# *Color Science in Dentistry*

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VRIJE UNIVERSITEIT

# *Color Science in Dentistry*

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*“My head is bursting with the joy of the unknown.
My heart is expanding a thousand fold.”*

***- Rumi***

To my Family

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*" After a certain high level of technical skill is achieved, science and art tend to coalesce in esthetics, plasticity, and form.*
*The greatest scientists are always artists as well."*

***— Albert Einstein***

# CHAPTER 1

## *Introduction to Color Science in Dentistry*

## 1.1 Introduction

Woody Allen once wrote a humorous essay entitled ‘What if the impressionists were dentists’ (1) where the whole play deals with a parody on the life of the impressionist painter Vincent van Gogh as a dentist. Though this is intended as a comical piece, in the field of esthetic dentistry it has somewhat become a reality. Dentists are doctors of the mouth yet in the last three decades their final work is judged ever more by the level of their artistic talents. Not all dentists have the advantage of such innate skills, and increasing the level of predictability and evidence into the subjective field of esthetics is the solution for dental clinicians of today. Art is inevitably meeting science in dentistry. Esthetic restorations of today, especially in the anterior region, demand that the dental restorative materials have similar optical properties to teeth. Therefore, it is important for the clinician to have an understanding of color science, along with the experience and education to apply this knowledge. Only after this basis does the outcome rely on the artistic talents of the dental clinicians.

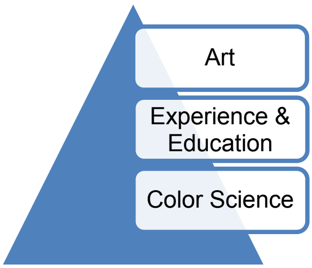


**Figure 1.1** Pyramid of Esthetic Dentistry

Despite all of the advances in clinical dentistry over the past decades, the production of dental-restorations that exactly match the color of the neighboring teeth remains surprisingly difficult and unpredictable (2). The exact reproduction of color has a similar esthetic importance in dentistry as it has in the garment and automobile industry. For instance a dark red car would look unpleasant if just one of the doors would have a somewhat brighter color. In the same way, if one of the frontal teeth needs to be replaced with artificial materials, the whole facial expression would be negatively influenced if there is no color match between the dental restoration and the adjacent teeth. In contrast to other basic determinants of esthetics in dentistry (tooth shape, size, and position), which are relatively easy to harmonize with the remaining natural teeth and the patient’s face characteristics; shade matching and reproduction are the most complicated procedures in esthetic dentistry. In The Netherlands alone approximately 45 million Euros worth of resources are being used to *re*make dental restorations due to the fact that the final outcome was not a good color match[1]. Also 80% of patients can notice a difference in the shade of their natural teeth compared with their restorations (3). Finally it has been stated that color is unimportant to the physiological success of dental restoration, yet that it could be the controlling factor in overall acceptance by the patient (4). Both these statements prove how important color matching and hence color science is to the overall outcome of an esthetic treatment in dentistry.

There are two important issues that have to be considered when an esthetical appearance of a dental restoration is required: tooth color determination (managed by dentist), and tooth color reproduction (managed by dental technician).

## 1.2 Tooth color determination

The contemporary way of color determination in clinical dentistry is by visual matching of tooth color with the existing shade tabs (most widely used visual shade-guide, Vita Classical, Vita, Bad Säckingen, Germany, has 16 shade-tabs). This method is predominantly based on a trial-and-error technique, it depends on many external and internal factors and the esthetic results are directly proportional to the clinician's experience, skills of dental technicians, and quality of the available materials for color reproduction. The external conditions are the variable illumination, the examiners eye-brain sensitivity (e.g. color blindness from viewer) and the quality of the shade-guide. The internal conditions are determined by the morphology of teeth and their surface roughness. Natural teeth consist of two tissues which influence their appearance: dentin (organic matrix and its thickness are mainly responsible for shade) and enamel, the most outer tissue (96% mineral and mainly responsible for translucency). The thickness, shade and translucency of those two tissues are different within the population, which cause different appearances of teeth. By means of visual color determination dentists can only compare a resultant color caused by the interplay of both the tooth layers and surrounding light, with that of the comparable homogeneous shade-tab. Using this method, color reproduction is not predictable. Therefore, attempts must be made to translate the physical facts of color, to the psychologic

[1] According to data from the CBS (Central Bureau Statistiek, Den Haag) and NMT (Nederlandse Maatschappij der Tandheelkunde) for the year 2006

(perceptual) facts of color, providing a base for color determination (e.g. standard observer, standardized light sources) (5). This is rather a complex process.

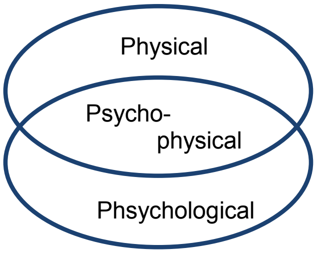


**Figure 1.2** Color Perception

Existing shade-guides are associated with many errors, such as limited shade ranges, unsystematic distribution within the 3D color space and variation in shade between different batch numbers of the same shade-tabs. Most importantly they are made out of homogeneous material (plastic) of which the optical properties are not related to the stratified natural teeth. The lack of proper communication between the dentist and dental laboratory, including possible discrepancies amongst their shade-tabs, can also affect the color reproduction process.

In order to be able to produce the matching color mix in other color industries, electronic devices are being used to determine the amount of different pigments in the substrate. One of the most accurate electronic devices for color measurement is a spectrophotometer. A spectrophotometer is a device that consists of three principle elements: a light source; a means to direct the light source to an object and receive the light reflected or otherwise returned from the object; and a spectrometer that determines the intensity of received light as a function of wavelength. A spectrophotometer can collect light that reflects from the material surface and translate it into three color coordinates. Those are the three numbers that exactly describe a position of the color in the 3D color space. Fundamentally speaking, these three coordinates are indicating the proportion of red, green and blue in the color mixture of the homogeneous materials. Nowadays, spectrophotometers have also been introduced to dentistry, which means that there is an available methodology to determine the objective color data of a tooth. However, due to the complexity of the tooth's internal structure and its surface roughness this methodology is not sustainable to give a guideline for tooth color reproduction. This methodology only translates the overall tooth color into three numbers, but the magnitude of different factors that influence the total color is still not detectable. For proper color reproduction it is very important that the tooth structure is mimicked with dental materials. This means that dental materials should substitute the tooth's two layers (replica of dentin and enamel) of similar thickness, shade, translucency and surface roughness as the tooth itself.

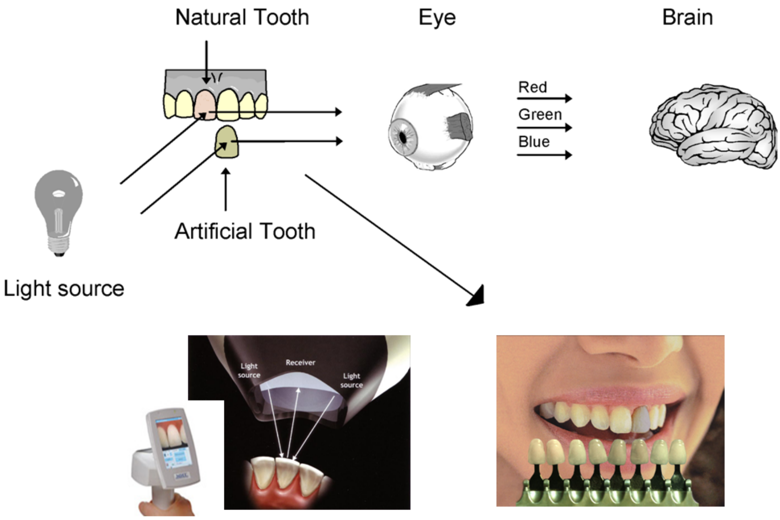


**Figure 1.3** Color Determination in Dentistry

Due to the fact that color has three dimensions which can be measured, it is possible to quantify tooth color along one measured area or point. The color specification system for use in dentistry is the CIE-L*a*b* color system. CIE stands for the Commission Internationale de l'Eclairage, which is the International Commission on Color established in 1931 in order to give standardization for color topics. L*, a*, and b* are the three color axes plotted in the 3D color space. The L*-axis is known as the lightness and extends from 0 (black) to 100 (white). The other two axes a* and b* represent redness-greenness and yellowness-blueness respectively. These three specific coordinates are recalculated from the three absolute color stimuli (X, Y, Z) that can be measured with spectrophotometers.

The reason for the introduction of the L*a*b* model was the need to make uniform distances between two color stimuli, in order to be able to define the exact color difference ($\Delta E^*$). The $\Delta E^*$ is used as a measure of color differences and can be calculated according to the following Equation (1.1):

$$\Delta E^* = \sqrt{((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)} \qquad \text{Eq (1.1)}$$

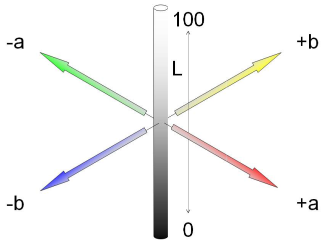


**Figure 1.4** CIE L*a*b* Color Space

The higher the ΔE* value, the bigger the difference in color and hence the more perceptible the difference is to the human eye. Perceptibility Threshold (PT) is the threshold at which the difference in color (ΔE*) can be detected by 50 % of observers, with the other 50 % of observers noticing no difference in color between the compared objects. Acceptability Threshold (AT) is the threshold at which the difference in color is considered acceptable by 50 % of observers, with the other 50 % of observers replacing or correcting the restoration.

## 1.3 Tooth color reproduction

The reproduction of tooth color in dental materials is a very critical process that starts with determination and description of tooth appearance, and sometimes continues with the appearance communication between dentist and dental laboratory, then the porcelain selection and manufacturing of the restoration at the dental laboratory, and finally ends with the placement of the restoration and evaluation of its color at the dental office. Figure 1.5 shows the clinical steps to predictable color management in esthetic restorative dentistry based on the study of Chu et al. (6).

After the first step of evaluation, the dentist makes a shade analysis either visually or with electronic color measuring devices. In the case of direct restorations the importance of a mock-up must not be forgotten. For indirect restorations, an interpretation of this information is made and sent to the dental technician whom translates this given shade information into a fabrication of the requested restoration. This finally gets sent back to the dentist who verifies the accuracy of the shade matching.

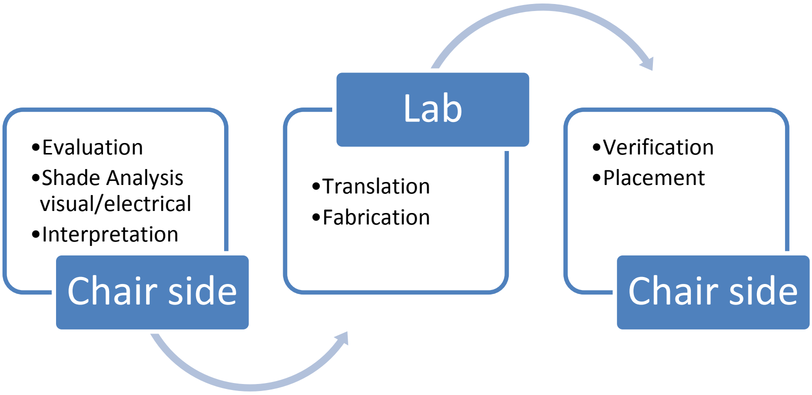


**Figure 1.5** Steps to Predictable Color Management

This process is further complicated by the fact that often the technician has to reproduce the color prescribed by the dentist without ever having seen the patient's mouth (Figure 1.6). As already described all steps in this process are sensitive to a large scale of factors which can lead to color mismatch and esthetical problems. This can cause frustration not only for the patients but also for all dental professionals that take part in the production process, professionals who seek the excellence in their work. Therefore, it is very important to reduce the number of factors which can affect the accurate determination and reproduction of tooth color.

**Figure 1.6** Often the restoration is first fabricated on a model at the lab, and then sent back to the patient to be placed at chair side.

Even though digital color measurement has become available, the use of this information by dental technicians to formulate (ceramic) materials and fabricate individualized porcelain restorations still does not guarantee a predictable color outcome due to human error by color reproduction. Thanks to contemporary achievements in digitalized dentistry, we enter an era in which all-ceramic dental restorations can be made fully automatically using CAD/CAM-based techniques (computer-aided design/computer-aided manufacturing). This development increases the quality of restorations because some human related errors are excluded from the manufacturing process.

Due to CAD/CAM technology, the thickness of different layers of porcelain (dentin and enamel) can be precisely fabricated. Even though this is possible, there is still no standardized way developed to alter the amount of pigments in the porcelain which simulate the optical characteristics of the natural teeth. Moreover, the porcelain samples need to be made in a stratified fashion to imitate teeth. When we manage to also standardize these variables, a digital model can be developed that links the tooth color data and the data of the different standardized-porcelain-samples in order to acquire the closest match ($\Delta E^* \leq 1$). This model can then be integrated with thickness data and applied in the CAD/CAM technology.

Also when it comes to the reproduction of tooth color with composite resins, as with porcelain, stratified application methods must be standardized, and the translucency dimension of teeth have to be considered. Once the correct color and layering technique for composite resins have been reproduced it is also of great importance to consider the color stability of such materials in order to maintain the correct color match over time.

## 1.4 Scope and outline of this research

Esthetic dentistry is the epitome of a progressive trend that is patient-driven within dentistry. It has been confirmed that the achievement and maintenance of an esthetic appearance is one of the most important reasons why patients visit the dentist (7). Patients have become increasingly aware of the appearance of their teeth and smiles, as society puts more emphasis on cosmetic dentistry and the whitening of their teeth (8). Yet, where in the past it was considered acceptable to place crowns on all six anterior teeth to achieve a ‘Hollywood smile’ especially young patients are now choosing for more conservative procedures (9) as they are understanding the significance of preserving enamel for future restorative options. To meet this demand, dental clinicians need to adapt to these realities, realizing that unnecessarily sacrificing enamel for the convenience of color matching is in fact sacrificing the patient. Conservative dentistry will continue as the driving force in emerging trends in cosmetic dentistry (9). My research on color science within dentistry has the general aims of emphasizing the importance of evidence based dentistry onto a platform where art meets science; and where ethics goes hand in hand with esthetics.

**Chapter 2** aims to determine the perceptibility and acceptability thresholds for color differences currently used in color research by means of a systematic review. The next two chapters deal with electronic tooth color measurement as a continuation of the thesis of A. Dozic in 2005 on 'Capturing Tooth Color' (10), at the time it was found that spectrophotometers were the gold standard for color measurement **(Chapter 3). Chapter 4** aims to evaluate two different spectrophotometers were evaluated for their ability to exchange data for color scientists and for the communication between dental clinicians. Though electronic tooth color measurement has been available for dental clinicians and extensively studied, visual tooth color determination remains the go-to method for the daily practitioner based on the use of 'classical' shade-guides. **Chapters 5 and 6** are on the topic of visual determination where **Chapter 5** studies the coverage error of some of the different shade-guides that are currently available, and introduces the concept of a newly developed shade-guide system for visual color determination in dentistry. **Chapter 6** aims to evaluate what the effect is of rearranging the shade tabs of the classical shade-guide in order of lightness to test the theory that the human eye is more sensitive to the 'value' dimension of color than to different hues.

In an ideal world, esthetic restorations would have the same reflection spectra as the tooth, resulting in no visible distinction between the restoration material and the tooth in question, under all normal types of illumination (11). Yet as this is not the case, extensive research has been done in all areas of dental materials to mimic the natural tooth color. **Chapters 7 and 8** aim to study the dental materials porcelain and resin composites, respectively, on the topic of color and appearance. The specific organic build-up of a tooth makes it quite difficult to mimic with dental restorative materials, and therefore **Chapter 7** evaluates the translucency of different tooth colored composites in order to find a layering-concept for the dental clinician that results in the most predictable outcome; and **Chapter 8** aims to specifically looks at the influence of different dentin and cement colors when layered on top of each other, on the final color of porcelain veneers. Finally **Chapter 9** concerns pink resin composites which are used to mimic the color of the human gingiva. A color stability study was performed to evaluate the change in color of different pink resin composites in different clinical situations over a period of time.

It is clear that in a society where esthetic values are of increasing significance the relevance of this thesis will be to develop evidence-based methodologies for predictable results within prosthetic and restorative dentistry.

A list of terms used within color science in dentistry used in this thesis can be found in the glossary.

*The chapters in this thesis can be read independently, as they have been written in a form suited for publication in international scientific journals. This has resulted in some unavoidable overlap.*

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# CHAPTER 2

*Perceptibility and Acceptability Thresholds*
*- A Systematic Review -*

## 2.1 Abstract

*Introduction*: Data on acceptability (AT) and perceptibility thresholds (PT) for color differences vary in dental literature. There is consensus that the determination of ΔE* is appropriate to define AT and PT, however there is no consensus regarding the values that should be used. The aim of this clinical review was to provide a systematic review on the topic of color science of high clinical relevance to dental research.

*Materials and Methods*: MEDLINE/PubMed, WoS and EBSCO databases were searched up to January 7, 2013; the outcome was restricted to English, and to clinical studies were spectrophotometers were used for measurement.

*Results*: Forty-eight studies were eligible and met the inclusion criteria. Of the 48 studies there appeared to be a trend in their source references: 44 % referred to the same study for the PT (ΔE*=1); and 35% referred to the same article for the AT (ΔE*=3.7).

*Conclusions*: More than half the studies defined PT as ΔE* =1, and one third of the studies referred to ΔE* =3.7 as the threshold at which 50% of observers accepted the color difference. Most clinical studies refer to the same few *in vitro* studies that have attempted to determine PT and AT from decades ago.

## 2.2 Introduction

*Color science in Dentistry*

Color science is an area within dental research that has been extensively studied over the last three decades. An initial search for the words 'color' or 'colour' within dental journals included in PubMed yields over 5400 articles. Color has become an increasingly important topic partially because many different research areas such as prosthodontics, esthetics and dental materials science, use color quantification to gain scientific data. The clinical relevance of such studies depends on how much color change is considered perceptible and/or acceptable. Considering the fact that color perception and/or acceptability are subjective, and can vary significantly among people, it is important to agree upon perceptibility and acceptability threshold values to be used within dental color research.

*Color assessment*

Different color difference formulas exist which are designed to provide a quantitative representation of the perceived color difference between 2 objects within dental research. The most extensively used color difference formula within dental research is derived from the CIE-L*a*b* system (1) which approximates uniform distance between color coordinates while entirely covering the visual color space:

$$\Delta E^* = \sqrt{((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)} \qquad \text{Eq (2.1)}$$

$\Delta L^*$, $\Delta a^*$, and $\Delta b^*$ are the differences in lightness-darkness, green-red coordinate and blue-yellow coordinate, respectively. $\Delta E^*$ is the color difference between two objects, where the higher the value the bigger the difference in color and hence the more perceptible the difference is to the human eye. The mere determination of a color difference between 2 objects is of little clinical value (2) without an understanding of the magnitude of color difference that is visually detectable (perceptibility threshold) and the magnitude that constitutes an unacceptable alteration to dental esthetics (acceptability threshold). The ISO Standardization Technical Report (3) also suggests such interpretation through color difference thresholds, and provides guidelines for future standardization related to dental shade conformity and interconvertibility.

All dental research that evaluates color, involves the author selecting a perceptibility and/or acceptability threshold with which to compare the results. The quantitative assessment of a color difference is worthless unless the following two thresholds are identified; the difference that is perceivable to an observer and the color difference that is clinically acceptable (2). Ample literature exists on perceptibility and acceptability thresholds in dentistry (4-6); however there has never been a systematic review on this subject, and therefore this will be a key element of evidence-based dentistry. As more and more research is performed on color science in dentistry there appears to be no consensus on the thresholds of perceptibility and acceptability. This systematic review of the color literature is intended to define current practices and trends in the use of ΔE* and to provide a basis for setting an acceptable and consistent standard for determining color in a practical setting. It will also help researchers improve the accuracy of clinical interpretations of color differences and aid research targeted at refining the color reproduction process in dentistry (5).

This review aims to establish, through the available literature, what is currently the color difference value used in dental research as the perceptibility threshold (PT) and the acceptability threshold (AT). The general objective is to suggest the need for a uniformed PT and AT to be used in clinical research. The specific review questions to be addressed are:

1) Which PT and AT values are currently used in dental research.
2) What are the original source references for these ΔE* values.

## 2.3 Materials & Methods

*Search strategy*

To ensure a complete assessment of the dental literature, bibliographic records were retrieved from PubMed/MEDLINE (NCBI), Web of Science (Thomson), and Dental and Oral Sciences Sources (EBSCO) on 7 January 2013 using terms for color acceptability, color perceptibility, color mismatch, or ΔE* and terms for teeth, prostheses, or restorations (Appendix 2.1 gives complete search strategies). Headings from controlled vocabularies were used when available. To ensure a consistent pool of studies with high relevance to dental practice, we limited the search to records that included terms or indexing for *in vivo* spectrophotometric determination of color differences (Appendix 2.1).

*Study inclusion criteria*

A number of inclusion criteria were adopted to make this systematic review methodologically sound and technically feasible. All studies where ΔE* threshold values are explicitly reported were included, but not sensitive to whether only AT, PT or both are reported. The papers included patients where intact tooth color was measured and not dentures; hence only *in vivo* studies were included. The instrument used for measuring the tooth color was the spectrophotometer as this can be considered the gold standard of color measuring devices (7) excluding any discussion on the comparability of data. The color measuring instrument had to be a spectrophotometer intended for clinical use, and not for industrial use. Therefore studies using spectroradiometers, colorimeters, and digital cameras were eliminated. This due to high predictability and repeatability of spectrophotometers (7) and the elimination of edge-loss due to the shape of the teeth (6). By concentrating on *in situ* studies on tooth color, measured with clinical spectrophotometers, the project remained practical, while the amount of data included concentrated on a study design which came closest to defining what the perceptibility and acceptability thresholds of color differences were.

Furthermore the PT and/or AT of all the articles were collected, as well as the source reference from which they were derived. Once the source references were found, each was searched on the Web of Science as a 'cited reference search' in order to see how many times they are cited in total, outside the scope of this article.

*Study selection process*

Two reviewers independently screened all identified items at two levels. Level 1 screening entailed a broad screen based on item titles and/or abstracts, as available. The full-text of all items passing Level 1 screening was retrieved for Level 2 screening: an ascertainment of final eligibility for the review. Discrepancies were resolved by consensus.

