minimum color differences for discriminating mismatch between composite and tooth color. *J Esthet Restor Dent* 2001;13:41–8.
- [25] Johnston WM, Kao EC. Assessment of appearance match by visual observation and clinical colorimetry. *J Dent Res* 1989;68:819–22.
- [26] Douglas RD, Brewer JD. Acceptability of shade differences in metal ceramic crowns. *J Prosthet Dent* 1998;79:254–60.
- [27] Vichi A, Ferrari M, Davidson CL. Color and opacity variations in three different resin-based composite products after water aging. *Dent Mater* 2004;20:530–4.
- [28] Li Q, Yu H, Wang YN. In vivo spectroradiometric evaluation of colour matching errors among five shade guides. *J Oral Rehab* 2009;36:65–70.
- [29] Inokoshi S, Burrow MF, Kataumi M, Yamada T, Takatsu T. Opacity and color changes of tooth-colored restorative materials. *Oper Dent* 1996;21:73–80.
- [30] Kim HS, Um CM. Color differences between resin composites and shade guides. *Quintessence Int* 1996;27:559–67.
- [31] Um CM, Ruyter IE. Staining of resin-based veneering materials with coffee and tea. *Quintessence Int* 1991;22:377–86.
- [32] Douglas RD, Steinhauer TJ, Wee AG. Intraoral determination of the tolerance of dentists for perceptibility and acceptability of shade mismatch. *J Prosthet Dent* 2007;97:200–8.
- [33] Lindsey DT, Wee AG. Perceptibility and acceptability of CIELAB color differences in computer-simulated teeth. *J Dent* 2007;35:593–9.
- [34] Ishikawa-Nagai S, Yoshida A, Sakai M, Kristiansen J, Da Silva JD. Clinical evaluation of perceptibility of color differences between natural teeth and all-ceramic crowns. *J Dent* 2009;37(Suppl. 1):e57–63.
- [35] Paravina RD. Performance assessment of dental shade guides. *J Dent* 2009;37(Suppl. 1):e15–20.
- [36] Park JH, Lee YK, Lim BS. Influence of illuminants on the color distribution of shade guides. *J Prosthet Dent* 2006;96:402–11.
- [37] Paravina RD, Powers JM, Fay RM. Color comparison of two shade guides. *Int J Prosthodont* 2002;15:73–8.
- [38] Hammad IA. Intrarater repeatability of shade selections with two shade guides. *J Prosthet Dent* 2003;89:50–3.
- [39] Bayindir F, Kuo S, Johnston WM, Wee AG. Coverage error of three conceptually different shade guide systems to vital unrestored dentition. *J Prosthet Dent* 2007;98:175–85.
- [40] Paravina RD, Johnston WM, Powers JM. New shade guide for evaluation of tooth whitening-colorimetric study. *J Esthet Restor Dent* 2007;19:276–83.
- [41] Paravina RD. New shade guide for tooth whitening monitoring: visual assessment. *J Prosthet Dent* 2008;99:178–84.
- [42] JADA. Dental shade guides. *J Am Dent Assoc* 2002;133:366–7.
- [43] Ahn JS, Lee YK. Color distribution of a shade guide in the value, chroma, and hue scale. *J Prosthet Dent* 2008;100:18–28.
- [44] Corcodel N, Rammelsberg P, Jakstat H, Moldovan O, Schwarz S, Hassel AJ. The linear shade guide design of Vita 3D-master performs as well as the original design of the Vita 3D-master. *J Oral Rehabil* 2010. July 14 [Epub ahead of print].
- [45] Curd FM, Asinevicius TR, Graves A, Cox V, Sadan A. Comparison of the shade matching ability of dental students using two light sources. *J Prosthet Dent* 2006;96:391–6.
- [46] Jasinevicius TR, Curd FM, Schilling L, Sadan A. Shade-matching abilities of dental laboratory technicians using a commercial light source. *J Prosthodont* 2009;18:60–3.