## 2.4 Results

A total of 682 records were retrieved from bibliographic databases. Removal of duplicate records left 380 unique articles. Of these 326 were excluded based on review of the titles and abstracts. Full text articles were obtained for the remaining 54 records. Six of these did not meet the inclusion criteria. 48 articles were included in the review

(Figure 2.1). Table 2.1 shows the details of studies proposed for inclusion in the systematic review.

*Original Source References*

Looking at the literature included in this review, only 9 articles have self-defined values for AT and PT, but the majority refer to another source reference for their obtained threshold values. Table 2.2 lists the top 8 studies that serve most as the source references of the literature ranked by total citations in Web of Science.

*Research Areas/Included studies*

A quarter of the literature is on the topic of bleaching, and almost the same percentage was allocated to investigating color measuring devices. The relationship between instrumental and visual assessments of color differences have been investigated in 17 % of the studies, additionally Table 2.3 shows the rest of the percentages of studies allocated to the different research areas. Only articles in the English language were included in the results of this review.

*Excluded studies*

The majority of articles that were on the topic of bleaching were rejected after full-text review, because even though they were clinical studies, there was no mention of perceptibility or acceptability thresholds. These studies all aimed for a high $\Delta E^*$ value to prove that their bleaching methodology resulted in a big change in color (towards lighter) in comparison to the original tooth color.

Almost all articles on the evaluation of color stability were rejected too because all color stability articles are done *in vitro* as they test the change in color of sound tooth specimens and dental materials over time, after immersion in different beverages.

Some articles were rejected after full-text review because the methodology revealed that spectroradiometers, as in the study of Douglas *et al.* (2) or digital cameras and sometimes even colorimeters were used instead of clinical spectrophotometers.

Studies in which color difference values were measured on interchangeable denture teeth (2, 4) were also excluded as we were seeking clinical research on natural intact tooth color.

**Figure 2.1** Selection of articles for inclusion into the review.

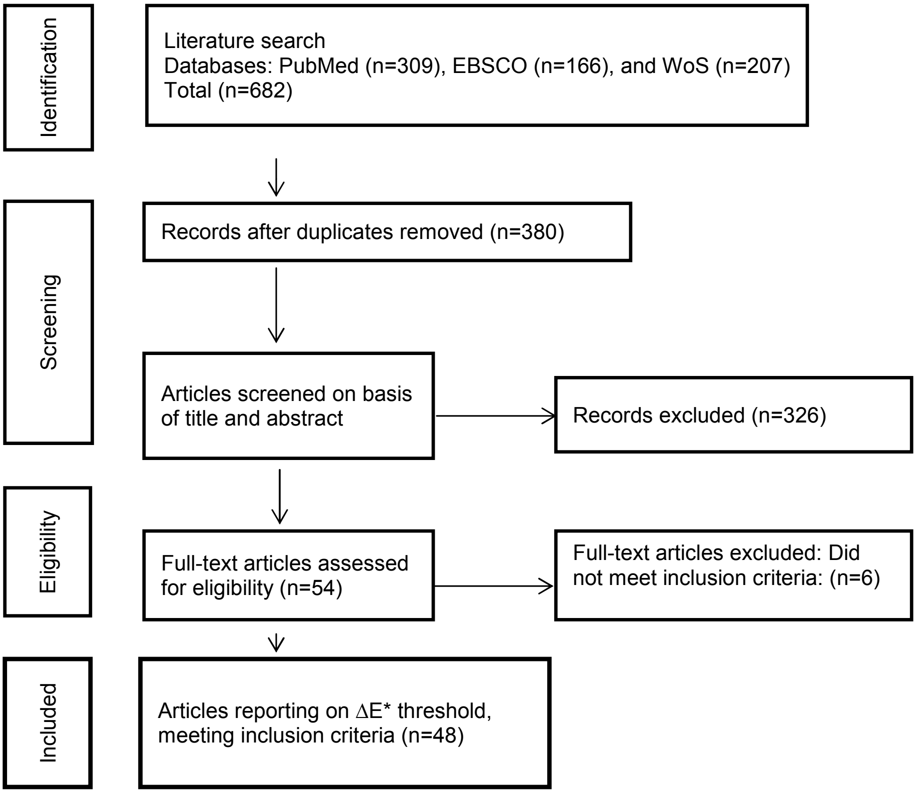

**Table 2.1** Details of studies proposed for inclusion in the systematic review.

| | Authors | PT/ΔE* | AT/ΔE* | Source Reference | Research Area |
|---|---|---|---|---|---|
| **1** | O'Brien,1991 (8) | n/a | 3.5 | Self-defined | Shadeguides |
| **2** | Russell, 2000 (9) | 1 | n/a | Kuehni, 1979 (10) | Tooth Dehydration |
| **3** | Paul, 2002 (11) | 1 | 3.7 | Johnston, 1989 (12)<br>Kuehni, 1979 (10) | Visual v. Digital |
| **4** | Chu, 2003 (13) | 1 | 4 | Self-defined | Bleaching |
| **5** | Ishikawa-Nagai, 2004(14) | 1.6 | 3.6 | Self-defined<br>Johnston, 1989 (12) | Bleaching |
| **6** | Paul, 2004 (15) | 1 | 3.7 | Johnston, 1989 (12)<br>Kuehni, 1979 (10) | Visual v. Digital |
| **7** | Hassel, 2007 (16) | 0.4 | 3.7 | Johnston, 1989 (12)<br>O'Brien, 1990 (17) | Color Measuring Devices |
| **8** | Karamouzos, 2007 (18) | 1 | 3.7 | Johnston, 1989 (12)<br>Kuehni, 1979 (10)<br>O'Brien, 1990 (17)<br>Seghi, 1989 (19) | Color Measuring Devices |
| **9** | Kim, 2007 (20) | 1.16 | 2.7 | Ragain (21) | Tooth Color |
| **10** | Paravina, 2007 (22) | 1 | 3.7 | Johnston, 1989 (12)<br>Kuehni, 1979 (10) | Tooth vs. Shadeguide |
| **11** | Sailer, 2007(23) | 1 | 3.7 | Johnston, 1989 (12)<br>Kuehni, 1979 (10) | Color Stability |
| **12** | Benbachir, 2008 (24) | 1.7 | n/a | Other | Bleaching |
| **13** | Da Silva, 2008 (25) | n/a | 2.69 | Self-defined | Color Measuring Devices |
| **14** | Paravina, 2008 (26) | 1 | 2.7 | Kuehni, 1979 (10)<br>Ragain, 2000 (21) | Shadeguides |
| **15** | Browning, 2009 (27) | 1 | 2.7 | Kuehni, 1979 (10)<br>Ragain, 2000 (21) | Visual vs. Digital |
| **16** | Cocking, 2009 (28) | 1 | 2.0 | Kuehni, 1979 (10)<br>O'Brien, 1990 (17) | Tooth vs. Shadeguide |
| **17** | Hassel, 2009 (29) | n/a | 2.9 | Self-defined | Color Measuring Devices |
| **18** | Hassel, 2009 (30) | n/a | 3.7 | Johnston, 1989 (12) | Tooth v. shadeguide |
| **19** | Ishikawa-Nagai, 2009 (6) | 1.6 | n/a | Self-defined | Perceptibility Thresholds |
| **20** | Li, 2009 (31) | 1 | 2.72 | Ragain, 2000 (21)<br>Seghi, 1989 (19) | Bleaching |

| | | | | | |
|---|---|---|---|---|---|
| **21** | Ontiveros, 2009 (32) | 1 | n/a | Kuehni, 1979 (10) | Bleaching |
| **22** | Bernardon, 2010 (33) | 3.3-3.7 | n/a | Kuehni, 1979 (10)<br>Ruyter, 1987 (34) | Bleaching |
| **23** | Choi, 2010 (35) | 1-2 | 3.7 | Johnston, 1989 (12)<br>Seghi, 1989 (19) | Visual vs. Digital |
| **24** | Chu, 2010 (36) | 1 | 2.7<br>3.3 | Kuehni, 1979 (10)<br>Ragain, 2000 (21)<br>Ruyter, 1987 (34) | Color Measuring Devices |
| **25** | Corcodel, 2010 (37) | n/a | 2.1 | Other | Tooth vs. Shadeguide |
| **26** | da Costa, 2010 (38) | 1 | 3.3 | Douglas, 2007 (2)<br>Kuehni, 1979 (10)<br>Ruyter, 1987 (34) | Bleaching |
| **27** | Ishikawa-Nagai, 2010 (39) | 1.16 | n/a | Self-defined | Color reproduction |
| **28** | Jaju, 2010 (40) | n/a | 2.69 | Da Silva, 2008 (25) | Visual vs. Digital |
| **29** | Karamouzos, 2010 (41) | 1 | 3.7 | Johnston, 1989 (12)<br>Kuehni, 1979 (10) | Orthodontics |
| **30** | Turkun, 2010 (42) | 1 | 3.3 | Kuehni, 1979 (10)<br>Ruyter, 1987 (34) | Bleaching |
| **31** | Yoshida, 2010 (43) | 3.6 | n/a | Self-defined | Color Reproduction |
| **32** | Grobler, 2011 (44) | 3.3 | n/a | Kuehni, 1979 (10)<br>Ruyter, 1987 (34) | Bleaching |
| **33** | Haddad, 2011 (45) | 1 | 3.7 | Johnston, 1989 (12)<br>Kuehni, 1979 (10) | Tooth Color |
| **34** | Kristiansen, 2011 (46) | 1.6 | 2.69 | Da Silva, 2008 (25) | Color Measuring Devices |
| **35** | Sluzker, 2011 (47) | 1 | 3.7 | Johnston, 1989 (12)<br>Kuehni, 1979 (10) | Color Measuring Devices |
| **36** | Salem, 2011 (48) | 2<br>3.7 | n/a | Johnston, 1989 (12)<br>O'Brien, 1990 (17)<br>Seghi, 1989 (19) | Bleaching |
| **37** | Lehmann, 2011 (49) | 1 | 3.5 | Johnston, 1989 (12)<br>Kuehni, 1979 (10) | Color Measuring Devices |
| **38** | Alsaleh, 2012 (50) | 1 | 3.7 | Johnston, 1989 (12)<br>Kuehni, 1979 (10) | Visual vs. Digital |
| **39** | Burki, 2012 (51) | 2.6 | 4.0 | Douglas, 2007 (2) | Tooth Dehydration |
| **40** | Dietschi, 2012 (52) | 1.1 | 3.3 | Self-defined | Visual vs. Digital |

| | | | | | |
|---|---|---|---|---|---|
| **41** | Forner, 2012 (53) | 1 | 2.7 | Douglas, 2007 (2)<br>Seghi, 1989 (19) | Bleaching |
| **42** | Khashayar, 2012 (54) | 2 | 3.7 | Self-defined | Shadeguide |
| **43** | Khashayar, 2012 (55) | 2 | 3.7 | Johnston, 1989 (12)<br>O'Brien, 1990 (17) | Color Measuring Devices |
| **44** | Lopes Filho (56) | 1 | 3.7 | Other | Orthodontics |
| **45** | Olms, 2012 (57) | 4 * | 3.3 | Ruyter, 1987 (34) | Color Measuring Devices |
| **46** | Ongul, 2012 (58) | 2 | 3.7 | Johnston, 1989 (12) | Visual vs. Digital |
| **47** | Ontiveros, 2012 (59) | 1.7 | 3.5 | Ghinea, 2010 (5) | Bleaching |
| **48** | Sarafianou, 2012 (60) | 1 | 3.3 | Kuehni, 1979 (10)<br>Ruyter, 1987 (34)<br>Seghi, 1989 (19) | Color Measuring Devices |

*$\Delta E^*$ = 4 is considered the distance where there was clearly a perceivable difference in shade.

**Table 2.2** Top 8 original source references of above articles in descending order cited from the 48 articles reporting AT and PT thresholds (from table 2.1).

| Source reference | PT and/or AT | Study type | Citing Articles |
|---|---|---|---|
| Johnston and Kao, 1989 (12) | AT=3.7 (38%) | *in vivo* | 295 |
| Ruyter *et al.*, 1987 (34) | AT= 3.3 | *in vitro* | 233 |
| Kuehni, 1979 (10) | PT= 1.0 (42%) | *in vitro* | 141 |
| Seghi *et al.*, 1989 (19) | PT= 2.0 | *in vitro* | 84 |
| Ragain, 2000 (21) | AT= 2.7 | *in vitro* | 65 |
| O' Brien *et al.*, 1990 (17) | AT= 2.0 | *in vitro* | 59 |
| Douglas *et al.*, 2007 (2) | PT= 2.6 and AT= 5.6 | *in vivo* | 66 |
| Da Silva *et al.*, 2008 (25) | AT=2.7 | *in vivo* | 24 |

**Table 2.3** Percentage of studies allocated to the different research areas.

| Research area | % |
|---|---|
| Bleaching | 25 |
| Color Measuring Devices | 23 |
| Visual vs. Digital determination | 17 |
| Shade guides | 8 |
| Tooth color v. Shade guides | 8 |
| Color reproduction | 4 |
| Orthodontics | 4 |
| Tooth Dehydration | 4 |
| Primary Teeth | 2 |
| Perceptibility Thresholds | 2 |
| Color Stability | 2 |

## 2.5 Discussion

Clearly the dental literature does not unanimously agree on how much color difference establishes an acceptable shade mismatch or how much color difference constitutes as perceivable to observers. Looking at the results of this study we can see that 54% of the literature reports a ΔE* value of 1 as visually detectable 50% of the time (PT). The majority of these studies refer to the same articles (Kuehni 1979 (10), Seghi *et al*., 1989 (19), Ruyter *et al*., 1987 (34)) for the above PT value.

As for the acceptability threshold, its value ranges between 2.0 and 4.0, where as much as one third of the literature refers to its value as being 3.7 and all refer to the same source (Johnston and Kao 1989 (12)).

Looking further at the original source references (Table 2.2) it is worth mentioning that each had a different study design, whether *in vivo* or *in vitro* which may have influenced the resulting values for PT and AT. Johnston and Kao (12) studied the assessment of appearance match by visual observation and clinical colorimetry and reported that the average color difference between compared teeth rated as a “match” in the oral environment was 3.7. Even though their study was performed under clinical settings the device used for color assessment was not validated for intraoral application and is known to be subject to edge loss errors (2) that maybe associated with their large standard deviations. Another study often referred to was that of Seghi *et al*. (19) who also recognized that an acceptable color difference can often be up to twice the amount of the detectable limits (PT). Ruyter *et al*. (34) looked at discoloration and suggested that an acceptable amount of discoloration is at a ΔE* value of 3.3. The literature that are referred to the most are mainly from the late 80's, which is remarkable because so many recent studies are still referring to a period of time well before the high esthetic demands of the present society. As more and more patients have high esthetic demands (36), one would expect that color thresholds in dentistry should reflect such clinical trends. Surprisingly when looking at the ΔE* values for PT and AT over the increasing years they do not decrease as much as would be expected due to high esthetic demands. Perhaps this has to do with the fact that most studies are performed by (trained) dental professionals and not by the general population (patients), who could have lower color-matching expectations. Ragain *et al.* (21), did however examine the acceptable color differences for dental restoratives, and reduced the mean 50:50% acceptability thresholds to ΔE*=2.7. An *in vivo* study by Da Silva *et al*. (25) also lowered the acceptability thresholds to a ΔE* of 2.67 in 2008 after which 9% of the literature followed.

It was remarkable to see how many times these source references have been cited not limiting to only the included studies in this present systematic review. Looking at Table 2.2, we can see that, the article of Johnston and Kao (1989), for example, has been cited 295 times on the Web of Science.

Furthermore, it is interesting to see that even though the inclusion criteria for this review was to look at only clinical studies, most of these clinical studies used PT and AT values obtained from *in vitro* studies. Only three of these source references are actually performed under *in vivo* conditions. One of these *in vivo* studies, that is commonly referred to, is the study by Douglas *et al.* (2); where the authors concluded that for the shade mismatch between two artificial acrylic resin teeth the tolerances for perceptibility were significantly lower than for acceptability. In this study the mean color perceptibility tolerance for perceptibility for 50% of observers was 2.6 ΔE* units. This is higher than the PT value of Kuehni (investigated non dental materials) (10); which has been vastly used within the literature (44%). The mean acceptability tolerance was 5.6 ΔE* units, which is higher than any of the studies included in this review. They explain these higher thresholds by suggesting that clinicians are more tolerant of shade mismatch in a clinical scenario than under controlled, *in vitro* conditions. However, the study of Douglas *et al*. (2) was not included in our results as it was performed on denture teeth and the color was not measured with a spectrophotometer, rather with a spectroradiometer not intended for clinical use.

Ishikwa-Nagai *et al.* (6) established a need for standardization of acceptability and perceptibility thresholds and aimed to set a gold standard for the color difference at which all-ceramic crowns cannot be distinguished from natural teeth. However as long as other researchers do not follow and fail to agree on such a gold standard we will still continue to come across studies that refer to the same older source references.

## 2.6 Conclusions

The following conclusions were made within the limitations of the studies included in the present systematic review:

1) More than half the studies use a threshold of perceptibility of $\Delta E^* = 1$, and one third of the studies refer to $\Delta E^* = 3.7$ as the threshold at which 50% of the observers accepted the color difference.
2) Most clinical studies refer to the same few literature that have attempted to determine perceptibility and acceptability thresholds from three decades ago under *in vitro* conditions.

*Future Directions for Research*

This is the first study to systematically review the literature on the perceptibility and acceptability threshold values used within color science in dentistry.

- Clinical studies included in this systematic review mainly referred to the same few studies which can be considered as outdated and unsuitable.
- A new prospective controlled (clinical) study is necessary to quantify a color difference threshold in order to be able to interpret all the aspects related to color research in dentistry and provide a consensus for dental researchers.

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## 2.8 Appendix

**PubMed**

("Spectrophotometry"[mesh] OR spectrophotomet*[tiab])

AND

("Color"[mesh] OR "Color Perception"[mesh] OR "Prosthesis Coloring"[mesh] OR color match*[tiab] OR colour match*[tiab] OR shade match*[tiab] OR color mismatch*[tiab] OR colour mismatch*[tiab] OR shade mismatch*[tiab] OR color stabil*[tiab] OR colour stabil*[tiab] OR shade stabil*[tiab] OR color percept*[tiab] OR colour percept*[tiab] OR shade perception*[tiab] OR color acceptability[tiab] OR

colour acceptability[tiab] OR shade acceptability[tiab] OR clinical acceptability[tiab] OR clinically acceptable[tiab] OR color threshold*[tiab] OR colour threshold*[tiab] OR color difference*[tiab] OR colour difference*[tiab] OR shade difference*[tiab] OR color change*[tiab] OR colour change*[tiab] OR shade change*[tiab] OR perceptibility threshold*[tiab] OR acceptability threshold*[tiab] OR DeltaE[tiab] OR delta e[tiab] OR L*a*b*[tiab])
AND
("Dental Porcelain"[mesh] OR "Composite Resins"[mesh] OR "Dental Prosthesis"[mesh] OR "Tooth"[Mesh] OR composite resin*[tiab] OR resin composite*[tiab] OR shade guide*[tiab] OR porcelain*[tiab] OR ceramic*[tiab] OR crown*[tiab] OR filling*[tiab] OR prothesis[tiab] OR prosthetic[tiab] OR prostheses[tiab] OR restoration*[tiab] OR restorative[tiab] OR veneer*[tiab] OR "tooth"[tiab] OR "teeth"[tiab] OR cuspid*[tiab]
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**Dentistry & Oral Sciences Source**
(DE "SPECTROPHOTOMETRY" OR DE "ABSORBANCE scale (Spectroscopy)" OR DE "SPECTROPHOTOMETER" OR DE "ABSORPTIOMETER" OR DE "MICROSPECTROPHOTOMETRY" OR DE "MONOCHROMATOR" OR TI spectrophotomet* OR AB spectrophotomet*)
AND
(DE "COLOR in dentistry" OR DE "COLOR" OR TI "color match*" OR TI "colour match*" OR TI "shade match*" OR TI "color mismatch*" OR TI "colour mismatch*" OR TI "shade mismatch*" OR TI "color stabil*" OR TI "colour stabil*" OR TI "shade stabil*" OR TI "color percept*" OR TI "colour percept*" OR TI "shade perception*" OR TI "color acceptability" OR TI "colour acceptability" OR TI "shade acceptability" OR TI "clinical acceptability" OR TI "clinically acceptable" OR TI "color threshold*" OR TI "colour threshold*" OR TI "color difference*" OR TI "colour difference*" OR TI "shade difference*" OR TI "color change*" OR TI "colour change*" OR TI "shade change*" OR TI "perceptibility threshold*" OR TI "acceptability threshold*" OR TI "DeltaE" OR TI "delta e" OR AB "color match*" OR AB "colour match*" OR AB "shade match*" OR AB "color mismatch*" OR AB "colour mismatch*" OR AB

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AND
(TI "in vivo" OR TI "in situ" OR TI intraoral OR TI "intra oral" OR TI patient OR TI patients OR TI clinical OR TI vital OR TI natural OR TI subject OR TI subjects OR TI human OR TI participant* OR AB "in vivo" OR AB "in situ" OR AB intraoral OR AB "intra oral" OR AB patient OR AB patients OR AB clinical OR AB vital OR AB natural OR AB subject OR AB subjects OR AB human OR AB participant*)

**Web of Science**
TS=spectrophotom*
AND
TS=("in vivo" OR "in situ" OR intraoral OR "intra oral" OR patient OR patients OR clinical OR vital OR natural OR subject OR subjects OR human OR participant*)
AND

TS=("composite resin*" OR "resin composite*" OR "shade guide*" OR "porcelain*" OR "ceramic*" OR "crown*" OR "filling*" OR "prothesis" OR "prosthetic" OR "prostheses" OR "restoration*" OR "restorative" OR "veneer*" OR "tooth" OR "teeth" OR "cuspid*" OR "incisor*")
AND
TS=("color match*" OR "colour match*" OR "shade match*" OR "color mismatch*" OR "colour mismatch*" OR "shade mismatch*" OR "color stabil*" OR "colour stabil*" OR "shade stabil*" OR "color percept*" OR "colour percept*" OR "shade perception*" OR "color acceptability" OR "colour acceptability" OR "shade acceptability" OR "clinical acceptability" OR "clinically acceptable" OR "color threshold*" OR "colour threshold*" OR "color difference*" OR "colour difference*" OR "shade difference*" OR "color change*" OR "colour change*" OR "shade change*" OR "perceptibility threshold*" OR "acceptability threshold*" OR "DeltaE" OR "delta e" OR "l a b")

# *Electronic Tooth Color Measurement*

*"Computers are useless.*
*They can only give you answers."*

***— Pablo Picasso***

# CHAPTER 3

## *Performance of Five Commercially Available Tooth Color-measuring Devices*

## 3.1 Abstract

*Introduction*: Visual tooth color assessment is neither accurate nor precise due to various subjective and objective factors. As newly developed tooth color-measuring devices for dental application provide the possibility of a more objective means of color determination, their performance *in vitro* and *in vivo* must be evaluated. The objective of this study was to evaluate the accuracy and precision of five commercially available tooth color-measuring devices in standardized and in clinical environments.
*Materials and Methods:* In an *in vitro* study, standards (A1, A2, A3, A3.5, and A4 shade tabs of Vita Lumin) were measured five times with five electronic devices (ShadeScan, Easyshade, Ikam, IdentaColor II, and ShadeEye) by two operators. In an *in vivo* study, the right upper central incisor of 25 dental students was measured with the same electronic devices by a single operator. Vita shade tab codes were expressed as CIE (International Commission on Illumination) L*a*b* values and in terms of the precision and accuracy of ΔE* color differences. The Mann-Whitney statistical test was used to analyze the differences between the two operators in the *in vitro* study, and the Kruskal-Wallis one-way analysis of variance on ranks with the post-hoc Tukey test was used to analyze the accuracy and precision of electronic devices.
*Results*: No statistically significant difference was found between the different operators in the *in vitro* study. The obtained precision was Easyshade> ShadeScan ≅ Ikam> IdentaColor II> ShadeEye. The obtained accuracy was Easyshade > ShadeScan ≅ Ikam > ShadeEye > IdentaColor II. In the *in vivo* study, the Easyshade and the Ikam were the most precise, and the ShadeEye and the IdentaColor II were more precise than the ShadeScan. With respect to accuracy, there was no statistical difference between the ShadeScan, Ikam, and the Easyshade. The IdentaColor II was considered inaccurate ($\Delta E_a$= 3.4).
*Conclusions:* In the clinical setting, the Easyshade and Ikam systems were the most reliable. The other devices tested were more reliable in vitro than *in vivo*.