- [47] Gokce HS, Piskin B, Ceyhan D, Gokce SM, Arisan V. Shade matching performance of normal and color vision-deficient dental professionals with standard daylight and tungsten illuminants. *J Prosthet Dent* 2010;103:139–47.

- [48] Davison SP, Myslinski NR. Shade selection by color vision-defective dental personnel. *J Prosthet Dent* 1990;63:97–101.
- [49] Donahue JL, Goodkind RJ, Schwabacher WB, Aeppli DP. Shade color discrimination by men and women. *J Prosthet Dent* 1991;65:699–703.
- [50] Haddad HJ, Jakstat HA, Arnetzl G, Borbely J, Vichi A, Dumfahrt H, et al., Corcodel N, Marada G, Reshad M, Hannak WB. Does gender and experience influence shade matching quality? *J Dent* 2009;37(Suppl. 1):e40–4.
- [51] Capa N, Malkondou O, Kazazoglu E, Calikkacaoglu S. Evaluating factors that affect the shade-matching ability of dentists, dental staff members and laypeople. *J Am Dent Assoc* 2010;141:71–6.
- [52] Klemetti E, Matela AM, Haag P, Kononen M. Shade selection performed by novice dental professionals and colorimeter. *J Oral Rehabil* 2006;33:31–5.
- [53] Della Bona A, Barrett AA, Rosa V, Pinzetta C. Visual and instrumental agreement in dental shade selection: three distinct observer populations and shade matching protocols. *Dent Mater* 2009;25:276–81.
- [54] Technology JLL. Vita Easyshade Technology. Bad Sackingen, Vita GmbH; 2003. p. 5–7.
- [55] Hassel AJ, Cevirgen E, Balke Z, Rammelsberg P. Intraexaminer reliability of measurement of tooth color by spectrophotometry. *Quintessence Int* 2009;40:421–6.
- [56] Okubo SR, Kanawati A, Richards MW, Childress S. Evaluation of visual and instrument shade matching. *J Prosthet Dent* 1998;80:642–8.
- [57] Tung FF, Goldstein GR, Jang S, Hittelman E. The repeatability of an intraoral dental colorimeter. *J Prosthet Dent* 2002;88:585–90.
- [58] Paul S, Peter A, Pierobon N, Hammerle CHF. Visual and spectrophotometric shade analysis of human teeth. *J Dent Res* 2002;81:578–82.
- [59] Kim-Pusateri S, Brewer JD, Dunford RG, Wee AG. In vitro model to evaluate reliability and accuracy of a dental shade-matching instrument. *J Prosthet Dent* 2007;98:353–8.
- [60] Kim-Pusateri S, Brewer JD, Davis EL, Wee AG. Reliability and accuracy of four dental shade-matching devices. *J Prosthet Dent* 2009;101:193–9.
- [61] Derdilopoulou FV, Zantner C, Neumann K, Kielbassa AM. Evaluation of visual and spectrophotometric shade analyses: a clinical comparison of 3758 teeth. *Int J Prosthodont* 2007;20:414–6.
- [62] Browning WD, Chan DC, Blalock JS, Brackett MG. A comparison of human raters and an intra-oral spectrophotometer. *Oper Dent* 2009;34:337–43.
- [63] Hugo B, Witzel T, Klaiber B. Comparison of in vivo visual and computer-aided tooth shade determination. *Clin Oral Invest* 2005;9:244–50.
- [64] Fani G, Vichi A, Davidson CL. Spectrophotometric and visual shade measurements of human teeth using three shade guides. *Am J Dent* 2007;20:142–6.
- [65] Paul SJ, Peter A, Rodoni L, Pietrobon N. Conventional visual vs spectrophotometric shade taking for porcelain-fused-to-metal crowns: a clinical comparison. *Int J Perio Rest Dent* 2004;24:222–31.
- [66] Da Silva JD, Park SE, Weber HP, Ishikawa-Nagai S. Clinical performance of a newly developed spectrophotometer system on tooth color reproduction. *J Prosthet Dent* 2008;99:361–8.
- [67] Yoshida A, Miller L, Da Silva JD, Ishikawa-Nagai S. Spectrophotometric analysis of tooth color reproduction on anterior all-ceramic crowns. 2. Color reproduction and its transfer from in vitro to in vivo. *J Esthet Restor Dent* 2010;22:53–63.
- [68] Gehrke P, Riekeberg U, Fackler O, Dhom G. Comparison of in vivo visual, spectrophotometric and colorimetric shade determination of teeth and implant-supported crowns. *Int J Comp Dent* 2009;12:247–63.
- [69] Kielbassa AM, Beheim-Schwarzbach NJ, Neumann K, Nat R, Zantner C. In vitro comparison of visual and computer-aided pre- and post-tooth shade determination using various home bleaching procedures. *J Prosthet Dent* 2009;101:92–100.
- [70] Ishikawa-Nagai S, Yoshida A, Da Silva JD, Miller L. Spectrophotometric analysis of tooth color reproduction on anterior all-ceramic crowns. 1. Analysis and interpretation of tooth color. *J Esthet Restor Dent* 2010;22:42–52.
- [71] Lehmann KM, Igiel C, Schmidtmann I, Scheller H. Four color-measuring devices compared with a spectrophotometric reference system. *J Dent* 2010. July 24 [Epub ahead of print].
- [72] Chu SJ, Trushkowsky RD, Paravina RD. Dental color matching instruments and systems. Clinical and research aspects. *J Dent* 2010, doi:10.1016/j.jdent.2010.07.001.
- [73] Kelly JR, Nishimura I, Campbell SD. Ceramics in dentistry: historical roots and current perspectives. *J Prosthet Dent* 1996;75:18–32.
- [74] Wee AG, Monaghan P, Johnston WM. Variation in color between intended matched shade and fabricated shade of dental porcelain. *J Prosthet Dent* 2002;87:657–66.
- [75] Douglas RD, Brewer JD. Variability of porcelain color reproduction by commercial laboratories. *J Prosthet Dent* 2003;90:339–46.
- [76] Roberts HW, Berzins DW, Moore K, Charlton DG. Metal–ceramic alloys in dentistry: a review. *J Prosthodont* 2009;18:188–94.
- [77] Brewer JD, Akers CK, Garlapo DA, Sorensen SE. Spectrometric analysis of the influence of metal substrates on the color of metal–ceramic restorations. *J Dent Res* 1985;64:74–7.
- [78] Jacobs SH, Goodacre CJ, Moore BK, Dykema RW. Effect of porcelain thickness and type of metal–ceramic alloy on color. *J Prosthet Dent* 1987;57:138–45.
- [79] O'Neal SJ, Leinfelder KF, Lemons JE, Jamison HC. Effect of metal surfacing on the color characteristics of porcelain veneer. *Dent Mater* 1987;3:97–101.
- [80] Seghi RR, Johnston WM, O'Brien WJ. Spectrophotometric analysis of color differences between porcelain systems. *J Prosthet Dent* 1986;56:35–40.
- [81] Terada Y, Sakai T, Hirayasu R. The masking ability of an opaque porcelain: a spectrophotometric study. *Int J Prosthodont* 1989;2:259–64.
- [82] Woolsey GD, Johnson WM, O'Brien WJ. Masking power of dental opaque porcelains. *J Dent Res* 1984;63:936–9.
- [83] Crispin BJ, Seghi RR, Globe H. Effect of different metal ceramic alloys on the color of opaque and dentin porcelain. *J Prosthet Dent* 1991;65:351–6.
- [84] Ozcelik TB, Yilmaz B, Ozcan I, Kircelli C. Colorimetric analysis of opaque porcelain fired to different base metal alloys used in metal ceramic restorations. *J Prosthet Dent* 2008;9:193–202.