### 3.2 Introduction

The esthetics of a restoration depend on shape, surface form, translucency, and color. Esthetically acceptable restorations have become more achievable as a result of the improved material properties of composites and porcelains, and the use of layering techniques to mimic the color of natural teeth as closely as possible. Color assessment and reproduction remains one of the most challenging aspects of esthetic dentistry; however, matching of a restoration to existing tooth enamel is not predictable.

Color perception is the result of the interplay between the light source, an object, and the detector or perceiver. Human color observation depends on the color characteristics of the illuminant and the angles between the illuminant, the object, and the human eye. Because color registration via the eye is affected by previous eye exposure, aging of the eye, or color blindness, the color perception of an individual is not consistent. As a result of metamerism, the color match between two objects perceived under one illuminant can become a mismatch under a different illuminant. To avoid these inconsistencies, the electronic devices with integrated standardized illumination can be used to measure reproducible color parameters, which then should depend only on the angle formed between the illuminant, the object, and the detector.

Since the early 1970s several electronic devices for color assessment have been used for various purposes in dentistry. Spectrophotometers (1-11), colorimeters (12-14), spectroradiometers (8, 15, 16), and digital cameras (2) have been used for color determination. Some studies have compared the electronic devices by visual observation or evaluated two electronic devices (4, 5, 8, 14). Other studies have evaluated color and translucency in relation to the physical properties of porcelains (1, 11-13), and the color reproduction of porcelains (3, 6, 7). In addition, these devices have been used to evaluate tooth color distribution in natural teeth (9, 17), and to monitor the color changes of teeth or restorative materials during bleaching (18). Several studies have been performed in a clinical environment using vital teeth (2, 19, 20), while only a few studies have evaluated the accuracy and precision of the devices in a clinical setting (21-23).

The basic principles of these mechanisms have been described elsewhere (21, 24, 25). In general, the output of the color measurements can be classified and specified in several ways. The most common systems for describing color are Munsell's System and the International Commission on Illumination (CIE) L*a*b* color system. In the latter system, L* represents the darkness–lightness coordinate, a* the chromaticity between green (−) and red (+), and b* the chromaticity between yellow (+) and blue (−). The CIE- L*a*b* color system is commonly used in perceptual studies for dental color assessment because of its approximate visually uniform coverage of the color space. In this color space, color difference between two objects ($L^*_1$, $a^*_1$, $b^*_1$ and $L^*_2$ , $a^*_2$ , $b^*_2$) can be calculated according to Equation (3.1):

$$\Delta E^* = \sqrt{((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)} \qquad \text{Eq (3.1)}$$

Among the color difference values expressed as ΔE*, values greater than 1 unit were visually detectable by 50% of human observers in controlled conditions (26) and the color differences between 2.0 and 3.7 were visually detectable under clinical conditions (27). Unfortunately, for historical reasons, colors in dentistry are almost always reported in shade tab codes of different shade guides, e.g., Vita Lumin, Vitapan 3D-Master, Chromascop, etc. The problem with these color tabs is that their colors are not distributed uniformly throughout the color space, and as a consequence, comparison between the shade tabs is incorrect.

A color-measuring device should be easy to handle, shockproof, and above all, accurate and precise. This study evaluated the accuracy and precision of five commercially available tooth color measuring devices in laboratory circumstances and under clinical conditions. Two devices, the ShadeEye and the IdentaColor II, are based on colorimetric techniques. The ShadeScan and the Ikam both use CDD-digital camera techniques, and the Easyshade is a spectrophotometer. Most of the systems have multiple outputs, such as Vita Lumin, Vitapan 3D-Master, Chromascop, Hue, Chroma and Value, and CIE L*a*b*, but the most commonly known output of the five selected devices is the Vita Lumin shade guide.

The measured shade codes were converted into the CIE L*a*b* color system to evaluate the accuracy and precision by means of ΔE*. The aim of this study was to determine whether the investigated electronic devices have the same accuracy and precision under clinical conditions as they possess under laboratory conditions.

### 3.3 Materials and Methods

Five commercially available devices for tooth color measurements were evaluated. Brand names, manufacturers, and configurations are summarized in Table 3.1. All devices were tested in two setups. Standard colors from artificial teeth in a phantom jaw of a phantom head were measured (i) in standardized *in vitro* conditions and (ii) in a clinical trial.

**Table 3.1** Commercially Available Electronic Devices for Tooth Color-Measurement Tested.

| Device | Manufacturer | Configuration | Calibration | Illumination |
|---|---|---|---|---|
| Shade Scan | CYNOVAD®, Montreal, Canada | Digital camera | Nine colors | A-Illuminant |
| Ikam | DCM®, West Yorkshire, UK | Digital camera | Graycard | D-65 Illuminant |
| IdentaColor II | Identa®, Holbaek, DK | Spectrophotometer | Unknown | D-65 Illuminant |
| Shade Eye | Shofu®, Dental GMBH, Ratingen, Germany | Colorimeter | Zirconium Oxide | D-65 Illuminant |
| Easy Shade | Vident®, California, USA | Spectrophotometer | Unknown | D-65 Illuminant |

*In Vitro Study*

The shade tab A1, A2, A3, A3.5, or A4 of the Vita Lumin shade guide (Vita Zahnfabriek, Bad Sackingen, Germany) was placed in a phantom jaw of a phantom head in the location of the upper right central incisor and measured with one of the devices. The devices were calibrated according to the manufacturer's recommendations. The probes for determining the color were fixed in a standardized setup in such a way that the mesio-distal midline of the middle third of the labial surface of the shade tabs was selected for color determination. When translucent samples are measured, the background must be controlled so that reproducible results between devices can be obtained. For a consistent background a black velvet cloth was used to mimic the clinical environment as closely as possible. This setup was used for all devices, except for the Ikam in which the original manufacturer's "crown holder'' was used. Two operators measured each shade tab five times.

The colors determined by the ShadeEye, IdentaColor II, and the Easyshade were read out directly, while for the Ikam and the ShadeScan the acquired digital images were first analyzed with the manufacturer's software to obtain the color. All colors were determined as Vita Lumin shade guide colors.

*In Vivo Study*

For the clinical trial, a group of 25 dental students whose anterior teeth had not received dental treatment or been affected by dental disease (absence of: dental caries, restorations, endodontic treatment, and bleaching) participated in the study. A written informed consent was obtained from every individual after a full explanation of the experiment. The group consisted of 15 males and 10 females, with ages ranging from 19 to 27 years (mean = 21.9, sd = 2.0). The color of the upper right central incisor of each subject was assessed thrice by a single operator using the same five devices as used in the in vitro study. The devices were calibrated according to the manufacturer's recommendations. The probes of the ShadeEye, IdentaColor II, and the Easyshade were held against the middle third of the tooth during the measurement. The tooth color measured by the Ikam and the ShadeScan was obtained by selecting and analyzing the middle third of the tooth in the digital image.

*Data Evaluation*

As noted earlier, the colors of the Vita Lumin shade guide are not uniformly distributed, and it is therefore inappropriate to evaluate the electronic devices based on these values. To overcome this problem, the Vita Lumin shade guide codes were expressed as CIE L*a*b* color parameters by using previously reported values (28), which were also determined in the mesio-distal midline of the middle third of the labial surface of the shade tabs. The color difference ($\Delta E^*$) between two colors of the Vita Lumin shade guide can be calculated by Equation 3.1 (above).

The L*a*b* values for each Vita Lumin shade code and the calculated color differences ($\Delta E^*$) between all colors of the Vita Lumin shade guide and the investigated color A1, A2, A3, A3.5, and A4 are summarized in Table 3.2. Vita Lumin shade guide codes like B3.5 (characteristic for the IdentaColor II device) were calculated based on a weighted average of the L*a*b* for the same color group (in this case B3 and B4), and $\Delta E^*$ was calculated according to the equation noted above. The latter values were omitted in Table 3.2 for practical reasons.

The different devices and the effect of operator influence were statistically analyzed. As the color difference, $\Delta E^*$, is not normally distributed, analysis based on Gaussian functions was not justified. Therefore, a nonparametric method of evaluation, the Mann-Whitney test, was used to analyze the effect of the two operators in the *in vitro* study. In addition, the non-parametric Kruskal-Wallis one-way analysis of variance on ranks with post-hoc Tukey ($p = 0.05$) method of analysis was used to test the effect of the accuracy and precision of the devices. The latter method of analysis was used for both the *in vitro* study and the clinical trial. The software used was SigmaStat 3.1 (Systat Software Inc., Richmond, CA).

### 3.4 Results

The Vita Lumin shade guide tabs A1, A2, A3, A3.5, and A4 were measured five times by two operators under standardized laboratory conditions. The results for the devices are summarized in Table 3.3. Accuracy is a measure of how close the estimate is to the "true'' value, which, in this case, is the color difference, $\Delta E_a^*$, between Vita color and the value obtained using the device. The Vita colors were converted into CIE L*a*b* parameters, and the color differences were calculated according to Equation 3.1 (see Table 3.2). The average color difference for each color, $\Delta E_a^*$, and the average color difference for all the colors, $\Delta E_a^*$, are summarized in Table 3.3.

Precision is usually a statistical measurement of repeatability expressed as a variance or standard deviation. Unfortunately, color is described by parameters, which do not permit calculation of a standard deviation. Instead, the obtained Vita colors were converted into CIE L*a*b* parameters and the average L* a* and b* values were calculated. The precision is proportional to the average of the color difference between the obtained Vita colors and their averaged L*a*b* values. For example, $L^* = 77.0$, $a^* = -0.1$, $b^* = 16.5$ are the average values for the Vita colors, A1, A2, and A3. The color differences between the average L*a*b* values and A1, A2, and A3 are 4.5, 1.0, and 3.8, respectively, resulting in a mean color difference of 3.1. The latter values are summarized as $\Delta E_p^*$, in Table 3.3. The average values for all colors, $\Delta E_p^*$, were also calculated and are summarized in the same table.

Accuracy and precision were calculated for the two operators, separately. The non-parametric Mann-Whitney test showed that there was no significant difference between the operators in either accuracy ($p = 0.727$) or precision ($p = 0.892$). The values in Table 3.3 represent therefore, the mean value for both the operators. The non-parametric Kruskal-Wallis one-way analysis of variance on ranks was used to evaluate the accuracy and precision of the devices. The accuracy of the ShadeScan, Ikam, and the Easyshade were not significantly different under standardized laboratory circumstances, while the ShadeEye and IdentaColor II were significantly less accurate. The precision of the Easyshade was significantly higher than the ShadeScan and the Ikam, followed by the IdentaColor II and the ShadeEye (see Table 3.3). The clinical measurements were evaluated analogous to the laboratory study. An operator measured each anterior tooth thrice. The separate measurements of each anterior tooth per individual are summarized in Table 3.4. The precision of the three measurements was calculated as described above for the precision measured in the laboratory study. The observed shade tab color was converted into L*, a* and b* values and averaged.

The color difference between this average value and the separate measurements were expressed as ΔE* values, and reported in Table 3.4 as $\Delta E_p$*.

**Table 3.2** Colorimetric Values of Each Vita Lumin Shade Tab, and Color Differences Between Them.

| | L* | a* | b* | A1 | A2 | A3 | A3.5 | A4 |
|---|---|---|---|---|---|---|---|---|
| A1 | 79.6 | -1.6 | 13.1 | 0.0 | 5.3 | 8.3 | 11.8 | 13.9 |
| A2 | 76.0 | -0.1 | 16.7 | 5.3 | 0.0 | 3.3 | 6.5 | 8.8 |
| A3 | 75.4 | 1.4 | 19.6 | 8.3 | 3.3 | 0.0 | 3.8 | 6.9 |
| A3.5 | 72.3 | 1.5 | 21.8 | 11.8 | 6.5 | 3.8 | 0.0 | 3.8 |
| A4 | 68.6 | 1.6 | 21.0 | 13.9 | 8.8 | 6.9 | 3.8 | 0.0 |
| B1 | 78.9 | -1.8 | 12.3 | 1.0 | 5.5 | 8.7 | 12.0 | 13.9 |
| B2 | 76.7 | -1.6 | 16.6 | 4.6 | 1.7 | 4.4 | 7.4 | 9.7 |
| B3 | 74.1 | 0.5 | 22.3 | 11.0 | 6.0 | 3.1 | 2.1 | 5.8 |
| B4 | 71.8 | 0.5 | 22.2 | 12.1 | 6.9 | 4.4 | 1.2 | 3.6 |
| C1 | 74.2 | -1.3 | 12.6 | 5.4 | 4.7 | 7.6 | 9.8 | 10.5 |
| C2 | 71.0 | -0.2 | 16.7 | 9.5 | 5.1 | 5.5 | 5.5 | 5.2 |
| C3 | 68.8 | 0.0 | 16.7 | 11.4 | 7.2 | 7.3 | 6.4 | 4.6 |
| C4 | 64.8 | 1.6 | 18.7 | 16.1 | 11.5 | 10.6 | 8.2 | 4.4 |
| D2 | 75.3 | -0.5 | 13.5 | 4.5 | 3.4 | 6.4 | 9.1 | 10.3 |
| D3 | 72.6 | 0.6 | 16.1 | 8.0 | 3.6 | 4.5 | 5.7 | 6.4 |
| D4 | 71.9 | -1.0 | 17.8 | 9.1 | 4.4 | 4.6 | 4.8 | 5.3 |

**Table 3.3** Accuracy and Precision of Color-Measuring Devices Tested.

| | A1 | A2 | A3 | A3.5 | A4 | $\overline{\Delta E}_p$ / $\overline{\Delta E}_a$ |
|---|---|---|---|---|---|---|
| Shade Scan | 10A1 | 6A2/2B2/2C1 | 9A3/A2.5 | 2A3.5/8B4 | 10A4 | |
| $\Delta E_p$ / $\Delta E_a$ | 0.0 / 0.0 | 1.6 /1.3 | 0.3 / 0.2 | 0.3 / 1.0 | 0.0 / 0.0 | 0.5[abc] / 0.5[a] |
| Ikam | 5A1/5B2 | 10A2 | 10A3 | A3/9A3.5 | 10A4 | |
| $\Delta E_p$ / $\Delta E_a$ | 2.3 / 2.3 | 0.0 / 0.0 | 0.0 / 0.0 | 0.7 / 0.4 | 0.0 / 0.0 | 0.6[c] / 0.5[a] |
| IdentaColor II | 5A1/5A1.5 | 8A1.5/2B2 | 3A2/5A2.5/C1.5/D3 | 6B3.5/B2/3B3 | 10A3.75 | |
| $\Delta E_p$ / $\Delta E_a$ | 1.3 / 1.4 | 0.7 / 2.5 | 1.6 / 2.9 | 1.4 / 2.2 | 0.0 / 2.2 | 1.0[a] / 2.2 |
| Shade Eye | 5A1/4A2/D1.5 | 8A2/D1.5/D2 | 10A3 | 10A3.5 | 5C4/5C3 | |
| $\Delta E_p$ / $\Delta E_a$ | 3.9 / 3.7 | 2.3 / 1.5 | 0.0 / 0.0 | 0.0 / 0.0 | 2.4 / 4.5 | 1.7[ab] / 1.9 |
| Easy Shade | 10A1 | 10A2 | 10A3 | 10A3.5 | 10A4 | |
| $\Delta E_p$ / $\Delta E_a$ | 0.0 / 0.0 | 0.0 / 0.0 | 0.0 / 0.0 | 0.0 / 0.0 | 0.0 / 0.0 | 0.0 / 0.0[a] |

No significant differences were observed if the mean color difference is quoted with the same small letter (P = 0.05).

As there is no objective way to assess the “true’’ color of teeth, the average L*a*b* values of the ShadeScan, Ikam, and the Easyshade were used as “true’’ colors (see “Discussion’’). The nine shade tab color measurements from the ShadeScan, Ikam, and the Easyshade were converted into L*, a*, and b* values and averaged. This was considered the “true’’ color. The color difference, expressed as $\Delta E^*$, of each individual measurement and this “true’’ color were averaged, and reported in Table 3.4 as $\Delta E_a^*$.

The non-parametric Kruskal-Wallis one-way analysis of variance on ranks was used to evaluate the accuracy and precision of the devices for the averaged accuracy and precision, $\Delta E_a^*$ and $\Delta E_p^*$, for all patients. In a clinical setting, only the accuracy of the ShadeScan was significantly better than the accuracy of the IdentaColor II. On the other hand, the ShadeScan was significantly less precise than the Ikam and the Easyshade, which were the two devices with highest precision.

**Table 3.4** Color Measurements of the Anterior Teeth in Vita Lumin Shade Tab Colors of 25 Dental students, and the Color Difference for the Precision ($\Delta E_p$*) and Accuracy ($\Delta E_a$*) Between the Measurements and the Average from the ShadeScan, Ikam, and Easyshade Measurements

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Shade Scan | D2/C1/A2 | A2/2A3 | 2A2/C1 | 3C1 | 3B2 | 2D2/D3 | 2A2/A3 | B1/2D2 | A2/2A3 | 2A2/B2 | D2/2D3 | 2A3/C1 | 2D2/D3 | B1/2B2 |
| $\Delta E_p$ / $\Delta E_a$ | 1.8 / 2.1 | 1.5 / 1.0 | 2.1 / 1.7 | 0.0 / 2.8 | 0.0 / 1.0 | 1.8 / 1.3 | 1.5 / 2.0 | 1.8 / 1.9 | 1.5 / 4.3 | 0.7 / 2.7 | 1.8 / 3.4 | 3.4 / 3.0 | 1.8 / 2.2 | 2.2 / 2.0 |
| Ikam | 3A1 | 2A1/B2 | 2A1/B2 | 3B2 | 2A1/A2 | 3C1 | 3B2 | 3A1 | 3A1 | 3A1 | 3A1 | 3A1 | 3A1 | 3A1 |
| $\Delta E_p$ / $\Delta E_a$ | 0.0 / 2.9 | 2.0 / 5.5 | 2.0 / 2.1 | 0.0 / 3.1 | 2.4 / 2.0 | 0.0 / 2.4 | 0.0 / 1.8 | 0.0 / 1.3 | 0.0 / 3.7 | 0.0 / 3.1 | 0.0 / 3.6 | 0.0 / 3.7 | 0.0 / 3.6 | 0.0 / 1.0 |
| IdentaColor II | 3A1 | 3A2 | 2A1/A2 | 3A1 | 3B1 | 3D1.5 | A1/2C1 | 3B1 | 3A1 | 3B1 | 2A1/B1.5 | 3A1.5 | A1/2B1 | 3B1 |
| $\Delta E_p$ / $\Delta E_a$ | 0.0 / 2.9 | 0.0 / 1.8 | 2.4 / 1.9 | 0.0 / 6.1 | 0.0 / 3.9 | 0.0 / 9.6 | 5.4 / 3.5 | 0.0 / 0.8 | 0.0 / 3.7 | 0.0 / 2.9 | 0.4 / 3.6 | 0.0 / 1.1 | 0.4 / 3.2 | 0.0 / 1.4 |
| Shade Eye | 3A2 | A2/2A3 | 3A1 | 3D2 | 3C1 | 2C1/D2 | 3C2 | 3C1 | 2A1/A2 | 3A1 | 3A2 | 3A2 | 3A1 | 3A1 |
| $\Delta E_p$ / $\Delta E_a$ | 0.0 / 2.6 | 1.5 / 1.0 | 0.0 / 3.6 | 0.0 / 2.3 | 0.0 / 4.5 | 0.7 / 2.2 | 0.0 / 4.3 | 0.0 / 4.1 | 2.4 / 2.0 | 0.0 / 3.1 | 0.0 / 2.1 | 0.0 / 1.7 | 0.0 / 3.6 | 0.0 / 1.0 |
| Easy Shade | 3B2 | 4B4 | 3B2 | 3C2 | 3B2 | 2C2/D2 | 2C1/C2 | 3B1 | 3C1 | 3C1 | 3B2 | 3B2 | 3C1 | 3A1 |
| $\Delta E_p$ / $\Delta E_a$ | 0.0 / 2.1 | 0.0 / 5.2 | 0.0 / 1.3 | 0.0 / 3.4 | 0.0 / 1.0 | 0.0 / 3.1 | 2.4 / 3.0 | 0.0 / 0.8 | 0.0 / 3.2 | 0.0 / 2.9 | 0.0 / 1.8 | 0.0 / 1.3 | 0.0 / 2.0 | 0.0 / 1.0 |
| | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | | $\overline{\Delta E_p}$ | $\overline{\Delta E_a}$ |
| Shade Scan | A2/2B2 | 2A2/B1 | 3B1 | A2/2B2 | 3B2/C1 | A1/2B1 | C1/2D3 | 2A3/C1 | 3B2 | A2/2C1 | B2/2D2 | | | |
| $\Delta E_p$ / $\Delta E_a$ | 0.7 / 1.6 | 2.4 / 1.6 | 0.0 / 0.5 | 0.7 / 1.7 | 2.1 / 0.6 | 0.4 / 0.1 | 1.9 / 1.0 | 3.4 / 1.3 | 0.0 / 2.3 | 2.1 / 2.1 | 1.6 / 1.7 | | $1.5^{a}$ | $1.8^{b}$ |
| Ikam | 3A2 | 3A1 | A1/B1/C1 | 3A1 | 3A1 | 3A1 | 3A1 | A1/A2/B2 | 3A1 | 2A2 | 3A1 | | | |
| $\Delta E_p$ / $\Delta E_a$ | 0.0 / 1.7 | 0.0 / 4.8 | 2.3 / 0.9 | 0.0 / 3.1 | 0.0 / 4.6 | 0.0 / 0.6 | 0.0 / 5.9 | 2.3 / 3.6 | 0.0 / 2.8 | 0.0 / 1.3 | 0.0 / 2.8 | | $0.4^{b}$ | $2.9^{ab}$ |
| IdentaColor II | 2C3.5/C4 | 3B2 | 3A1 | 2A2/B2 | 2A1/B1.5 | 3B1 | 3B1 | C1/D3/D3.5 | 2B1/D1.5 | 3B1 | 2A1/B1 | | | |
| $\Delta E_p$ / $\Delta E_a$ | 2.1 / 8.4 | 0.0 / 1.1 | 0.0 / 1.3 | 0.7 / 2.0 | 0.4 / 4.5 | 0.0 / 0.4 | 0.0 / 5.6 | 1.6 / 4.3 | 7.0 / 3.0 | 0.0 / 4.7 | 0.4 / 2.8 | | $0.7^{ab}$ | $3.4^{a}$ |
| Shade Eye | 2D2/D3 | A1/2A2 | 2A1/C1 | 2A1/A2 | 2A2/D2 | 3A1 | 3C1 | A1/C1/D1 | 3B1 | 3A2 | 2A1/C1 | | | |
| $\Delta E_p$ / $\Delta E_a$ | 1.8 / 1.7 | 2.4 / 1.4 | 2.4 / 0.8 | 2.4 / 1.5 | 1.5 / 1.1 | 0.0 / 0.6 | 0.0 / 2.5 | 2.3 / 5.5 | 0.0 / 2.7 | 0.0 / 1.3 | 2.4 / 1.9 | | $0.7^{ab}$ | $2.4^{ab}$ |
| Easy Shade | 3C1 | 3B3 | 3B1 | 3B2 | 3C2 | 3B1 | B1/2D1 | 3B3 | 3D2 | 3B2 | 3B2 | | | |
| $\Delta E_p$ / $\Delta E_a$ | 0.0 / 3.1 | 0.0 / 6.2 | 0.0 / 0.5 | 0.0 / 1.5 | 0.0 / 4.9 | 0.0 / 0.4 | 7.0 / 4.9 | 0.0 / 4.2 | 0.0 / 2.2 | 0.0 / 1.4 | 0.0 / 2.0 | | $0.4^{b}$ | $2.5^{ab}$ |