- [85] Stavridakis MM, Papazoglou E, Seghi RR, Johnston WM, Brantley WA. Effect of different high-palladium metal–ceramic alloys on the color of opaque and dentin porcelain. *J Prosthet Dent* 2004;92:170–8.
- [86] Stevenson B, Ibbetson R. The effect of the substructure on the colour of samples/restorations veneered with ceramic: a literature review. *J Dent* 2010;38:361–8.
- [87] Kourtis SG, Tripodakis AP, Doukoudakis AA. Spectrophotometric evaluation of the optical influence of different metal alloys and porcelains in the metal–ceramic complex. *J Prosthet Dent* 2004;92:477–85.

- [88] Terada Y, Maeyama S, Hirasu R. The influence of different thicknesses of dentin porcelain on the color reflected from thin opaque porcelain fused to metal. *Int J Prosthodont* 1989;2:353–6.
- [89] Barghi N, Lorenzana RE. Optimum thickness of opaque and body porcelain. *J Prosthet Dent* 1982;48:429–31.
- [90] Jörn D, Waddell JN, Swain MV. The influence of opaque application methods on the bond strength and final shade of PFM restorations. *J Dent* 2010, doi:10.1016/j.jdent.2010.08.016.
- [91] Yılmaz B, Özçelik TB, Wee AG. Effect of repeated firings on the color of opaque porcelain applied on different dental alloys. *J Prosthet Dent* 2009;101:395–404.
- [92] Rosenstiel SF, Johnston WM. The effects of manipulative variables on the color of ceramic metal restorations. *J Prosthet Dent* 1988;60:297–303.
- [93] Barghi N. Color and glaze: effects of repeated firings. *J Prosthet Dent* 1982;47:393–5.
- [94] Barghi N, Goldberg P. Porcelain shade stability after repeated firing. *J Prosthet Dent* 1977;37:173–5.
- [95] Barghi N, Richardson JT. A study of various factors influencing shade of bonded porcelain. *J Prosthet Dent* 1978;39:282–4.
- [96] Ecker GA, Moser JB, Wozniak WT, Brinsden GI. Effect of repeated firing on fluorescence of porcelain-fused-to-metal porcelains. *J Prosthet Dent* 1985;54:207–14.
- [97] Jorgenson MW, Goodkind RJ. Spectrophotometric study of five porcelain shades relative to the dimensions of color, porcelain thickness, and repeated firings. *J Prosthet Dent* 1979;42:96–105.
- [98] O'Brien WJ, Kay KS, Boenke KM, Groh CL. Sources of color variation on firing porcelain. *Dent Mater* 1991;7:170–3.
- [99] Hammad IA, Stein RS. A qualitative study for the bond and color of ceramometals. II. *J Prosthet Dent* 1991;65:169–79.
- [100] Lacefield WR, O'Neal SJ, Compton HK. Color changes of porcelain fused to high palladium alloys after multiple firings. *J Dent Res* 1985;64:246.
- [101] Omar H, Atta O, El-Mowafy O. Difference between selected and obtained shade for metal-ceramic crown systems. *Oper Dent* 2008;33:502–7.
- [102] Fazi G, Vichi A, Corciolani G, Ferrari M. Spectrophotometric evaluation of color match to VITA classical shade guide of four different veneering porcelain systems for metal ceramic restorations. *Am J Dent* 2009;22:19–22.
- [103] Corciolani G, Vichi A, Goracci C, Ferrari M. Colour correspondence of a ceramic system in two different shade guides. *J Dent* 2009;37:98–101.
- [104] Corciolani G, Vichi A, Louca C, Ferrari M. Color match of two different ceramic systems to selected shades of one shade guide. *J Prosthet Dent* 2010.
- [105] Jarad FD, Moss BW, Youngson CC, Russell MD. The effect of enamel porcelain thickness on color and the ability of a shade guide to prescribe chroma. *Dent Mater* 2007;23:454–60.