No significant differences were observed if the mean color difference is quoted with the same small letter ($P = 0.05$).

### 3.5 Discussion

Tooth color is a complex phenomenon, in which the overall perception is influenced by various factors such as the lighting conditions, translucency, opacity, gloss, and the limitations of the human eye and brain. Besides visual assessment with a shade guide, tooth color can be measured with colorimetry, spectrophotometry, and digital cameras. Only a few reported studies have evaluated the precision of these devices in a clinical setting (10, 21, 29). Visual assessment with a shade-guide has been compared with color measurement of spectrophotometer (10). Tung *et al.* (23) found that the ShadeEye system agreed with itself 82% of the time, whereas clinicians agreed with each other on 73% of the selected shades. Remarkably, selections made by the colorimeter and the clinicians matched only 55% to 64% of the time. Although most previous studies have been designed to test the precision of the equipment on different measuring times and with different persons, accuracy is not often investigated. To test the accuracy of any electronic device intended for use in the oral environment, an intraoral standard must be developed; currently such a standard is not available. Despite this lack in standardization, the shade-guides are the "de-facto standard'' for color determination in dentistry. For this reason, the Vita Lumin shade guide was used to evaluate the precision and accuracy in standardized laboratory conditions.

The Vita Lumin shade guide is divided into four series with the letters A, B, C, and D. These shades have brown, yellow, gray, and red characters, respectively. Within a group (e.g., A1, A2, A3, A3.5, and A4) chroma increases and value decreases as you go up the shade scale. This group was measured with the five instruments. The obtained precision was in the order Easyshade > ShadeScan ≅ Ikam > IdentaColor II> ShadeEye. The IdentaColor II and the ShadeEye had precisions with $\Delta E_p$*> 1.0. Since differences greater than 1 ΔE* unit are visually detectable by 50% of human observers, measuring color with the latter devices will give visually observable color differences, confirming the findings of Tung *et al.* (23). The common output of all the devices was the Vita Lumin shade guide code, and by measuring the Vita tabs the accuracy was evaluated. The obtained order was Easyshade > ShadeScan ≅ Ikam > ShadeEye > IdentaColor II. Based on both the accuracy and precision, the ShadeScan, Ikam, and the Easyshade perform better than the IdentaColor II and the ShadeEye. Apparently, there is no difference in performance of measuring tooth color under standardized conditions with a spectrophotometer or a digital camera.

Evaluation of a color-measuring device in the oral environment is much more complicated than under standardized laboratory circumstances. Because there is no "gold standard'' for the oral environment, the evaluation is not straightforward. In this study 25 teeth were measured with the five color-measuring devices. Tooth color was determined thrice with each device by a single operator. These circumstances were chosen, because they represent a typical clinical setting in a dental laboratory or practice and because, from the results of the *in vitro* study, it could be concluded that there was no statistically significant difference between the two operators. The precision was evaluated as in the laboratory study, showing that the ShadeScan was less precise, compared with the IdentaColor II and the ShadeEye. In the clinical study, the Ikam and the Easyshade were also the most precise. The in vitro study showed that there were no significant differences between the accuracy of the ShadeScan, Ikam, and the Easyshade. Moreover, the average accuracy of the Easyshade was so high ($\Delta E_a^* < 0.5$) that the visual perceptibility of color difference is not expected. For each patient, the average L*a*b* values of tooth color were calculated by averaging the obtained colors for the ShadeScan, Ikam, and the Easyshade. The color difference between this "gold standard'' and each measurement was then calculated. The ShadeScan was the most accurate device, followed by the ShadeEye, Easyshade, and the Ikam. The IdentaColor II was rather inaccurate with $\Delta E_a^* = 3.4$. The ShadeScan, Ikam, and the Easyshade were the most reliable devices in the *in vitro* setting, but only the Ikam and the Easyshade performed equally well with respect to precision in the clinical setting.

In contrast to the *in vitro* study, it is clear that accuracy of the devices (see Table 3.4) is not high enough to create predictable shades using different electronic devices. Apparently, the devices are still too sensitive to patient or equipment movement. Furthermore, factors such as the pressure, the angle and position of the probe, and the anatomic shape of the tooth surface may play a role in color determination. Moreover, the accuracy of the light source in the device can change over the time, influencing the observed color.

In this study, the shade tabs of Vita Lumin shade guide were used as a standard, and their L*a*b* values, estimated in one earlier study (28), were used as the gold standard. The problem with different shade guides is that their shade tabs do not always match each other, although they represent the same color. This is due to the lack of standardization during the manufacturing of shade guides, which is visual instead of instrumental. As a result, the gold standard used in this study may not exactly represent the output colors of different electronic devices; however, this fact is not of importance for the comparison of the accuracy of the different systems.

Within the limits of this study, it can be concluded that different commercial electronic devices have different accuracy and precision *in vitro* and *in vivo*. Colorimeters are significantly less reliable than spectrophotometers and the specific digital cameras used in this study. The precision of the ShadeScan decreased in clinical circumstances. Most of the devices used in this study are more reliable in vitro than *in vivo*, whereas the Easyshade and the Ikam show the same results in both standardized and clinical conditions.

### 3.6 Conclusions

Commercially available electronic systems for tooth color measurements show different levels of accuracy and precision. Within the limits of this study, the following conclusions can be drawn:

1) Generally, the colorimeter (ShadeEye, Identa- Color II) was less reliable than the spectrophotometer (Easyshade) and the digital cameras used in this study (Ikam).
2) The spectrophotometer (Easyshade) was the most reliable instrument in both *in vitro* and *in vivo* circumstances.
3) The ShadeScan (digital camera) was less precise in the clinical environment.

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# CHAPTER 4

## *Data Comparison Between Two Dental Spectrophotometers*

## 4.1 Abstract

*Objectives*: The objective of this study was to clinically test whether the data from two different spectrophotometers, based on spot and surface measurements, can be compared.

*Materials and Methods:* Under standardized clinical conditions two devices (Vita Easyshade and SpectroShade-Micro) were used to record the color of three areas (cervical, middle, and incisal) per tooth for three upper maxillary anterior teeth in 102 participants. Each position was measured three times to attain an average for the CIE L*a*b* coordinates and to attain the corresponding Vita Classical shade tab integrated in the software of both devices. Vita tabs were also described as L*a*b* values using earlier published translations so that color differences (ΔE*) could be calculated between them.

*Results:* The regression analysis between the two devices showed that the independent correlation coefficients of the L*a*b* values are low. Yet when the suggested shade codes are compared with Vita colors instead of L*a*b*, 40% of the cases were equal and 51% were clinically acceptable.

*Conclusion:* According to this study the two devices do not give a comparable shade selection output, and thus the exchange of L*a*b* values between the two spectrophotometers cannot be recommended.

*Clinical Relevance:* Different color measuring devices (CMDs) are used to determine tooth color and the color of the matching restoration during the manufacturing process. This study questions whether it is possible to communicate color accurately when dentists and dental laboratories use different CMDs at different locations.

## 4.2 Introduction

The subjective character of visual shade determination makes color assessment one of the most complex aspects of restorative dentistry (1-4), whereas precise information on color is essential for the creation of an esthetic dental restoration. An escalating number of electronically based devices for tooth color determination have entered the market, compelling dental laboratories and dentists to invest in these devices. Such color measuring devices (CMDs) eliminate the subjectivity related to color determination and increase the level of consistency in the color determination process (3, 5-7). Henceforth, CMDs can be beneficial for the process of shade determination.

Different types of CMDs are based on different technologies, such as colorimetery, focal optics, and spectrophotometry. Dental colorimeters are designed to directly measure color as a function of light reflection perceived by the human eye. They use three filters corresponding to three color stimuli: red, green, and blue (RGB). Measuring tooth color is also possible by analyzing digital images, where a multitude of pixels are measured in RGB units corresponding to RGB stimuli. Spectrophotometers are devices that determine the intensity of reflected or transmitted light as a function of a light-source wavelength (8).

The optical light settings used in CMDs can have different geometries; illumination at 0 degrees and observation at 45 degrees (0/45), illumination at 45 degrees and observation at 0 degrees (45/0), or a 0/0 degree optical geometry where the light beam and the light detector are in the exact opposite direction (1).

There are not only different optical geometries between different CMDs but also different methods for measuring optical light (9): spot-measurement devices and complete-tooth-measurement devices. Spot measurements are made by an optical device with an aperture of about 3-5 mm in diameter. Therefore, several recordings must be taken to obtain a more extensive shade distribution over the entire tooth surface. On the other hand, complete-tooth-measurement devices can measure the entire tooth and produce a color map of the tooth in one image.

There are several systems in which the output of the color measurements can be categorized and identified quantitatively. One of the most commonly used systems is the CIE L*a*b* color system because it approximates uniform distances between color coordinates while entirely covering the visual color space (10, 11). This system has a lightness scale, L*, ranging from 0 (black) to 100 (white), and two opposing color axes: axis a* for redness (+) and greenness (-) and axis b* for yellowness (+) and blueness (-). The output of the absolute color values, expressed as L*, a*, and b* can be translated into shade guide codes, for instance the A, B, C, and D codes of the Vita Classical (Vita, Bad Säckingen, Germany), for clinical use. It is unclear which L*a*b* values different manufacturers apply in their devices to express the different Vita shades. Moreover, the color consistency of the different Vita Shade tabs used by different manufacturers may vary, too. In a study by O'Brien and others (12), a CIE L*a*b* translation table of the Vita shade guide was presented, as measured by a spectrophotometer. This has been, so far, the only standard where the shade tabs of the Vita shade guide are expressed as L*a*b* values.

The visual color space of teeth covers a small volume in the whole L*a*b* color space. As a consequence, the resolution of dental CMDs has to be high to be able to differentiate the whole possible color range of teeth. For the same reason, not only the resolution of the devices is of importance but also the high reproducibility of the measurement itself (13). For instance, for most CMDs it is extremely important to keep the angle of measurement constant when repeating the measurement.

In an earlier study (8), we evaluated the repeatability and accuracy of five commercially available CMDs and concluded that, of the different CMDs, spectrophotometer measurements were the most reproducible in repeating measurements. The most reliable device *in vitro* and *in vivo* was the Easyshade (ES; Vita, Bad Säckingen, Germany) (8), which is a handheld spot-measurement device that needs to be brought into direct contact with the tooth surface when a measurement is being made. The fiber-optic tip is 5 mm in diameter and uses a pseudocircular 0/0 measuring geometry (14). Another dental spectrophotometer that was tested in this earlier study was the SpectroShade-Micro (SS, MHT S.p.a., Verona, Italy. This device has the ability to measure the whole tooth surface and is based on illumination at 45 degrees and observation at 0 degrees (45/0) (15).

In principle, CMDs are designed to enhance communication between clinicians and dental laboratories, but the commercialization of the dental market results in the use of different devices among different professionals. However, besides the differences in working mechanisms, the basic signal of most CMDs is an electrical current originating from sensors that are transferred into color data by internal software. This can lead to possible errors when two different systems are used to determine tooth color and the color of the matching restoration during the manufacturing process. A growing number of dental practices work with large dental laboratories abroad; hence, color has to be communicated precisely, especially in such cases where no direct contact is possible between the technician and the patient to determine color. Therefore, the question is whether it would also be possible to communicate color when dentists and dental laboratories use different CMDs at different locations. The objective was to evaluate whether the measurements of two different devices can be exchanged without resulting in a visible color difference. For this study, a color difference of $\Delta E^* \leq 2.0$ units was regarded as the perceptibility threshold (12), whereas a color difference of $\Delta E^* \geq 3.7$ was regarded as the acceptability threshold, and can be considered clinically imperceptible for 50% of the viewers (1, 12).

The hypothesis of this research was that the absolute color data, measured as a spectrum and expressed as CIE L*a*b* values, are comparable between the ES and SS spectrophotometers and therefore can be exchanged.

## 4.3 Materials and Methods

The tooth color of 102 participants was measured at the Academic Centre for Dentistry in Amsterdam (ACTA, the Netherlands). A written informed consent was obtained from every subject after a full explanation of the experiment. The group consisted of 42 male and 60 female subjects, and ages ranged from 14 to 58 years (average age=23 years). Tooth color was measured under standardized clinical conditions by one operator using the Vita Easyshade and the SpectroShade-Micro CMDs.

The maxillary central and lateral incisors and the canines from the left or the right side of the maxilla were selected based on the following criteria: 1) absence of dental caries, 2) absence of restorations, 3) no previous endodontic treatment, and 4) no previous bleaching treatment or use of whitening toothpaste. Shade was recorded for all selected teeth at three sites: cervical, middle, and incisal. Thus, nine total locations were measured in 102 participants, resulting in 918 independent color measurements with the ES and SS, respectively. During measurements the participants were asked to keep their tongue in a relaxed position away from the maxillary teeth, lean their head against the headrest of the dental chair, and keep their mouth slightly opened; this was in order to prevent moving or fogging that could possibly affect the measurements. The devices were used and calibrated according to the manufacturer's instructions.

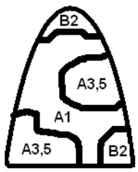
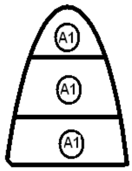
<table>
<tr><td colspan="2"><br></td></tr>
<tr><td>SpectroShade Micro</td><td>EasyShade</td></tr>
<tr><td><br><br>Complete tooth Measurement</td><td><br><br>Spot Measurement</td></tr>
<tr><td>1 shot</td><td>3 shots</td></tr>
<tr><td>Spectrophotometer</td><td>Spectrophotometer</td></tr>
<tr><td>45/0 geometry</td><td>0/0 geometry</td></tr>
</table>

**Figure 4.1** Comparison between the two CMDs.

*Color Measurement with Vita Easyshade*

Before measuring tooth color with the ES, the selected tooth was polished using a rubber cup and polishing paste for approximately 10 seconds, after which the mouth was kept closed for at least 1 minute to allow rehydrating. A disposable infection-control polyurethane barrier (Vita Infection Control Sleeves; Vita Zahnfabrik) was used on the tip of the probe, and the device was calibrated for each participant by placing the probe with a diameter of 5 mm against a calibrated block inside the machine. Measurement proceeded by placing the probe on the previously determined area of the tooth and pressing the probe switch, taking care that the probe was not moved during a measurement and/or set at a different angle. The specific area of the tooth (Figure 4.1) was determined using a caliper to establish the midposition of each point and the equal distance between the three measuring areas: cervical, middle, and incisal. Tooth colors expressed in CIE L*a*b* values and the corresponding suggested

Vita Classical shade codes were directly obtained for each position along the labial surface of each tooth.

*Color Measurement with SpectroShade*

An infection-control mouthpiece and adhesive pad were placed on the optic handpiece, and then the SS was calibrated. During measurement the mouthpiece was carefully positioned over the tooth required. The screen display permitted the operator to view the whole tooth surface under the right angle, as verified by a horizontal green line (representing accurate geometry); after this the color could be recorded. After color registration of three teeth, the results were imported into the software, which automatically outlined the CIE L*a*b* values and the derived Vita Classical shade codes for each position on each tooth. The three positions were determined by locating the software tool circle with the radius of 5 mm in the cervical, middle, and incisal area and by this way approximating the same area of color measurement as used with the ES.

*Data Evaluation*

Three different methods were used to evaluate the two sets of data from the two devices:

1. Direct comparison of the measured L*a*b* values obtained with the two instruments expressed in ΔE*. The following Equation (4.1) was used:

$$\Delta E^* = \sqrt{((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)} \qquad \text{Eq (4.1)}$$

2. In this equation the ΔL*, Δa*, and Δb* are the mathematical differences between the ES and the SS L*a*b* values. In previous studies it was shown that color differences between 2.0 and 3.7 were visually detectable under clinical conditions, but they resulted in an acceptable color difference (1, 12). Therefore, in this study clinically relevant data were obtained by counting the number of cases of ΔE*>2.0 and ΔE*>3.7, respectively.
   To ensure that the measurements of both devices were comparable, the relation between their individual measurements at the L*, a* and b* levels was evaluated by comparing the obtained L*, a*, and b* values of both instruments in a linear regression analysis.
3. As differences in the outcome of the L*a*b* measurements per spectrophotometer might be taken into account in the internal software to

suggest an appropriate color in Vita shades, the coinciding suggested color codes were also compared. In order to quantify this data, the coinciding suggested Vita codes given by the devices were changed into the L*a*b* values, by using the referential values to shade guide codes as published by O'Brien and others (12) (Table 4.1). The color differences (ΔE*) between the derived values of the Vita Classical shade guide for the two devices were also calculated according to Equation 1.

*Statistical Analysis*

Initially, the mean color differences between direct comparison of CIE L*a*b* values and the derived CIE L*a*b* values of the Vita Classical shade codes were analyzed with one-way analysis of variance (ANOVA). Analysis showed that the mean color difference was not normally distributed, and analysis based on Gauss distributions was not justified. Therefore, a nonparametric Mann-Whitney U test and Kruskal-Wallis one-way ANOVA on ranks with post hoc Tukey ($p$=0.05) were used to evaluate different data. The data sets of L*, a*, and b* values of equal specimens measured by the two different devices were subjected to a linear regression model to analyze the correlation between the obtained values of the ES and the SS. The software used for this purpose was SigmaStat 3.1 (Systat Software, Inc, Richmond, CA, USA).

**4.4 Results**

The mean CIE L*a*b* values (n=918) obtained after measuring the three locations per tooth of three teeth in each of 102 subjects with the ES and SS, respectively, are summarized in Table 4.2. The mean color difference (ΔE*) for all L*a*b* measurements between the two devices was 12.1 (3.0), and the medians and quartiles are summarized in Table 4.3.

The Vita Classical shade guide codes were converted to CIE L*a*b* parameters, and the color differences between them were calculated for both devices according to Equation 4.1 (see Table 4.1). The mean color difference (ΔE*) was 3.1 (3.3), and the medians and quartiles are summarized in Table 4.3. Mann-Whitney U test showed that the mean differences between CIE L*a*b* values and the converted CIE L*a*b* values of the Vita Classical shades were significantly different (T=1262876; $p$<0.001). Furthermore, the converted CIE L*a*b* values of the Vita Classical shades per region (cervical, middle, and incisal) are summarized in Table 4.3. Statistical analysis showed that there were no significant differences between the three measured regions (H=0.096; $p$=0.953).

The linear regression plots are depicted in Figure 4.2, and the obtained formulas and their correlation coefficients summarized in Table 4.4.

**Table 4.1** CIE L*a*b* Translation Table of the Vita Shade Guide

| Color tab | L* | a* | b* |
|---|---|---|---|
| A1 | 79.6 | –1.6 | 13.1 |
| A2 | 76.0 | –0.1 | 16.7 |
| A3 | 75.4 | 1.4 | 19.6 |
| A3.5 | 72.3 | 1.5 | 21.8 |
| A4 | 68.6 | 1.6 | 21.0 |
| B1 | 78.9 | –1.8 | 12.3 |
| B2 | 76.7 | –1.6 | 16.6 |
| B3 | 74.1 | 0.5 | 22.3 |
| B4 | 71.8 | 0.5 | 22.2 |
| C1 | 74.2 | –1.3 | 12.6 |
| C2 | 71.0 | –0.2 | 16.7 |
| C3 | 68.8 | 0.0 | 16.7 |
| C4 | 64.8 | 1.6 | 18.7 |
| D2 | 75.3 | –0.5 | 13.5 |
| D3 | 72.6 | 0.6 | 16.1 |
| D4 | 71.9 | –1.0 | 17.8 |

**Table 4.2** Mean CIE L*a*b* Values (Standard Deviations) Obtained for Nine Locations in 102 Subjects Measured with the Easyshade and the SpectroShade-Micro.

| | L* | a* | b* |
|---|---|---|---|
| Easyshade | 71.6 (2.8) | 6.7 (1.6) | 20.8 (3.0) |
| SpectroShade-Micro | 80.9 (4.2) | 0.1 (0.1) | 26.6 (5.8) |

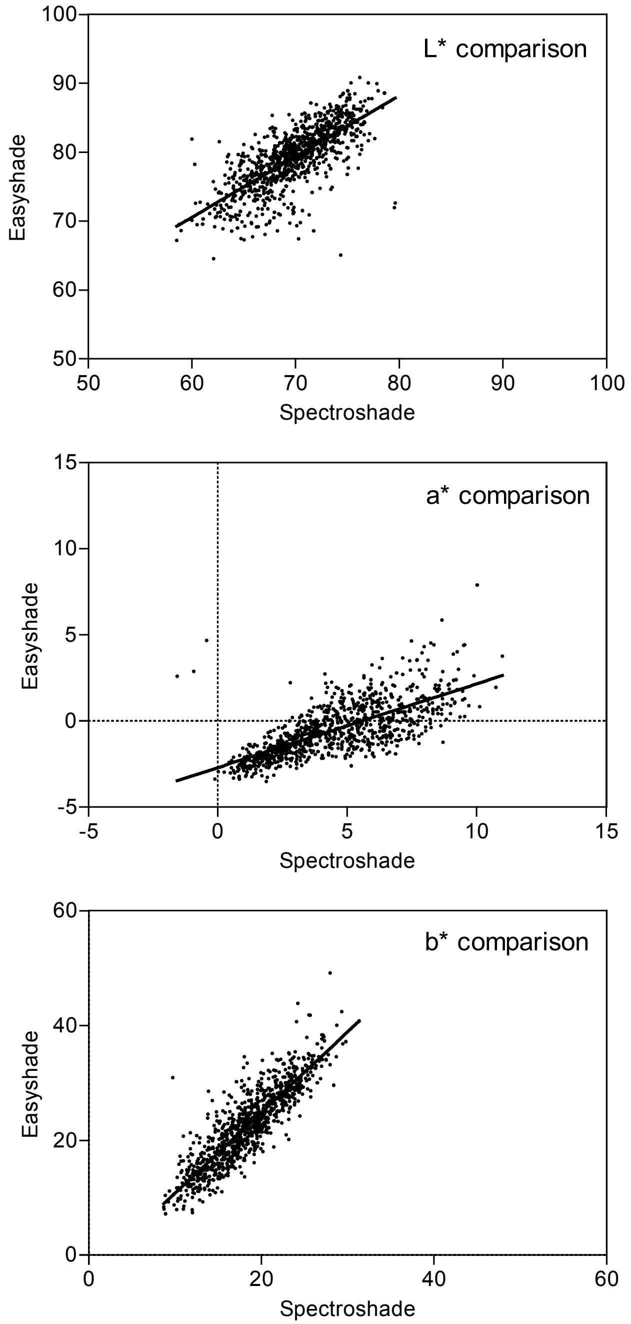



**Figure 4.2** The linear regression plots of the L*, a*, and b* values of the Easyshade and the SpectroShade obtained at 918 different points.

**Table 4.3** Means (Standard Deviations), Medians, and Quartiles of the Calculated E Values by 3 Different Evaluation Methods Obtained for 918 Measured Locations and Number of Clinical Cases with E Cut-off Values of 2.0 and 3.7.

| | ΔE*(L*a*b*) | ΔE* (Vita) | ΔE* (Vita) Cervical | ΔE* (Vita) Middle | ΔE* (Vita) Incisal |
|---|---|---|---|---|---|
| Mean | 13.7 (2.9) | 3.1 (2.1) | 3.1 (2.2) | 3.1 (2.1) | 3.0 (2.0) |
| Median | 13.9 | 3.3 | 3.2 | 3.5 | 3.2 |
| 25% | 12.0 | 1.5 | 1.5 | 1.5 | 1.5 |
| 75% | 15.5 | 4.6 | 4.6 | 4.6 | 4.6 |
| ΔE<2.0 | 0% | 40.0% | 41.0% | 40.0% | 39.7% |
| ΔE<3.7 | 0% | 55.1% | 55.4% | 53.4% | 57.0% |

**Table 4.4** Regression Formulas and Correlation Coefficients for L*a*b* Data Exchange Between the Easyshade and the SpectroShade-Micro.

| Color Coordinate | Regression Formula | Correlation Coefficient |
|---|---|---|
| L* | $L^*_{Easyshade} = L^*_{SpectroShade} * 0.88 + 17.6$ | $r^2 = 0.51$ |
| a* | $a^*_{Easyshade} = a^*_{SpectroShade} * 0.49 - 2.7$ | $r^2 = 0.50$ |
| b* | $b^*_{Easyshade} = b^*_{SpectroShade} * 1.41 - 3.3$ | $r^2 = 0.76$ |

## 4.5 Discussion

The purpose of this study was to reveal whether it is possible to compare color data between two different spectrophotometers. The results show that when L*a*b* values for the same tooth area are considered, both instruments differ to such an extent that in no case was comparable color data obtained. However, the best results were achieved when the Vita code suggestions were compared. When the suggested Vita shades were compared, in 40% of the cases both devices gave an equal suggestion, and a total of 51% resulted in clinically acceptable suggestions. The fact that 49% of the cases led to an unacceptable color measurement between the two devices can be interpreted as a poor result. However, in comparison to *visual* shade determination, where shade selections matches in only 26.6% of cases(3) this might be interpreted as a valuable contribution in dental color selection.

In the present study, the data were collected by the ES, which can be categorized as a spot-measurement device, and by the SS, which is a complete-tooth-measurement device. It has been stated that the data collected by spot-measurement devices may not be entirely accurate because of the non-homogenous shade structure of the tooth, the increased potential for tooth dehydration, and errors in image capture (16). The color measurement of the exact same spot on a curved tooth surface can also prove to be challenging, which may affect the consistency of the measurements (Figure 4.1) (17). However, one study explains that the spot measurements in particular are more accurate because measurements are made with the tip of the probe (18). In contrast, in devices such as SS, software calculations of an average value for the three tooth areas may decrease accuracy of measured color. On the other hand, in contrast to the ES, the complete tooth measurement with SS presents a topographical color map of the entire tooth in only one image, making the color readings from different areas much more consistent (Figure 4.1). The color of human teeth has a specific distribution pattern according to the different regions of the tooth surface (19) (segment relation in color from cervical to middle and incisal). These relations in color have been established by use of a digital camera, which recorded images of the whole tooth (20). Looking at Table 4.3, it is evident that the three different tooth regions do not influence the measurements taken by the two devices.

When evaluating the regression analysis between the two devices, the correlation coefficients of the L*a*b* values are independently so low that further analysis was not considered. On average, the SS assessed higher b* values than the ES (Figure 4.2), meaning that the SS determines the color of a tooth as being more yellow than the ES indicates. On the other hand, the ES constantly measured a much higher a* value for the same spot than the SS (Table 4.2), which means that the same tooth is determined as being more red with the ES. Such results could be attributable to the fact that the ES and SS have different optical geometries and that they irradiate tooth surface in different ways. The SS irradiates the tooth at an angle of 45 degrees, and the detector receives the reflected light from the tooth at the location of 0 degree. The ES irradiates the tooth surface and receives the reflected light at 0 degree. Therefore, the area of irradiation is smaller with the ES than with the SS. In previous studies it was shown that the CIE L*a*b* values, which use a smaller irradiated area, are shifted toward green and blue and to lower brightness relative to the actual color coordinates (17, 21, 22). This means that the ES should have lower L*, a* and b* values than the SS. The results of this study are in agreement with these findings for L* and b* but not for a*. This might be attributable to fact that the optical geometries are different, but this has not been studied previously. The origin of the fact that CIE L*a*b* values depend on the irradiated area, could be the wavelength-dependent edge loss that occurs by small area colorimeters and spectrophotometers. It has been shown that the edge loss for green light is approximately 85% of the edge loss for red light, and this effect could have been decreased by using larger measuring areas (17).

The corresponding CIE L*a*b* values of the Vita shade tabs originate from the study of O'Brien (12). Although other reports have described absolute values of the Vita Classical shade tabs (18, 23-25), only O'Brien actually described the results as CIE L*a*b* values. The fact remains that even different shade guides from the same manufacturer are not identical (26, 27), which means that the CIE L*a*b* values used in this present study are specific for this study only.

One can assume that one of the reasons for the findings in this study could be the fact that the evaluation of a CMD in the oral environment is very complex. Many handling errors with the different instruments could play a role in the results. In a clinical setting, the instruments can be sensitive to the patient's movement, fogging, the angle and position of the probe, different inclinations, and different shapes of the teeth. Moreover, the accuracy of the incorporated light source can change over time, influencing the measured values (8).

Although the L*a*b* values are absolute and standardized, they were not interchangeable between the two investigated devices. This means the dentist and the dental laboratory that work together are obliged to use the same device to communicate color between them. Manufacturers of these devices should consider putting more effort into standardization to improve the reproducibility of the data in clinical circumstances.

### 4.6 Conclusions

The color values (L*a*b*) of teeth, measured with two different spectrophotometers, were not comparable in this study. Therefore, the exchange of the L*a*b* values between two spectrophotometers cannot be recommended.

The two devices match each other better when the output of the tooth color is given as the closest corresponding shade tab according to the device's database. This is because the devices automatically select the closest color match from an internal database of Vita shade codes.

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# *Visual Tooth Color Measurement: Shade-guides*

*"In writing, a knowledge of spelling has nothing to do with an understanding of poetry. Equally, a factual identification of colors within a given painting has nothing to do with a sensitive seeing..  "*

***— Josef Albers***

# CHAPTER 5

*Color Coverage of a Newly Developed System for Color Determination and Reproduction in Dentistry*

## 5.1 Abstract

*Objectives:* A newly developed system for color determination and reproduction is logically arranged and systematically combines a few components to acquire its broad color range. The objective was to evaluate color coverage of human teeth with the range of the new system and to compare it with other existing systems.

*Materials and Methods:* The systems for color determination used in this study were: New system Standard (NS), New system Expanded (NE), Vita Classical (VC) and Vita 3D-Master (V3D) (Vita Zahnfabriek, Germany), Vintage Halo (VH) (Shofu, Japan), Chromascope (CH) (Ivoclar Vivadent, Lichtenstein). The tabs of all systems were measured with digital spectrophotometer, SpectroShade-Micro (MHT, Italy), and their L*a*b* values were compared with the L*a*b* values of 198 teeth (mean age = 30.10; SD = 13.15) to obtain their coverage errors. The $\Delta E^* \leq 1.6$ was established as threshold for perceptibility.

*Results*: Wilcoxon-signed rank test showed that the coverage of the teeth with the NE range was the best, as indicated by the lowest mean minimal ΔE value, followed by the NS range. Both ranges had statistically significant lower mean minimal ΔE values than all the other systems ($p > 0.01$). The percentage of $\Delta E^* \leq 1.6$ was significantly higher for NS and NE range than for the other systems ($p > 0.01$).

*Conclusions*: The newly developed color determination and color reproduction system could cover the range of human teeth, used in this study, below the level of perceptibility ($\Delta E \leq 1.6$) better than four other available contemporary systems.

## 5.2 Introduction

Color of teeth, required for the reproduction in porcelain, is most frequently assessed visually and defined descriptively by means of a code that belongs to a matching shade standard (tab). The defined shade tab is likewise a prescription for the porcelain powder selection for production of the restoration. However, many different variables can negatively influence the accuracy of tooth color reproduction in porcelain, utilized by this approach. Probably the most important variables are the eye's subjectivity and surrounding illumination type followed by the inadequate distribution and inconsistent arrangement of the shade guides within the color range of human teeth (1, 2).

The eye's subjectivity and variability of the surrounding illumination can be eliminated using electronic devices in dentistry. From five devices of different optical engineering the spectrophotometer Easy Shade proved to be the most repeatable (3) and from three spectrophotometers, an area spectrophotometer SpectroShade-Micro was the most repeatable in clinical conditions (4). The spectral data of the tooth surface can be bundled and represented as a radiance curve that can be compared with the radiance curve of the shade tab in order to define a match. Therefore, dental spectrophotometers have a database of spectral data of the shade guides incorporated. For practical reasons a three coordinate color system CIE L*a*b* is most frequently used in dental research, representing lightness (L*), redness-greenness (a*) and yellowness-blueness (b*) (5). In this color system the equal color distances correspond to equal perceptual difference. Therefore, the Euclidean distance (ΔE*) of the two color points corresponds to a perceptual difference between the two colors (6). It has been established that the spatial color difference of 1 ΔE* unit can be perceived by approximately 50% of experienced observers (perceptibility threshold) (7). Given that this perceptibility of color difference depends on the environmental conditions, different authors have established different levels of perceptibility for dental conditions ranging from ΔE* = 2.6 for denture teeth (8) to ΔE* = 1.6 for all ceramic crowns (9). In the similar trend, researchers suggest that perceptible color difference can still be accepted as a clinical optimum, defining different thresholds for acceptability, such as ΔE* = 2.7 (10) and ΔE* = 6.8 (11). However, Lindsey and Wee showed that in controlled circumstances, using computerized models and not allowing for eye adaptation, the perceptibility and acceptability of small color differences are equivalent and lower than earlier established (12).

Although the optical properties of teeth are unique for each individual and it is to expect that there are millions of different tooth colors available in the natural environment, the custom shade guide range needs to be restricted to a number that can be used in the daily dental practice. The highest number of tabs of all contemporary shade guide systems is 38 from Shofu (Menlo Park, CA, USA), but the most widely used shade guide system in dentistry, Vita Classical (Vita Zahnfabrik, Bad Säckingen, Germany) contains 16 tabs. The concept of this system involves four groups: A, B, C and D, which represent reddish, yellowish, reddish-gray and yellowish-gray teeth respectively. Each group has a small range within, which represents a simultaneous increase in pigment saturation and decrease in lightness per tab of the same group. However, the increments of these color gradients are arbitrarily arranged making it very challenging to translate the shade code of the tab into the accurate color reproduction. In order to improve the accuracy of color selection according to three Munsell's dimensions the same company introduced a new shade guide of 29 tabs, Vita 3D Master, which proved to be more uniformly and more widely distributed within the range of human teeth (13, 14). Also the image modalities of Vita classical shade guide showed possibility for improved coverage of tooth colors (15).

Dental patients of today have sky-high demands and are very well informed about the excellent esthetic results that can be achieved using porcelain. Therefore, a high number of porcelain restorations are not being accepted due to color miss-match. In order to improve the overall satisfaction and cost effectiveness in dentistry the translation of tooth color into porcelain needs to be improved. A sustainable challenge is to manufacture a new shade guide using dental porcelain in an appropriate way. This system must simplify the color reproduction process by adopting only the most necessary elements and organizing them in a logical manner with uniformed modalities that will always be traceable after color determination.

The basic color science teaches us that the full visible color range can be created by means of mixing three primary colors (red, green and blue Hues). In subtractive color mixing processes, like the color reproduction in dentistry, mixing of more different color pigments will produce a darker effect (decrease in Value) whereas the additional amount of one particular pigment in the mixture will produce more color intensity of that particular pigment (increase of Chroma). Spectral measurements in dentistry showed that mainly yellow and red Hues are clearly present in teeth (16, 17). Tooth color can also have different darkness/lightness levels and different saturation levels (16, 17). Thus, although it is logical to use only yellow and red Hues to produce color standards in dentistry, their darkness/lightness levels need to be simulated by addition of black and white pigments because of the absence of other primary colors. Therefore, it is reasonable to use red, yellow, black and white pigments for subtractive mixing of porcelain in tooth color reproduction. Furthermore, these elements should be precisely weighted in porcelain mixtures and the shade tabs should mimic the thickness of different layers of natural teeth. In doing so a database of differently composed, yet standardized, shade tabs can be created. Using a spectrophotometer a large number of accurate data from both human teeth and standardized porcelain tabs is collectable. Finally, the color matching between these tabs and teeth can be utilized and a color reproduction recipe can be obtained. In order to keep this system applicable for the visual as well as for the electronic color determination, the redundant color standards can be subsequently eliminated after the number of tabs necessary for sufficient color coverage of human teeth, has been defined.

The aim of this study was to evaluate the color coverage of a newly developed, systematically and logically arranged color determination and color reproduction system and to compare this with the color coverage of four different contemporary systems. It is expected that the new system can cover the human tooth range below the level of perceptibility for porcelain restorations $\Delta E^* = 1.6$ more precisely than the existing ones.

## 5.3 Materials and methods

*The concept*

The concept of the new color determination and color reproduction system is based upon the presence of two Hues (red and yellow), darkness/lightness level and different color intensities in teeth. It adopts those elements and combines them in a comprehensible manner resulting in layered porcelain tabs configured like natural dentin and enamel.

The elementary, highly chromatic red and yellow components of this system were established by long-term experience of dental technicians. The color intensity and lightness were manipulated by addition of white pigment in the “dentine” part of the tabs (body), whereas the “enamel” part of the tabs (translucency) was kept colorless for this study. The darkness level was manipulated by addition of middle gray (mixture of white and black pigments) in the body. The engineered mixtures of porcelain and pigments were highly chromatic in order to estimate the boundaries on the left and on the right sides of the system, see Figure 5.1. They were then diluted by addition of deliberated amounts of white pigment up to an achromatic white in the middle of the system. It was chosen to make seven dilution steps from both sides creating a total of 14 tabs (white is excluded). From this first range (bright) the second range for adult teeth (basic) and third for elderly teeth (gray) were manufactured adding the deliberated amounts of gray pigment (2% and 4% respectively) to the bright range (Figure 5.1). By this way a standard range of 42 tabs was created with a logical and uniformed arrangement. Due to a mathematical approach and reduced amount of the elements of the new system the standard range could be enlarged to a huge database of different combinations. For this study the aspect of "dentine Hue" was manipulated by mixing red and yellow chromatic versions in 50%:50% ratios creating an expanded range of 63 tabs (Figure 5.2). By addition of 2% and 4% gray to that manipulated scale the basic and gray versions of the system also became available.

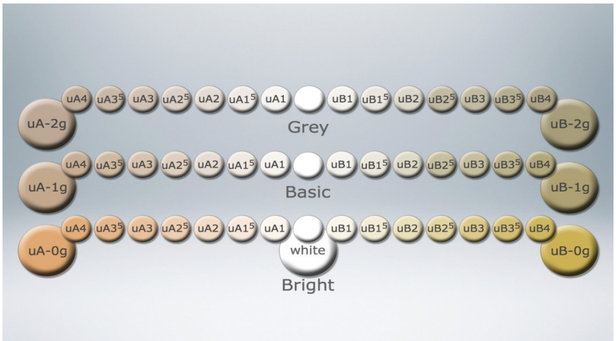


**Figure 5.1** The representation of the New color determination and color reproduction system; uA- red, uB- yellow, 0g – no gray, 1g- 2% gray, 2g - 4% gray.

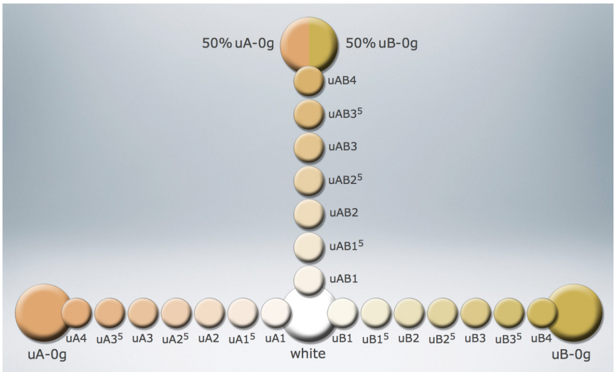


**Figure 5.2** The representation of the expanded range, mixture of red and yellow chromatic elements in 50:50 amounts.

*Production of tabs*

In order to be able to reproduce constant thicknesses of two configuring parts (body and translucent) of the tabs a Computer Aided Design (CAD) model was generated. From this model a two-part mold was produced using Computer Numerical Control (CNC) technology. It consisted of a single mold base and two covers, one for the body and the other one for the translucent layer.

An achromatic version of contemporary porcelain PLH (Wieland Dental Ceramics, Pforzheim, Germany) was mixed with pigments according to an invented formula. A substantial amount of this porcelain was mixed with a build-up liquid to a consistence of slurry, then applied to the lower concave part of the mould and closed with the first cover. The cover was kept under constant pressure allowing the porcelain excess to be expressed from the cavity. The evaporation of the residual liquid from the mixture was obtained by curing at 90 °C for 5 min. After curing the first cover was released and the controlled amount of transparent porcelain, PLH, was applied on top of the body. The curing process was repeated and the preformed tab was released from the mould. The tab was fired under vacuum at 920 °C in Multimat MCII furnace (Detrey-Dentsply, York, PA, USA), which resulted in a naturally glazed surface. To control the reproducibility of color production 10 times three tabs (total of 30) of different color mixtures were measured with spectrophotometer in three regions (cervical, middle and incisal). Their CIE L*a*b* values were almost identical with maximum 0.3 $\Delta E^*$ difference.

*Sample*

198 individuals signed in for the experiment after the explanation of the procedure. The group consisted of 76 male and 122 female individuals, ranging in age from 18 to 80 years (mean = 30.10, SD = 13.15). They were asked to clean their teeth gently with a cotton pallet and water in order to remove the pellicle and plaque accumulation of the tooth surface. They were asked to stop after 30 s to prevent dehydration of teeth. Either left or right upper central incisors were measured per person. A small to moderate tooth inclinations, small to moderate abrasions of incisal edges, tiny cracks and small-area discolorations were acceptable. The exclusion criteria were: restorations, severe abrasion, endodontic treatment, bleaching, and intrinsic and/or extrinsic tooth discolorations.