- [106] Corciolani G, Vichi A, Louca C, Ferrari M. Influence of layering thickness on the color parameters of a ceramic system. *Dent Mater* 2010;26:737–42.
- [107] Yılmaz C, Korkmaz T, Demirköprülü H, Ergün G, Özkan Y. Color stability of glazed and polished dental porcelains. *J Prosthodont* 2008;17:20–4.
- [108] Zhang Y, Griggs JA, Benham AW. Influence of powder/liquid mixing ratio on porosity and translucency of dental porcelains. *J Prosthet Dent* 2004;91:128–35.
- [109] Barghi N, Pedrero JA, Bosch RR. Effects of batch variation on shade of dental porcelain. *J Prosthet Dent* 1985;54:625–7.
- [110] Lund PS, Piotrowski TJ. Color changes of porcelain surface colorants resulting from firing. *J Prosthet Dent* 1992;5:22–7.
- [111] O'Neal SJ, Leinfelder KF, Lemons IE, Jamison HC. Effect of metal surfacing on the color characteristics of porcelain veneer. *Dent Mater* 1987;3:97–101.
- [112] Raigrodski A. Contemporary materials and technologies for all-ceramic fixed partial dentures: a review of the literature. *J Prosthet Dent* 2004;92:557–62.
- [113] Luthardt RG, Holzhuter M, Sankuhl O, Herold V, Schnapp JD, Kuhlisch E, et al. Reliability and properties of ground Y-TZP-zirconia ceramics. *J Dent Res* 2002;81:487–91.
- [114] Manicone PF, Rossi Iommetti P, Raffaelli L. An overview of zirconia ceramics: basic properties and clinical applications. *J Dent* 2007;35:819–26.
- [115] Eschbach S, Wolfart S, Bohlens F, Kern M. Clinical evaluation of all-ceramic posterior three-unit FDPs made of In-Ceram Zirconia. *Int J Prosthodont* 2009;22:490–2.
- [116] Schmitt J, Holst S, Wichmann M, Reich S, Gollner M, Hamel J. Zirconia posterior fixed partial dentures: a prospective clinical 3-year follow-up. *Int J Prosthodont* 2009;22:597–603.
- [117] Ozkurt Z, Kazazoglu E. Clinical success of zirconia in dental applications. *J Prosthodont* 2010;19:64–8.
- [118] Della Bona A, Kelly JR. The clinical success of all-ceramic restorations. *J Am Dent Assoc* 2008;139(Suppl.):8s–13s.
- [119] Chistensen GJ. Choosing an all-ceramic restorative material: porcelain-fused-to metal or zirconia based? *J Am Dent Assoc* 2007;138:662–5.
- [120] Brodbelt RH, O'Brien WJ, Fan PL. Translucency of dental porcelains. *J Dent Res* 1980;59:70–5.
- [121] Watts DC, Cash AJ. Analysis of optical transmission by 400–500 nm visible light into aesthetic dental biomaterials. *J Dent* 1994;22:112–7.
- [122] ten Bosch JJ, Coops JC. Tooth color and reflectance as related to light scattering and enamel hardness. *J Dent Res* 1995;74:374–80.
- [123] Sorensen JA, Cruz M, Mito WT, Raffainer O, Meredith HR, Foser HP. A clinical investigation on three-unit fixed partial dentures fabricated with a lithium disilicate glass-ceramic. *Pract Perio Aesthet Dent* 1999;11:85–106.
- [124] Antonson SA, Anusavice KJ. Contrast ratio of veneering and core ceramics as a function of thickness. *Int J Prosthodont* 2001;14:316–20.
- [125] Heffernan MJ, Aquilino SA, Diaz-Arnold AM, Haselton DR, Stamford CM, Vargas MA. Relative translucency of six all-ceramic systems. I. Core materials. *J Prosthet Dent* 2002;88:4–9.
- [126] Chen YM, Smales RJ, Yip KH, Sung WJ. Translucency and biaxial flexural strength of four ceramic core materials. *Dent Mater* 2008;24:1506–11.