*Color measurements*

The full surface area spectrophotometer configured with 45-0° optical geometry, SpectroShade-Micro (MHT S.p.a., Verona, Italy), was used for color measurements. It was calibrated after each patient using white and green tiles integrated in the cradle of the mouth piece. Three consecutive measurements of the teeth were taken by an experienced operator with a short pause in-between in order to allow for tooth rehydration. Shade tabs of the new system and four other shade guides (Table 5.1) were mounted and measured in the phantom jaw in order to imitate the clinical situation. The obtained spectral data were translated into focal images within the software, and those images were used to depict the area on the tooth surface, which consisted only of intact tooth tissue. A circle of 3 mm diameter was positioned around the middle of each tooth and its CIE L*a*b* values were collected (Figure 5.3).

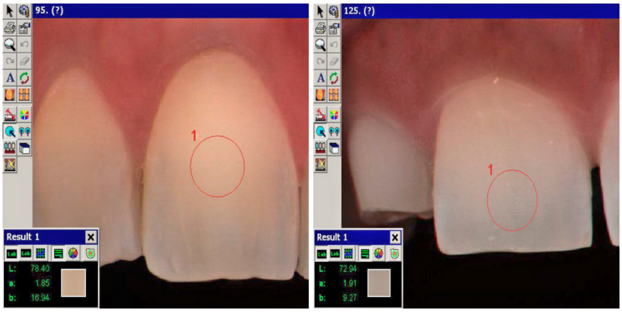


**Figure 5.3** Selection of the region for color comparison using available software.

In order to establish the number of tabs which could cover the color range of the sample with $\Delta E^* \leq 1.6$, the color differences were calculated between each tooth and each tab of all systems using the spreadsheets of Excel program. The tabs with $\Delta E^* \leq 1.6$ were considered "necessary tabs" for color match. In case when more than one tab obtained the match with the same tooth only the tab with the lowest color difference was accepted. The total frequency of matches between the tooth and "necessary tabs" per system was calculated. Therefore, the frequency of the matches per system is equal to the number of teeth that have been color-matched.

*Statistical analysis*

For each system the best color match of all teeth with a shade tab, represented by the minimal $\Delta E^*$ value, was assessed. Per system these minimal $\Delta E^*$ values were averaged and this mean can be regarded as the coverage error of the system, also expressed as coverage error index (CE). The coverage error was compared using a non-parametric test (Friedman test, post hoc Wilcoxon-signed rank tests). In addition, per system the percentage of teeth with a minimum ΔE* value of 1.6 are given. These percentages are compared between the systems using the McNemar test.

## 5.4 Results

Table 5.2 shows that from all used tabs the NS scored the best with 26 “necessary tabs” out of 42 and the frequency of 133 color matches (out of 198 teeth) established with these 26 tabs. The frequency of matches increased with NE (155), yet the number of necessary tabs did not increase accordingly, which means that more matches could be established with fewer tabs.

The minimal ΔE* values for the new system standard range (NS) and for the expanded range (NE) were established between 0.25 and 8.18 (Table 5.3). The mean ΔE* values (coverage error) of four other shade systems are also represented in Table 5.3. A Friedman test rejected the null hypothesis that the ΔE* values were equal for the systems ($p < 0.001$). Wilcoxon-signed rank tests indicated that the coverage of the NE range was the highest (as indicated by the lowest mean minimal ΔE* value), followed by the NS range ($p < 0.01$). Wilcoxon-signed rank tests further indicated that both ranges had statistically significant lower mean minimal ΔE* values than all the other systems ($p < 0.01$; see Table 5.3).

The percentage of ΔE* values ≤ 1.6 is given in Table 5.3 as well. McNemar tests showed that these percentages were significantly higher for NS and NE range than for the other systems ($p < 0.01$).

**Table 5.1** Different color determination systems used in this study.

| Color determination system | Abbreviations | Manufacturer |
|---|---|---|
| New System, standard | NS | Newly developed |
| New System, expanded | NE | Newly developed |
| Vita Classical | VC | Vita Zahnfabrik, Bad Säckingen, Germany |
| Vita 3D-Master | V3D | Vita Zahnfabrik, Bad Säckingen, Germany |
| Vintage Halo | VH | Shofu, Kyoto, Japan |
| Chromascop | CH | Ivoclar Vivadent, Schaan, Liechtenstein |

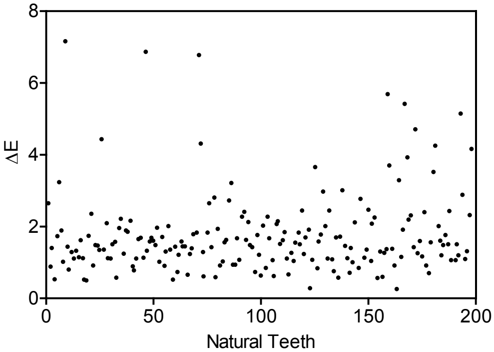


**Figure 5.4** ΔE* between natural teeth and the New color determination and color reproduction system - Standard range.

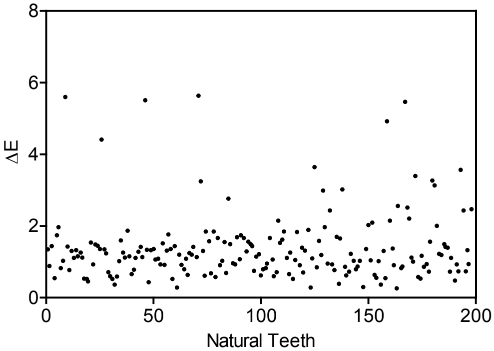


**Figure 5.5** ΔE* between natural teeth and the New color determination and color reproduction system - Expanded range.

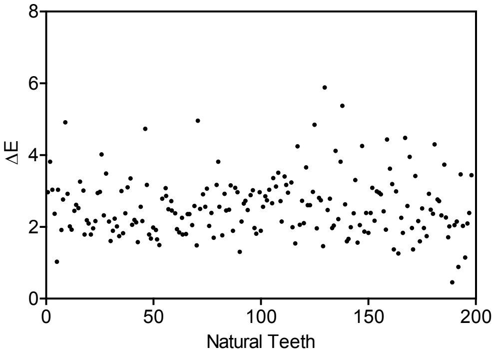


**Figure 5.6** ΔE* between natural teeth and Vita Classical.

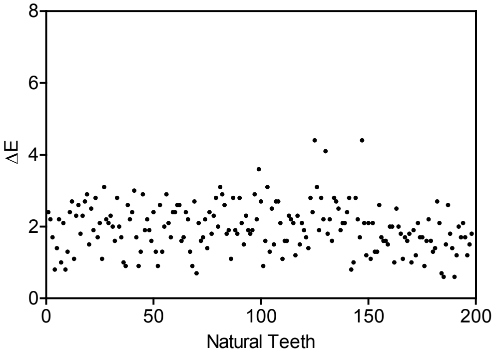


**Figure 5.7** ΔE* between natural teeth and Vita 3D Master.

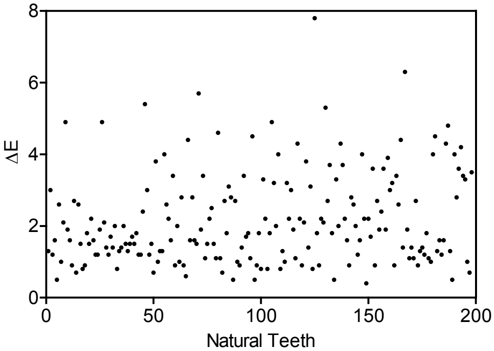


**Figure 5.8** ΔE* between natural teeth and Vintage Halo.

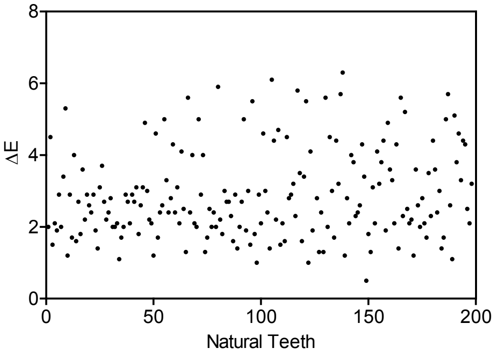


**Figure 5.9** ΔE* between natural teeth and Chromascope.

Table 5.4 shows the sort and the frequencies of NS and NE tabs that matched the teeth ($\Delta E^* \leq 1.6$) and Figures 5.4 – 5.9 present the distribution of the five different systems for color determination and one expanded version of the new system within the range of the human teeth in a graphical way.

**Table 5.2** The tabs used for color coverage, per system.

| Color system | NS | NE | VC | V3D | VH | CH |
|---|---|---|---|---|---|---|
| Total number of natural teeth used | 198 | 198 | 198 | 198 | 198 | 198 |
| Total number of tabs used | 42 | 63 | 16 | 29 | 38 | 20 |
| Frequency of matches ≤ 1.6 | 133 | 155 | 20 | 63 | 90 | 26 |
| Total number of tabs necessary for match ≤ 1.6 | 26 | 33 | 6 | 10 | 14 | 9 |

**Table 5.3** Range, mean with the standard deviation in parenthesis, and percentages ≤ 1.6 of the minimal $\Delta E^*$ values for each system.

| | Range ΔE* | Mean ΔE* ( SD) | % ΔE* ≤ 1.6 |
|---|---|---|---|
| NS | 0.3-8.2 | 1.8 (1.2) | 57.6 |
| NE | 0.3-8.2 | 1.4 (1.1) | 77.3 |
| VC | 0.5-5.9 | 2.6 (0.8) | 5.6[b] |
| V3D | 0.6-4.4 | 2.0 (0.7)[a] | 28.8 |
| VH | 0.4-7.8 | 2.2 (1.3)[a] | 41.9 |
| CH | 0.5-8.9 | 2.9 (1.3) | 11.6[b] |

a: equal characters represent non-significant difference with Wilcoxon-signed rank test ($p>0.05$)

b: equal characters represent non-significant differences with McNemar test ($p>0.05$)

## 5.5 Discussion

The reproduction of tooth color has relied on visual methods for many years now and the creation of the ideal optical properties of teeth has been solely achieved by means of trial and error, because there are no standardized guidelines for color reproduction in accordance with the determined shade standard. This has brought high costs within dental industry and often disappointments for dental professionals and their patients. The color mismatch in dentistry can be a consequence of many variables, starting from subjectivity of visual color assessment, overall inconsistency in colors and coverage error of the conventional shade tabs to human imprecision in the process of color reproduction. All those variables need to be controlled in such a way so that color determination and color reproduction in dentistry turns out to be a predictable process which will lead to less effort and better esthetic results and satisfy the needs of each dentist and each patient.

Many researchers and dental companies are striving to achieve that goal through improvement of materials and the development of innovative concepts (18, 19). A new system has been proposed in this study for the improvement of color determination and color reproduction. All composing elements of each separate tab of this system are previously measured and combined in a logical manner to get an optical appearance corresponding to the natural teeth. Therefore, when the color match with the tab is found, the color reproduction guideline should be easily reproducible.

Different studies addressed the problem of limited distribution of existing shade guides using a coverage error (CE) index (15, 20, 21) between teeth and shade tabs. CE is the index that shows the mean value of the minimal color differences among the specimens of one set (like shade tabs of one shade guide system) with each specimen of another set (like a set of natural teeth). The average of these color differences is defined as the CE. All those studies show that an increased number of tabs could cover the human dentition color range more precisely. However, the total number of tabs needed to achieve that level of precision in the dental practice has not been described before.

Different studies adopted different thresholds for perceptibility in dentistry (8-12) which were higher than $\Delta E^* = 1$ (earlier established for 50% of the observers). Since the shade tabs of the new system are made of porcelain to simulate the appearance of all ceramic crowns, in this study $\Delta E^* \leq 1.6$ was chosen as the threshold for perceptibility because it is representative for porcelain crowns (9). The results of this study (Table 5.2 and Table 5.3) show that a new, logically arranged system, can cover the teeth color range of $\Delta E^* \leq 1.6$ in 57.6% of the cases (42 tabs), and if the system is expanded in 77.3% of the cases (63 tabs), which is a significantly higher coverage compared to the other four conventional systems. These results are also illustrated in Figure 5.4 – 5.9. It should be noted that the new system included a greater number of tabs compared to other systems. However, after the establishment of the minimum number of tabs necessary for optimal color coverage this system was comparable to other systems. Table 5.2 shows that an number of only 26 tabs for standard range and 33 tabs for expanded range of the new system were necessary to get the optimal color coverage for this group of subjects. This number of tabs is comparable to V3D master (29) and VH (36) and can therefore also be recommended for use in everyday practice.

Due to systematical and logical arrangements a further expansion of this system is possible and this will perhaps result in even more precise coverage of human tooth colors. However, this will involve creating a large database of tabs and their production methods, which will not be exploitable for visual color determination. The electronic color communication is not widely adopted in dentistry yet. The dentists and dental technicians prefer to use one of the familiar systems, especially when they are continuously improving. Most probably the development of other digital systems in dentistry, such as 3D scanning of tooth shape, will stimulate the incorporation of the electronic color data in the near future.

*Future Prospects*

- The relation in color between different regions of the labial tooth surface (cervical, middle, incisal) or between different teeth should be established for a large group of people as it was done before for a smaller sample size (16, 17).
- The tabs of the new system are configured according to tooth morphology; therefore they need to be measured in different areas (like cervical, middle, incisal) to correlate the color of these areas to the tooth database. From those data also the aspect of thickness of different layers can be integrated into precise color reproduction.
- Finally, before a new concept can be adopted for general use, successful clinical data have to be demonstrated. Therefore, clinical research is necessary to show that the measured or visually assessed color match, using the newly developed system can be precisely reproduced in porcelain restorations.

## 5.6 Conclusion

Within the limitation of this study it can be concluded that the newly developed color determination and color reproduction system, which is logically and systematically arranged and simplified could cover the range of human teeth below the level of perceptibility ($\Delta E^* \leq 1.6$) better than four other available contemporary systems.

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# CHAPTER 6

## *Clinical Success of Shade-guides Arranged According to Lightness Measured Digitally*

## 6.1 Abstract

*Introduction:* The aim of this study was to objectively evaluate whether a Vita Classical shade-guide system, arranged systematically according to decreasing Lightness (L*) allows clinicians to select the correct shade match more frequently than with a conventional arrangement based on Hue groups.

*Materials and Methods:* An evaluation panel of fifty 5th year dental students independently determined the shade of tooth #11 of three patients with two differently arranged and blinded shade guides, under standardized conditions (D65 Munsell Cabin). The L*a*b* values of the chosen shade tabs were then compared to the previously determined L*a*b* values of the teeth, using a clinical spectrophotometer, SpectroShade-Micro.

*Results:* There were no statistically significant differences between the two arrangements of the shade-guides for the three patients (pp1 $\alpha$=0.754, pp2 $\alpha$ =0.638, pp3 $\alpha$=0.238). Correct color match was selected 0% of the time for tooth # 1, 12% for tooth # 2, and 50% for tooth # 3 when arranged by increasing Value.

*Conclusions:* Dental students who used the shade-guide system arranged according to an increase in Lightness were not more or less successful in selecting the correct tooth shade. The evaluation panel had more success in determining color within the perceptibility level when the conventionally arranged shade-guide was used.

## 6.2 Introduction

Dental shade-guides have been an imperative tool in the process of shade determination since the 50's. It is also a fact that dentists and dental technicians usually accept products and recommendations, sometimes without further inquiries (1); which is perhaps why although it has been stated in several previous studies that the Vitapan classical shade-guide (Vita Zahnfabrik, Bad Säckingen, Germany) only has a 6-11% coverage of the natural tooth color range (2-6), it is still used as a gold standard in dentistry today (7, 8).

The determination of color is the interplay between light, the object, and the observer, which can be done electronically or by the eye. The human visual system consisting of light sensitive nerve cells is one of the variables in perceiving a color match between a shade tab and the natural tooth. Four different kinds of photoreceptors exist: three cones and one rod. The rods (higher in quantity) than cones, are extremely sensitive to light and register brightness. Therefore it has been explained that human vision is more sensitive to changes in lightness (Value), than in the perceived color (Hue) (9). The cones are densely arranged together and each responds to the visible spectrum of light by absorbing a portion of it, e.g. red, green or blue and are responsible for color perception. Due to this close arrangement of the cones it is more difficult to discriminate color. Therefore the more peripheral rods are brought more into action in the process of color discrimination, and the critical judgment of color declines (10). This is partially why humans cannot always distinguish between small color differences and hence the electronic method of tooth color measurement was implemented to bring objectivity into the process of color matching (11, 12).

There are several systems in which the output of the color measurements can be categorized and identified quantitatively. One of the most commonly used systems is the CIE L*a*b* color system because it approximates uniformed distances between color coordinates while entirely covering the visual color space (13, 14). This system has a lightness scale, L*, from 0 (black) to 100 (white), a*, and two opponent color axes: axis a* for redness (+) and greenness (-) and axis b* for yellowness (+) and blueness (-). The output of the absolute color values, expressed as L*, a* and b* can be translated into shade guide codes, for instance A, B, C, and D codes of Vita Classical (Vita, Bad Säckingen, Germany) for clinical use.

Despite the digitalization of the process of color matching, the dental practice did not benefit directly from these developments and visual assessment is nevertheless considered to be the best approach (15). The standard allocation of the Vita shade tabs is based on four Hue groups (A1-4, B1-4, C1-4, D1-4) of increasing chroma and decreasing lightness. It is frequently suggested and generally accepted that the process of visual color determination could be more successful and predictable when shade tabs are arranged according to order of lightness (1, 16, 17). The most commonly used shade-guide system, Vita Classical, offers clinicians an order of shade tabs arranged according to lightness. Up to now there are no reports that this alternative from "lightest" to "darkest" (1) shade-guide-order helps clinicians to select the correct shade match more frequently than when the conventional arrangement is used.

The aim of this study was therefore to evaluate whether a Vita Classical shade-guide system, arranged systematically according to lightness (L*) allows clinicians to select the correct shade match more frequently than with a conventional arrangement based on Hue groups (A1-4, B1-4, C1-4, D1-4). The hypothesis was that by arranging the conventional shade guide according to an increase in lightness, a correct color match would be selected more often.

## 6.3 Materials and Methods

The mean L*a*b* values for each Vita color code of five Vitapan Classical shade-guides was determined by using a SpectroShade-Micro (SS) spectrophotometer (MHT S.p.a., Verona, Italy). The tabs were measured by removing them from the shade-guide, and placing them in a standardized manner in the position of tooth #11 of a Frasaco jaw, with a black background (Figure 6.1). The tooth color was determined according to the manufactures instructions.

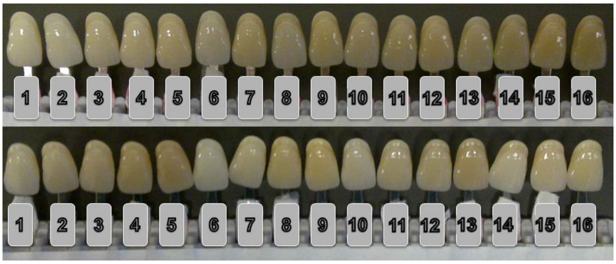


**Figure 6.1** Two arrangements for the Vita Classical shade-guide. The top row is arranged according to order of decreasing Lightness (A1, B1, B2, A2, A3, C1, B3, D2, B4, D3, D4, A3,5, C2, C3, A4, C4), and the bottom row is the regular arrangement (A1-A4, B1-B4, C1-C4, D2-D4).

**Figure 6.2** Standardized Measurements.

The tooth color of the upper right central incisor of three patients was visually and electronically determined. A written informed consent was obtained from all three patients after a full explanation of the experiment. The upper right central incisor of each patient agreed with the following criteria: (a) absence of dental caries, (b) absence of restorations, (c) no previous endodontic treatment, and (d) no previous bleaching treatment or use of whitening toothpaste. An evaluation panel of 50 fifth year dental students independently determined the shade of tooth #11 of the three patients with two differently arranged and blinded shade guides (Figure 6.2) under standardized conditions (D65 Munsell viewing box). The two shade-guides with the L*a*b* values as close as possible to the mean L*a*b* values were selected for the clinical tooth color determination. One shade-guide was arranged in the classical order A1-4, B1-4, C1-4, D1-4, while the other shade-guide was arranged in order of decreasing lightness as measured in the Frasaco jaw, e.g. A1, B1, B2, A2, A3, C1, B3, D2, B4, D3, D4, A3.5, C2, C3, A4, C4; see also Table 6.1. The students were already familiar with this shade-guide system and had been using them at the clinics at the Academic Centre of Dentistry in Amsterdam (ACTA, The Netherlands). The electronic method of tooth color measurement was carried out with a SS spectrophotometer. The color measurements of the teeth were imported into the SS software, which automatically outlined the CIE L*a*b* values and the closest average derived Vita Classical shade code for the tooth.

*Data Evaluation*

The L*a*b* values of the chosen shade tabs by the evaluation panel were then compared to the previously electronically determined L*a*b* values of the patient's teeth, using the following Equation (6.1):

Eq (6.1)

In previous studies it was shown that color differences between 2.0 and 3.7 were visually detectable under clinical conditions but they resulted in an acceptable color difference (18, 19). Therefore, in this study clinically relevant data were obtained by counting the number of cases 2.0 ≤ ($\Delta E^* \leq 3.7$ (perceptible) and ($\Delta E^* > 3.7$ (not acceptable) respectively.

*Statistical Analysis*

Using the Wilcoxon statistical analysis the shortest distances to the original values of the teeth were calculated within the acceptance ($\Delta E^* \leq 2$) and perceptibility ($2.0 \leq \Delta E^* \leq 3.7$) level and correlated to both shade-guide arrangements.

## 6.4 Results

**Table 6.1** The mean L*a*b* values of each shade tab of five different Vita shade guides.

| Shade Tab | Mean L* | Mean a* | Mean b* |
|---|---|---|---|
| A1 | 78.2 | -0.2 | 15.3 |
| B1 | 75.7 | -0.3 | 14.1 |
| B2 | 74.8 | 0.1 | 18.2 |
| A2 | 74.2 | 1.4 | 18.8 |
| A3 | 72.0 | 1.9 | 21.1 |
| C1 | 71.7 | 0.0 | 15.1 |
| B3 | 70.7 | 1.5 | 24.1 |
| D2 | 70.4 | 0.5 | 14.0 |
| B4 | 69.0 | 1.1 | 24.3 |
| D3 | 68.7 | 1.8 | 18.4 |
| D4 | 68.7 | 0.7 | 21.2 |
| A3.5 | 68.4 | 2.8 | 23.7 |
| C2 | 68.1 | 1.2 | 19.0 |
| C3 | 65.8 | 1.6 | 20.1 |
| A4 | 64.2 | 3.3 | 23.6 |
| C4 | 61.1 | 2.7 | 21.4 |

The L*a*b* values for each Vita shade tab of the five Vitapan Classical shade-guides measured in the Frasaco jaw as well as their mean are summarized in Table 6.1. The distribution amongst the chosen tabs (%) by the evaluation panel with the conventional arrangement according to Hue (H), and the proposed arrangement according to lightness (L) for each patient is shown in Table 6.2. There were no statistically significant differences between the two arrangements of the shade-guides for the three patients (pp1 $\alpha = 0.754$, pp2 $\alpha = 0.638$, pp3 $\alpha = 0.238$).

**Table 6.2** Amount of times a tab was chosen (%) with the conventional arrangement according to Hue (H) groups, and the proposed arrangement according to Lightness (L).

| Tab | Patient 1 H | Patient 1 L | Patient 2 H | Patient 2 L | Patient 3 H | Patient 3 L |
|---|---|---|---|---|---|---|
| A1 | 2% | 2% | 26% | 18% | 50% | 20% |
| B1 | 6% | 2% | 24% | 36% | 38% | 74% |
| B2 | 12% | 16% | 2% | 2% | | |
| A2 | 8% | 6% | 12% | 0% | 4% | |
| A3 | 16% | 12% | | | | |
| C1 | 20% | 12% | 28% | 18% | 6% | 6% |
| B3 | 2% | | | | | |
| D2 | 12% | 32% | 6% | 6% | 2% | |
| B4 | | | | | | |
| D3 | 6% | 8% | 2% | 2% | | |
| D4 | 2% | 2% | | | | |
| A3.5 | | 2% | | | | |
| C2 | 10% | 6% | | | | |
| C3 | 4% | | | | | |
| A4 | | | | | | |
| C4 | 0% | 0% | | | | |
| | 100% | 100% | 100% | 100% | 100% | 100% |

The electronic measurements of the teeth resulted in the following color codes: C4, A2, and A1, respectively for the patients 1, 2, and 3. According to Eq (1) and the values in Table 6.1 the matches between the electronically and shade-guide method can be evaluated in terms of, correct color (($\Delta E^* \leq 2$), clinically acceptable (($\Delta E^* \leq$

3.7), and clinical unacceptable ((ΔE *> 3.7). These results are graphically depicted in Figure 6.3.

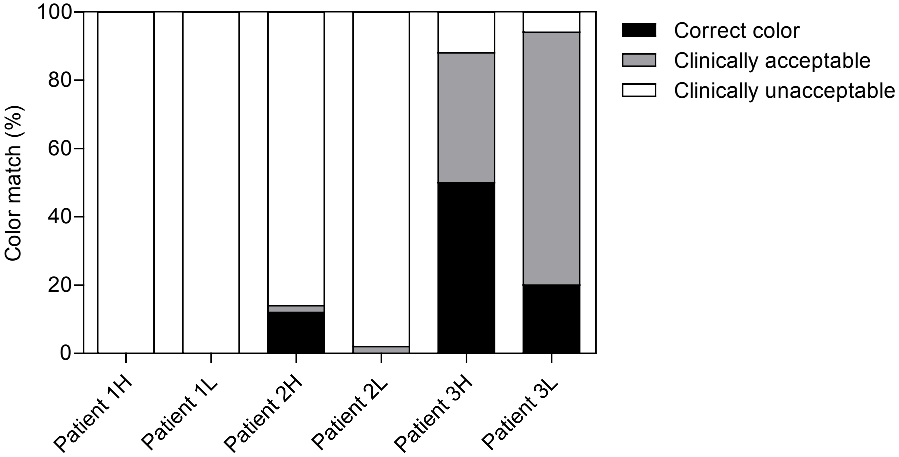


**Figure 6.3** The % of color match for the three patients, based on the two arrangements, H (Hue) and L (Lightness).

**Figure 6.4** Vita Classical tab C4 in an in-vitro set up (left) vs. tooth # 11 of Patient 1, according to SS also a shade C4 (right).

## 6.5 Discussion

When measured with the spectrophotometer, our value arrangement differs from the reported value arrangement of Vita manufacturers and other previously reported studies (1). This is probably due to fact that each shade guide consists of tabs from a different production time or different manufacturer. Those tabs are not consistent in color meaning that each spectral measurement of each shade guide could record different color values of tabs. The problem lies with the shade guides itself, because dental shade guides initially were designed to identify and communicate the color desired for prosthetic appliances (17), as opposed to an aid for the color determination of the natural dentition.

In contrast to our hypothesis, Dental students who used a Vita Classical shade-guide system arranged according to an increase in lightness were not more or less successful in selecting the correct tooth shade than when the same system was arranged according to the conventional design. Many authors claim that a shade-guide arrangement according to a logical color order would be an advantage and necessary to the user (17, 20), yet there were no statistically significant differences between the two arrangements of the shade-guides. Looking at the distribution of the visual color determinations, it is interesting to see that the majority of the evaluation panel chooses the lightest tab (B1) for the patient with color code A1. The shade most often chosen for the darkest tooth (C1) was the D2 tab. It seems out of simplicity either the darkest or lightest tabs are chosen during color determination, and that tabs ‘in between’ are easily over looked.

A color match with the electronically measured values was selected 0% of the time for tooth # 1, 12% for tooth # 2, and 50% for tooth # 3 when arranged in order of lightness. The evaluation panel had more success in determining color within the perceptibility level when the conventionally arranged shade-guide was used, whereas they could determine color within the acceptance level more often when using the value based arrangement of the shade guide in one of the three cases. According to O’Keefe *et al.* (21), using a shade-guide that is familiar and comfortable is a good idea, which could explain the results of this study; it may be that dental students and dentists are ultimately more used to using the conventionally arranged shade-guide in determining color.

The color code of patient 1 was measured as a C4, and independent of the arrangement used, no one of the group could determine a color match. This implies that some tooth colors are more difficult to match than others, regardless of the arrangement of the shade-guide. In Figure 6.4, it is evident that the natural tooth and the matching shade tab are very much different from each other, yet according to the spectrophotometer and the shade guide codes they should be a color match. This is in accordance to previous investigations where the Vita ‘C’ color code was established to be problematic in recognizing (4, 22). The translucency level cannot be determined with the shade-guide, even though it is evident that it has an influence on the color. Therefore one has to either look at the translucency degree separately, or the background color has to be standardized. The tooth of this patient was so translucent that the background color of the oral cavity was actually being measured.

## 6.6 Conclusions

The proposed arrangement according to order of decreasing lightness does not necessarily allow clinicians to select more frequently a correct shade match, than with a conventional arrangement based on Hue groups. Finally, the translucency of the tooth is an important factor that plays a role in the success of shade determination.

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# *Dental Materials: Layering and Color*

*"Make the workmanship surpass the materials"*

***— Ovid***

# CHAPTER 7

## *The Influence of Varying Layer Thicknesses on the Color Predictability of Two Different Composite Layering Concepts*

## 7.1 Abstract

*Introduction*: Optical properties of teeth are mimicked by composite layering techniques by combining a relatively opaque layer (dentin) with more translucent layers (enamel). However, the replacing material cannot always optically imitate the tooth when applied in the same thickness as that of the natural tissues. The natural layering composite system is available in two concepts: 1. Dentin (D) and Enamel (E) have the same shade but with different translucencies; 2. D and E have different shades where E is always the same high translucent shade. The objective was to evaluate the influence of varying thicknesses of E and D composites on the overall color and on the translucency for both concepts.

*Materials and Methods*: For each concept three composite brands were tested; Concept 1: Clearfil Photo Bright (Kuraray), Herculite XRV Ultra (Kerr), Venus Diamond (Heraeus Kulzer); Concept 2: Amaris (VOCO), CeramX Duo (DENTSPLY) and Point4 (Kerr). Two specimens of each shade (A1, A2, A3) per composite were made of standardized thicknesses with a poly-acrylic mold and Teflon cover, making 36 specimens of wedge-like dimension. The L*a*b* values were measured three times against a white and black background (n=216). Student t-tests revealed significant levels between the average ΔE* values of the 3 areas for each composite.

*Results*: Statistically significant differences ($p<0.05$) were found for all thicknesses and for all shades between the concepts. Concept 2 showed greater variations in ΔE* with increased thicknesses.

*Conclusions*: Concept 2 composites are more sensitive to layer thickness changes, which implicates less predictability in a daily clinical routine.

## 7.2 Introduction

The increased demand for esthetic restorations motivates the dentist to develop special skills and knowledge of dental restorative materials. Restorations in the anterior region of the mouth especially, should meet high esthetic demands. This can be achieved with resin composites as long the proper materials and techniques are applied. However, when working with resin composites it is important that a predictable satisfying result can be achieved within a reasonable time frame. Yet the materials that are available are quite technique-sensitive and may demonstrate more variation in the esthetic performance, especially when experience is lacking or scarce. To gain more of an understanding of the esthetic outcomes of these restorative materials one should first study the composition and anatomy of natural teeth.

The optical properties of a natural tooth are remarkable due to its internal buildup of organic and inorganic material at a molecular level. The two outermost layers of the crown of a tooth are enamel and dentin, and they play a major role in tooth color. One important esthetic property of natural teeth is their degree of translucency. This is related to how hydroxyapatite minerals in the organic matrix of the tooth scatter shorter wavelengths of light. The density of enamel decreases as we move away from the surface of the tooth and it is characterized by weak absorption over the visible wavelength (1). Its crystalline prismatic structure gives rise to the relative amount of light transmitted (translucency) through the enamel. As the thickness of enamel gradually decreases from the incisal one-third of the tooth, towards the cervical one-third, as does its translucency (2). It has been defined that the natural enamel is anisotropic (3) with respect to the orientation of the enamel rods and hence its optical properties, which becomes less translucent with increasing thickness (2, 4). Therefore, the chroma of natural dentin becomes less visible through thicker enamel, whereas the value increases. In contrast to enamel, restorative materials such as dental composites and porcelain are isotropic materials, which exhibit a different optical behavior. Increasing the thickness of these materials will reduce the influence of the background on the shade and is accompanied by a decrease in the value (5, 6). Hence, it is doubtful that the comparable thicknesses of the composite layer can mimic the optical properties of natural enamel and dentin. Ideally, if the anisotropy factor of the restoration material was equal to that of the natural tooth, then there would be no visible difference between them (7). This is why it is important to select restorative materials that can achieve accurate shades by having similar levels of translucency to that of a natural tooth.

The color distribution along the tooth surface has been studied repeatedly (8, 9) and it is generally agreed that teeth are polychromatic. According to O'Brien et al., there are both statistically and clinically significant color differences between the 3 regions of a natural tooth and this information is beneficial when esthetic restorations are required.

In order to attempt to replicate the "tooth-model" situation, contemporary composite systems are available in different layering concepts. There are both 2- and 3-layer techniques. It has been frequently reported that the ideal and simpler technique is the 2-layer approach (3, 10), which can be subdivided into two basic concepts: 1. Dentin and Enamel have the same shade for a particular shade-code (corresponding with Vita Classical guide) with variable translucency levels; 2. Dentin and Enamel have different shades where Enamel is universal and always highly translucent (Figure 7.1). The shade codes of the latter mostly correspond with the Vita shading system (Vita, Bad Säckingen, Germany) but sometimes employ a uniquely developed shade concept.

Even when the correct restorative material and shades are selected, errors in the optical appearance of the restoration may still occur due to difficulty of controlling the thickness of each layer. Ideally a material should possess similar optical properties to that of dentin and enamel. To that end manufacturers are introducing different layering concepts, which are aiming to embrace the nature and mimic the tooth tissues in all their optical characteristics. The objective of this study is to evaluate the influence of variations in the thickness of the Enamel and Dentin layer on the shade distribution and translucency of two different layering concepts.

## 7.3 Materials and Methods

For this study a comparison was made between the composites of six different commercially available brands, which use a layering restorative concept. An evaluation of combinations of different thicknesses of each layer was performed to determine the influence it has on the resulting color and translucency for the two different concepts.

*Concept 1*

The Concept 1 is based on the Classic layering concept. Concept 1 is the more traditional method of natural layering where the E and D are of coinciding shades (Fig 7.1). The composites tested for Concept 1 were: Clearfil Photo Bright (Kuraray), Herculite XRV Ultra (Kerr) and Venus Diamond (Heraeus Kulzer). For all these brands three combinations of enamel and dentin shades were produced coinciding with the shades A1, A2 and A3 of the VITA® Classical color guide (Vita, Bad Säckingen, Germany).

*Concept 2*

The Concept 2 which was evaluated for this study is based on the Modern two layered concept. This newer layering concept combines opaque dentin shades with always the same highly translucent enamel shade. The composites tested for Concept 2 were: Amaris (VOCO), CeramX Duo (DENTSPLY) and Point4 (Kerr). For all these composite brands three different dentin colors coinciding with the A1, A2 en A3 of the VITA® Classical color guide were chosen always in combination with the one same transparent shade provided by the manufacturer.

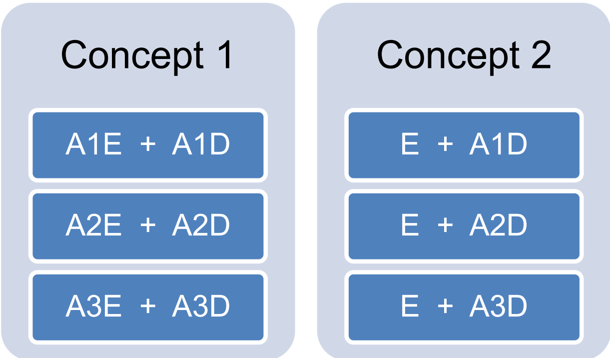


**Figure 7.1** Layering concepts 1 and 2.

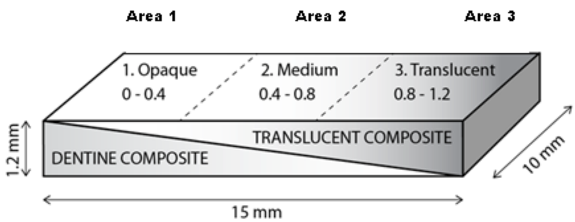


**Figure 7.2** The poly-acrylic mold used for production of the specimens, with its dimensions.

*Specimen Preparation*

In order to standardize the thicknesses of the composites a special poly-acrylic mold with a Teflon cover was designed in order to produce specimens of wedge-like dimensions in the following dimensions: Height increasing from 0 to 1.2 mm, a Width of 10 mm, and a Length of 15 mm (Figure 7.2). A total of 36 specimens (two specimens per shade A1, A2 and A3 per composite) were produced.

Prior to application, the composites where slightly heated in warm water reservoir in order to decrease its viscosity and make it easier to apply into the molds. First the dentin composites were applied into the mold and the Teflon cover was used to press against it into the right dimensions. While holding under pressure, the composite was light cured for 20 s with a halogen curing light (intensity of 500 $mW/cm^2$). The Teflon cover was then removed, and light curing was repeated. Hereafter the more translucent (or enamel) composite was directly applied in the same manner without any medium or bonding in between as the composite layers were still chemically reactive. Each specimen was kept in a dark and humid surrounding of 37°C in an incubator where no damage could occur.

*Color Measurement*

Color measurement of each specimen was carried out using a spectrophotometer, SpectroShade (MHT S.p.a., Verona, Italy) (11) under standardized conditions against both a black and a white background. The color system used for the output of the color measurements was the CIE L*a*b* color system because it approximates uniformed distances between color coordinates while entirely covering the visual color space (12, 13). This system has a lightness scale, L*, from 0 (black) to 100 (white), and two opponent color axes: axis a* for redness (+) and greenness (-) and axis b* for yellowness (+) and blueness (-). For each measurement, the color was repeated three times (after which the average was calculated) and in between these measurements, the SpectroShade was calibrated according to the manufacturer's instructions. The SpectroShade software automatically divided the specimen into three equal surfaces, from opaque to translucent, each with their own given L*a*b* values. Each specimen was measured six times in total, three times against a white- and three times against a black background, a total of 216 measurements were made.

*Data Evaluation and Statistical Analysis*

The L*a*b* values represent the average of spectral data collected from the three different areas of each specimen, along the wedges: Area 1. Opaque (Op) = 0-0.4 mm, Area 2. Medium (Me) = 0.4-0.8 mm and Area 3. Translucent (Tr) = 0.8-1.2 mm (Figures 7.2). The clinical relevance was set at ΔE* ≥ 3.7 (acceptability threshold) (14-16).

The translucency for each color combination was determined using the following Equation (7.1) for the translucency parameter (TP):

$$TP = \sqrt{((L_W^* - L_B^*)^2 + (a_W^* - a_B^*)^2 + (b_W^* - b_B^*)^2)} \qquad \text{Eq (7.1)}$$

W is the coordinate against a white background, and B against a black background. By comparing the TP values of each of the areas of the specimens it is possible to evaluate the influence of the different layer-combinations on the resulting translucency.

Using the L*a*b* values obtained from each measurement, the ΔE* was calculated according to the following Equation (7.2):

$$\Delta E^* = \sqrt{((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)} \qquad \text{Eq (7.2)}$$

For the statistical analysis the software SAS version 9.2 was used to facilitate the different ANOVA tests, and the student t-tests which were performed to analyze the relationship between the average ΔE* values of the different specimens. ANOVA tests revealed the influence the different layer thicknesses had on the TP between the different brands of composites. Student t-tests revealed the significance levels between the average ΔE* values of the three areas 1. Op, 2. Me and 3. Tr, for each composite.

## 7.4 Results

*Effect of layer thickness on the change in color $\Delta E^*$*

Table 7.1 shows the change in color, ΔE*, between each of the different combinations of the three areas 1-3 of the specimens, for each of the composite brands, against a white- and black background. Statistically significant values ($p<0.05$) were found when comparing the different brands for areas ΔE* 1-3 and ΔE* 2-3 against a white background as well as for all the ΔE* values for the specimens against a black background. The gray highlighted areas in the table are the ΔE* values above the acceptability threshold of 3.7.

When looking at the Classical layer concept 1 (Clearfil Bright, Herculite XRV and Venus Diamond) compared to the Modern layer concept 2 (Amaris, CeramX and Point4) there were statistically significant differences in the average ΔE* values for both concepts per area combination, against both black and white backgrounds, as shown in Table 7.2.

**Table 7.1** ΔE* per composite brand for the different combinations of the specimen areas (Areas 1-2, 2-3, 1-3). The values highlighted in gray are ΔE* values above the acceptability threshold (3.7).

| | | All Shades, Black Background | | | All Shades, White Background | | |
|---|---|---|---|---|---|---|---|
| Composite | Concept | ΔE* 1-2 | ΔE *2-3 | ΔE* 1-3 | ΔE *1-2 | ΔE *2-3 | ΔE* 1-3 |
| Clearfil | 1 | 1.4 | 1.8 | 1.6 | 2.8 | 2.4 | 2.1 |
| Herculite | 1 | 0.7 | 2.8 | 3.1 | 2.0 | 2.6 | 2.1 |
| Venus | 1 | 0.4 | 2.1 | 1.9 | 1.2 | 2,5 | 1.5 |
| Amaris | 2 | 1.7 | 3.4 | 4.9 | 3.0 | 4.6 | 6.2 |
| CeramX | 2 | 2.8 | 5.6 | 8.3 | 3.3 | 5.4 | 7.6 |
| Point4 | 2 | 1.8 | 4.1 | 5.6 | 3.2 | 4.9 | 6.9 |

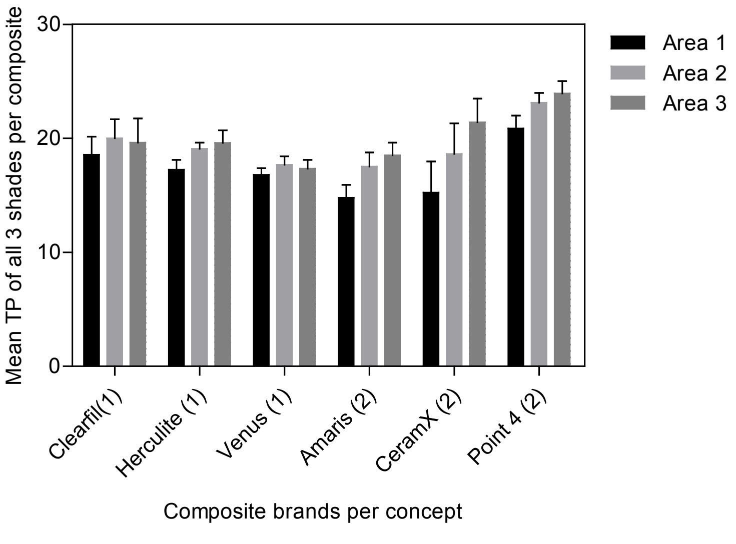


**Figure 7.3** The average translucency parameter per composite for areas 1, 2 and 3.

**Table 7.2** P-values for the differences between the two concepts in average ΔE* values for each area.

| Black | | White | |
|---|---|---|---|
| | P-value | | P-value |
| ΔE* 1-2 | P=0.004 | ΔE* 1-2 | P=0.017 |
| ΔE* 2-3 | P<0.001 | ΔE* 2-3 | P<0.001 |
| ΔE* 1-3 | P<0.001 | ΔE* 1-3 | P<0.001 |

**Table 7.3** Complete overview of the translucency parameters (TP) for each composite, at each area for all three shades A1, A2, A3.

| | | A1 | | A2 | | A3 | |
|---|---|---|---|---|---|---|---|
| Composite | Area | Mean | SD | Mean | SD | Mean | SD |
| | **1** | 18.1 | 0.7 | 20.1 | 1.5 | 17.5 | 1.5 |
| Clearfil Bright | **2** | 19.7 | 0.2 | 21.7 | 0.8 | 18.6 | 1.8 |
| | **3** | 19.5 | 1.2 | 21.5 | 1.1 | 17.9 | 2.6 |
| Herculite | **1** | 17.4 | 0.2 | 16.3 | 0.9 | 18.0 | 0.1 |
| | **2** | 19.0 | 0.0 | 18.7 | 0.8 | 19.6 | 0.4 |
| | **3** | 19.5 | 0.2 | 19.0 | 2.0 | 20.3 | 0.8 |
| Venus Diamond | **1** | 16.8 | 0.3 | 16.3 | 0.3 | 17.3 | 0.7 |
| | **2** | 17.4 | 0.1 | 17.1 | 0.1 | 18.6 | 0.7 |
| | **3** | 17.0 | 0.3 | 16.8 | 0.0 | 18.3 | 0.4 |
| Amaris | **1** | 13.5 | 0.1 | 15.5 | 0.8 | 15.4 | 0.9 |
| | **2** | 16.3 | 0.3 | 17.6 | 1.2 | 18.7 | 0.4 |
| | **3** | 17.9 | 1.4 | 18.0 | 0.5 | 19.7 | 0.3 |
| Ceram X | **1** | 12.6 | 0.5 | 15.7 | 0.0 | 19.3 | 0.1 |
| | **2** | 16.2 | 0.9 | 19.1 | 0.2 | 22.6 | 0.0 |
| | **3** | 19.5 | 0.9 | 21.9 | 0.5 | 24.3 | 0.2 |
| Point 4 | **1** | 21.0 | 0.3 | 19.5 | 0.2 | 22.0 | 0.0 |
| | **2** | 23.5 | 0.0 | 22.0 | 0.1 | 23.8 | 0.1 |
| | **3** | 23.7 | 0.9 | 23.1 | 1.0 | 25.0 | 0.5 |

*Effect on the increase in translucency (TP) for the different layer combinations*
Table 7.3 shows a complete overview of the translucency parameters (TP) for each brand, at each area for all three shades. Figure 7.3 graphically depicts the average TP of all three shades, per composite, for areas 1, 2, and 3.