- [127] Baldissara P, Llukacej A, Ciocca L, Valandro FL, Scotti R. Translucency of zirconia copings made with different different CAD/CAM systems. *J Prosthet Dent* 2010;104:6–12.
- [128] Volpato CA, Monteiro Jr S, de Andrada MC, Fredel MC, Petter CO. Optical influence of the type of illuminants, substrates and thickness of ceramic materials. *Dent Mater* 2009;25:87–93.
- [129] Vichi A, Ferrari M, Davidson CL. Influence of ceramic and cement thickness on the masking of various types of opaque posts. *J Prosthet Dent* 2000;83:412–7.
- [130] Chu FC, Chow TW, Chai J. Contrast ratios and masking ability of three types of ceramic veneers. *J Prosthet Dent* 2007;98:359–64.
- [131] Barath VS, Faber VJ, Westland S, Niedermaier W. Spectrophotometric analysis of all-ceramic materials and their interaction with luting agents and different backgrounds. *Adv Dent Res* 2003;17:55–60.
- [132] Manicone PF, Rossi Immetti P, Raffaelli L. An overview of zirconia ceramics: basic properties and clinical applications. *J Dent* 2007;35:819–26.

-
- [133] Conrad HJ, Seong W, Pesun IJ. Current ceramic materials and systems with clinical recommendations: a systematic review. *J Prosthet Dent* 2007;98:389–404.
- [134] Luo J, Zhang L. Effect of veneering techniques on color and translucency of Y-TZP. *J Prosthodont* 2010;19:465–70.
- [135] Chang J, Da Silva JD, Sakai M, Kristiansen J, Ishikawa-Nagai S. The optical effect of composite luting cement on all ceramic crowns. *J Dent* 2009;37:937–43.
- [136] Fazi G, Vichi A, Ferrari M. Influence of four different cements on the color of zirconia structures of varying ceramic thickness. *Int Dent SA* 2006;8:20–6.
- [137] Devigus A, Lombardi G. Shading Vita YZ substructures: influence on value and chroma. I. *Int J Comput Dent* 2004;7:293–301.
- [138] Lee YK, Cha HS, Ahn JS. Layered color of all-ceramic core and veneers. *J Prosthet Dent* 2007;97:279–86.
- [139] Aboushelib MN, Dozic A, Liem JK. Influence of framework color and layering technique on the final color of zirconia veneered restorations. *Quintessence Int* 2010;41:e84–9.
- [140] Hjerpe J, Narhi T, Froberg K, Vallittu PK, Lassila LV. Effect of shading the zirconia framework on biaxial strength and surface microhardness. *Acta Odontol Scand* 2008;66:262–7.
- [141] Ho-Jung S, Woong-Chul K, Sang-Ho J, Young-Su K, Sung-Won J, Jin-Soo A. Influence of dentin porcelain thickness on layered all-ceramic restoration color. *J Dent* 2010, doi:10.106/j.dent.2010.08.007.
- [142] Dozic 2003 Dozic A, Kleverlaan CJ, Meegdes M, van der Zel J, Feilzer AJ. The influence of porcelain layer thickness on the final shade of ceramic restorations. *J Prosthet Dent* 2003;90:563–70.
- [143] Heffernan MJ, Aquilino SA, Diaz-Arnold AM, Haselton DR, Stamford CM, Vargas MA. Relative translucency of six all-ceramic systems. II. Core and veneer materials. *J Prosthet Dent* 2002;88:10–5.
- [144] Celik G, Uludag B, Usumez A, Sahin V, Ozturk O, Goktug G. The effect of repeated firings on the color of an all-ceramic system with two different veneering porcelain shades. *J Prosthet Dent* 2008;99:203–8.
- [145] Ozturk O, Uludag B, Usumez A, Sahin V, Celik G. The effect of ceramic thickness and number of firings on the color of two all-ceramic systems. *J Prosthet Dent* 2008;100:99–106.