ANOVA tests revealed the influence the different layer thicknesses had on the TP between the different brands of composites. Statistically significant differences were found for all shades together (P=0.0015) for shade A1 (P=0.0002) and A2 (P=0.0285). Yet for shade A3 (P=0.2758) and there was no significant difference between the different brands.

## 7.5 Discussion

In esthetic dentistry a natural layering technique is required to get high esthetic results comparable to the natural dentition (17). With time, different concepts have been developed from this natural layering technique and different authors have different names for them: 'anatomic stratification' (18), 'natural layering concept'(19). These authors suggest that the thickness of enamel and dentin should be copied in an anatomically correct way to obtain a good esthetic result. This is based on the fact that there is an obvious difference between enamel and dentin, as enamel will transmit 70% of ascending light where this value is only 53% for dentin (2, 20). Besides for the different names given to this technique, also different concepts have been derived from the natural layering concept in an effort to mimic the characteristics of enamel and dentin more precisely.

Due to the high translucency of the enamel substitutes of these natural layering composite concepts, the variation in their thickness greatly influence the overall lightness (value) of the restorations, making them look more gray, which patients find unacceptable (6). Using a composite system with the same shade yet in two different translucencies is less sensitive for visible shade differences with varying layer thickness; and is more accepted by the patient. When layered, the Concept 1 composites were in general less translucent than the Concept 2 composites and this does not change with an increase in thickness (Figure 7.3). Of all composites tested, the translucency of Venus Diamond appeared to be the least sensitive for variation in layer thicknesses for all tested shades between each of its three areas.

Past studies have shown that the outer layer (enamel) of Concept 1 composites has more influence on the final color than the inner layer (dentin) (21, 22). Kamishima *et al.* showed that translucency of composite drops exponentially with an increase in composite thickness (23). Since the outer layer (enamel) is usually used as a thin covering layer it can be expected that the little change in the thickness of this layer could substantially influence the total color (24).

Friebel *et al.* has shown that the absorption coefficient values for dentin are higher than that of enamel (7), giving support to the fact that enamel composites must be more translucent. The study explained that the more translucent enamel colors of composites, with their lower scattering properties, resulted in an increased brightness of the dentin composites, but looking more carefully at their methodology it can be seen that they too only study the Concept 1 composites. Vichi *et al.,* also looked at the clinical efficacy of Concept 2 composites (21), and their study was in agreement with the results of the present study as they concluded that overall color depends on the thickness of each layer, and its predictability is technique sensitive.

As the natural tooth with its enamel and dentin consists of a layered material comprised of different optical properties, it is preferable to reproduce this layered structure using two optically different restorative materials (21, 22), which coincides more with the idea of Concept 1 and with the results of this present study. Statistically significant differences ($p<0.05$) in L*, a* and b* values were found for all thicknesses and for all shades between the two composite concepts using a black background. The Concept 2 composites showed more often $\Delta E^*$ above the acceptability threshold of 3.7 with increased thicknesses, than the Concept 1 composites.

A previous study by Ostervemb *et al.* (25), compared *in vitro* the esthetic result of various Concepts 1 and 2 composites. They concluded that 91 to 96% of the restorations were esthetically acceptable either way, and hence no difference between the two layering-concepts was found (25). However, an Extended Visual Rating Scale for Appearance Match was used to determine whether a restoration was acceptable, unlike the current study where the acceptability of the concepts was measured objectively. We found that the thickness of different composite layers influences the level of opacity of a restoration and hence its final shade. The magnitude of the layers should therefore be previously determined to create a predictable result (26), and according to the present study, this can be more successfully achieved with Concept 1 composites.

The limitation of this study was that we limited the tests to the Vita A hue groups, and no results are available for the other B, C, D groups. A previous study (27) similarly evaluated the translucency parameters of various resin composites for both

Vita hue groups A and B and found a distinct trend where both have similar translucency values.

The specimen preparations in the present study were made with the help of self-designed molds to mimick nature, where enamel varies in thickness over the tooth surface. Previous studies on measuring translucencies and layering concepts (7, 21, 28) have used circular specimen discs and layered them on top of each other. The wedge-like molds used in this study simulated the anatomical layering of the tooth and made it possible to make polychromatic oblique layers (8, 9).

## 7.6 Conclusion

In clinical cases the final color of a restoration will be influenced by even small thickness changes of those materials as statistically significant differences were found for all thickness combinations for all three shades between both concepts. Concept 1 composites are less sensitive to color change when layer thickness increases and may therefore offer more predictable results as it is difficult to control the layer thicknesses in a clinical situation.

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# CHAPTER 8

## *Color Management of Porcelain Veneers: Influence of Dentin and Resin Cement Colors*

## 8.1 Abstract

*Introduction*: Porcelain veneers have become an interesting treatment option to correct the shape and color of anterior teeth. Because of their limited thickness and high translucency, achieving a good color match is influenced by several variables. The aim of this work is to investigate the influence of natural dentin and resin cement colors on the final color match of porcelain veneers.

*Materials and Methods*: A preselected shade tab (A1) was chosen as the target color for a maxillary central incisor, and its color parameters (L*a*b*) were measured using a digital spectrophotometer (SpectroShade, MHT). Nine dentin colors (Natural Die Material, Ivoclar Vivadent) representing a wide range of tooth colors were used to prepare resin replicas of the maxillary central incisor with a standard preparation for porcelain veneers. The prepared porcelain veneers (IPS Empress Esthetic, A1, 0.6 mm thick, Ivoclar Vivadent) were cemented on the resin dies (nine groups of dentin colors) using seven shades of resin cement (Variolink Veneers, Ivoclar Vivadent). The L*a*b* values of the cemented veneers were measured, and ΔE* values were calculated against the preselected target color (A1). ΔE* greater than 3.3 was considered as a significant color mismatch detectable by the human eye.

*Results*: The seven shades of resin cement had no significant influence on the final color of the veneers, as the measured ΔE* values were almost identical for every test group. On the other hand, the color of natural dentin was a significant factor that influenced final color match. None of the 63 tested combinations (nine natural dentin colors and seven resin cement colors) produced an acceptable color match.

*Conclusions*: Thin porcelain veneers cannot mask underlying tooth color even when different shades of resin cement are used.

## 8.2 Introduction

Porcelain veneers have become an interesting treatment option for patients seeking better esthetics in the anterior region. Patients prefer these restorations because they require minimally invasive preparation of the tooth structure compared to other treatment options. The biocompatibility and translucency of porcelain materials provides not only healthy margins but also superior esthetics (1). Preparations of porcelain veneers are primarily limited to enamel and the thickness of these restorations does not usually exceed 0.6 mm. In such a thin section, porcelain veneers are supposed to mask the underlying color of the tooth structure in addition to providing the desired shade (usually a lighter shade as requested by many patients) (2). Retention of porcelain veneers depends on establishing a chemical bond between the silica phase of the porcelain and the resin cement provided by silane coupling agents. After bonding, porcelain veneers gain sufficient strength to resist the applied chewing forces. Nowadays, resin cements are supplied in different shades to enhance final color match. Some manufacturers also supply special opaque resin cements to mask the underlying dark or discolored dentin (3). Human dentin has a wide range of natural colors that vary among patients as well as ethnic groups (4). The color of natural dentin may influence the final shade match of thin and transparent porcelain veneers, leading to shade mismatch compared with the selected target color (Figure 8.1 (Left)). To assist the clinician in predicting the final color of porcelain veneers, resin dies can be fabricated using a wide range of colors representing those of natural dentin. During try-in of porcelain veneers on colored resin dies, the clinician can predict the final color of the restorations (Figure 8.1 (Right)). However, there are no general guidelines on the interaction between natural dentin color, shade of resin cement, and their interaction on the final color of porcelain veneers after cementation of the restorations. Other external factors, such as diverse illuminating conditions during color assessment, human perceptual subjectivity, and the limitations of classical shade guides, can all lead to errors during color measurement procedure (5). On the contrary, different types of digital tooth-color measuring devices, which operate independently of most external factors, have shown excellent performance and good repeatability under clinical circumstances (6, 7). Therefore, they can also be used to reduce human error during the color-evaluation process. Spectrophotometers collect spectral data from reflected light and translate these data into the three color coordinates (L*, a*, and b*) established by the Commission Internationale de l'Eclairage (CIE). According to CIE L*a*b* system, these three coordinates can be defined out of three original color stimuli, X, Y, and Z, to compensate for the human standard color space. In the L*a*b* color space, the distances between color stimuli are uniform and independent of light intensity (8). Due to this uniformity, the difference between two colors can be mathematically calculated with a Equation (8.1) known as ΔE*, which is expressed as a positive value:

$$\Delta E^* = \sqrt{((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)} \qquad \text{Eq (8.1)}$$

Moreover, the degree of human visual perceptibility for materials can also be expressed with the magnitude of ΔE*, which has been evaluated by several studies (9-14).

Most authors have adopted ΔE* values between 2.6 and 3.7 as the threshold for acceptability in their clinical research indicating acceptable color match, whereas higher values indicate color mismatch between the restoration and the tooth structure. The aim of this work was to evaluate the influence of natural dentin color and different shades of resin cement on the final color match of porcelain veneers prepared using the presson technique and measured with a spectrophotometer.

## 8.3 Materials and Methods

*Production of dies*

A student teaching model with interchangeable resin teeth was selected, and the maxillary right central incisor was prepared for porcelain veneer whereby a 0.6-mm-depth cutter bur (868 A. 314.018, Brasseler) and a tapered rounded fissure diamond (5850.314.016, Brasseler) were used to achieve equal depth over the whole buccal surface. The preparation was polished with two polishing cups (Polishing set 4313 A VW Dialite II, polishing no. 9652204060, Komet) and two polishing disks (Sof-Lex, no. 1981SF and 2382C, 3M ESPE). The depth of the preparation was controlled by means of silicone (Provil Novo Putty regular, Heraeus Kulzer) relined with a light-consistency material (Xantopren, Heraeus Kulzer). The impression of the prepared tooth was then cut through longitudinally with a scalpel, and the thickness of the Xantopren lining was measured in the cervical and middle areas with a digital caliper. Difference in preparation depth of 0.2 mm or less was considered acceptable (Figure 8.2). The prepared tooth model was duplicated using a silicone mold (Versyo-sil, Heraeus Kulzer) and reproduced using nine colors of natural dentin die material

(Natural Die Material Kit, Ivoclar Vivadent). Ten dies per color were produced, softly polished, and kept in a black box to maintain color stability.

*Production of veneers*

The prepared tooth model was reproduced in gypsum (Vel mix Stone, Kerr). The stone model was waxed up with Nawax compact (Yeti Dental Produkte) following application of two layers (30 µm thick) of die spacer material (Die spacer, Kerr). The die spacer was used to create a uniform cement space for homogenous thickness of the try-in resin cement pastes. The thickness of the wax model was controlled using the buccal guide/reference of the silicone index (Provil Novo, Heraeus Kulzer) (Figure 8.2). Both the wax cast and tooth preparation were scanned in a 3D scanning device (Zenotec, 3Shape D 200, Wieland), and 30 transparent polymethyl methacrylate (PMMA) veneers were produced using CAD/CAM (Zeno 4030, Wieland). The thickness of the PMMA veneers was measured with a digital caliper (Digimatic 500-311, CD 15-D 7227045, Mitutoyo) and when necessary corrected to 0.6 ± 0.2 mm thickness. The PMMA veneers were then imbedded and pressed using a high-temperature injection molding technique to press single veneers from ceramic ingots according to the manufacturer's instructions (IPS Empress Esthetic, Ivoclar Vivadent). Ceramic ingots of the required target color (A1) were used accordingly, and the veneers were finally self-glazed.

*Application of adhesive resin*

Seven colors of adhesive resin (Variolink Veneer, Ivoclar Vivadent) were used to test the influence of resin cement color on final color match of porcelain veneers. Resin cements were directly applied from the original syringes according to the manufacturer's instructions. Before each new application and color measurement, excess cement was wiped off and the external surface of the veneer was cleaned with alcohol.

*Color measurement*

Color measurement took place in a phantom mouth to imitate the conditions of the oral cavity. Color parameters of the target color (A1 shade tab) and of each colored dentin die were measured three times with a spectrophotometer (SpectroShade Micro, Handy Dental MHT) to establish the median values (Figure 8.3). After application of resin cement, the veneers were seated on the resin dies under 50 N pressure mimicking clinical conditions. Color parameters of each cemented veneer were measured three times, and L*a*b* values of the middle area were obtained. Five veneers (n = 5) were cemented for each combination of resin cement color with different colored resin dies (63 test groups). The spectrophotometer, SpectroShade, has a built-in aiming feature (represented by a horizontal green line) that enables reproducible positioning of the device perpendicular to the facial surface of the tooth. To ensure equal measurement conditions, it was necessary to record adequate tooth frame. The frame consisted of a small part of the gingiva above the tooth neck, both adjacent teeth, and a part of the black background (mouth). The device is equipped with a D65 light source (6,500 K) that is transformed into monochromatic light. Data were stored in a proprietary image file format that was used to create detailed CIE L*a*b* values. Differences in color between the target color (A1) and the cemented veneers were expressed in ΔE* values and calculated with the MHT analysis software (SpectroShade; dental software version 2.41). Synchronization module was used to correct for eventual die displacements, and three area measurements were used to attain color. Color data from the same middle area were always attained.

**Figure 8.1** (Left) The target color of porcelain veneers selected by the patient (shade tab in most cases) could not be reproduced simply by selection of a matching porcelain color as the final color of the cemented veneers could be influenced by the color of underlying dentin. (Right) To help the clinician predict the final color of porcelain veneers, it is recommended to cement porcelain veneers of the required color on resin dies that match the color of natural dentin.

*Color analysis*

Descriptive statistical analysis was performed for the CIE L*a*b* values including the median and standard deviations for each group using a spreadsheet program (Excel 5.02, Microsoft). Color difference between mean values of each test group and target color (A1) were calculated using the ΔE* formula. ΔE* values below 2.6 were registered as clinically indistinguishable (perfect color match), values between 2.6 and 3.3 as clinically acceptable, and values above 3.3 as clinically not acceptable (mismatch). In this study, ΔE* values between the target color and veneers were used to interpret the findings. The threshold for perceptibility and acceptability are clinically relevant.

**Figure 8.2** The prepared central incisor. Preparation depth was evaluated by relining a silicone template of uncut tooth structure. The same template was used as a guide during waxing of the stone casts.

**Figure 8.3** Measuring L*a*b* values of the veneers using a digital spectrophotometer. The device uses a calibrated daylight source with constant positioning feature and corrects for light reflectance on glossy surfaces.

## 8.4 Results

For every dentin color, the obtained L*a*b* values were almost identical using each of the seven colors of resin cement, indicating that resin cement color had no significant effect on final color match of the cemented porcelain veneers. These values were averaged for each dentin color. The color of natural dentin represented by the nine colors of resin dies had a significant influence on final color match, as there were large shifts in the calculated ΔE* values between the different tested groups. None of the tested combinations of resin cement color with different natural dentin color produced an acceptable color match with the target color (A1), as the lowest calculated ΔE* value (7.5) was achieved for the lightest natural dentin color (ND1). The degree of color mismatch was more influenced by darker shades of natural dentin dies (ND8 and ND9) compared to lighter shades (ND2 to ND7). These data are summarized in Figure 8.4.

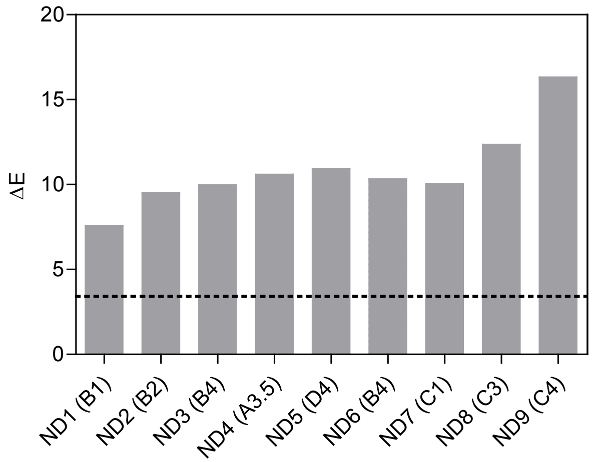


**Figure 8.4** ΔE* values of porcelain veneers (A1) cemented on different natural dentin colors (ND) and the target color (A1). The dotted line indicates level of clinical acceptance. Corresponding classical shade guide codes are listed.

## 8.5 Discussion

Internal factors that influence the final appearance of porcelain veneers are related to the interaction between optical characteristics of the ceramic used and to the color of residual tooth structure. Due to the possibility of obtaining absolute and repeatable color data with spectrophotometers, the influence of different internal variables on the overall color of porcelain veneers could be accurately investigated (15). In the present study, it was observed that obtained data had a very small standard deviation (1% to 2% of the mean values), indicating accuracy and repeatability of color measurement procedure. Different shades of resin cement did not influence the overall color of porcelain veneers, as the color parameters of the seven shades used with one colored resin die were almost identical. This could be related to the limited thickness (30 μm) and translucency of resin cement under the cemented veneers not being effective in creating color shifts. Under reflected light conditions, the color of the underlying tooth structure was more dominant than the color of resin cement. Confirming this finding was the evidence that color parameters of the translucent resin cement were almost similar to that of high chroma resin cement. Similar findings were reported by Vichi and his coworkers when they evaluated the masking potential of resin cements under ceramic crowns supported by post and core (16). External or internal shading of porcelain veneers was previously investigated using ceramic tints to correct for minor discrepancies in shade match (17).This method produced significant color shifts, but it was effective for only lighter shades of porcelain veneer. On the other hand, internal shading may interfere with proper seating of porcelain veneers, while external shading could impede the characteristic translucency of these restorations. In a previous study, a significant correlation was reported between the masking power of porcelain veneers and their opacity, as more opaque ceramics were more successful in blocking the underlying color of the tooth structure. Even though the veneers had a dense alumina core, it was also reported that the calculated color differences ($\Delta E^*$ values) were beyond the clinical acceptance level, which is in agreement with the present study (18). The problem of color matching porcelain veneers appears directly related to the limited thickness of these restorations and to the characteristic translucency of dental porcelain. The compromise between a better masking opaque ceramic and the need for translucency at incisal margins could be solved by incorporating two types of ceramic in one restoration. This double veneering technique produced promising results for all ceramic zirconia restorations and could also be incorporated for laminate veneers, which deserves further investigation (19). The bulk of the veneers could be fabricated using presson opaque ceramic ingots of the required shade, and the incisal edge could be layered using transparent enamel porcelain. Controlling final color relying on the optical properties of porcelain could generate more reliable effects compared to other previously discussed techniques (20). The influence of the number of porcelain firings has been reported (21-23). Authors found significant color changes due to repeated firings. However, these color changes were clinically acceptable. The press-on technique does not subject the veneers to thermocycling used in the manual layering technique. Furthermore, the influence of thickness, shade, and translucency of porcelain on the overall color of all-ceramic restorations have been previously evaluated (24-28). Authors revealed that changes in thickness, shade, or translucency of the porcelain can produce visually perceptible color changes in all-ceramic restorations. Similarly, the influences of different underlying layers on color of ceramic restorations have also been studied (28-31)(28-31). These studies described that the color of thin veneers could be perceptibly influenced by the interaction of all these variables.

## 8.6 Conclusions

Within the limitations of this study, thin porcelain veneers cannot mask the underlying tooth color even when different shades of resin cement are used.

## 8.7 References

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# *Dental Materials: Color Stability*

*"Orange is the happiest color"*

***— Frank Sinatra***

# CHAPTER 9

## *Evaluation of the Color Stability of Pink Resin Composites*

## 9.1 Abstract

*Introduction:* Pink colored composite restorations are an alternative technique for masking the effects of gingival recession. The purpose of this *in vitro* study was to evaluate the effect of immersion media on color stability of four different brands of pink resin composites.

*Materials and Methods:* Forty-eight identical preparations were made in the cervical area of denture teeth and restored with the four resin composites (Venus Pearl® (shade: GUM, Heraeus Kulzer, Hanau, Germany), Epricord™ (shade: Gingival P1, Kuraray Noritake Dental Inc. Okayama, Japan), Revolution Formula 2 (Kerr USA, California USA) and PermaFlo® Pink (Ultradent Products, INC, Utah, USA). Three specimens of each resin composite were immersed into four groups of immersion media: coffee, wine, orange juice (OJ), and water. A dental spectrophotometer (Crystal Eye, Olympus) was used to evaluate the color changes at baseline, one day, one week, three weeks and seven weeks. Specimens were stored in the media for 7 h/day, and brushed every hour. Fisher's exact tests were used to determine if the color change of the resin composite specimens was statistically significant.

*Results*: Color change in immersion media ranked in the same increasing order for Epricord™ and Pearl®: water < OJ < wine < coffee; Revolution Formula 2™: water < OJ < coffee < wine; and for PermaFlo®: OJ < water < wine < coffee. Coffee was observed to result in the greatest $\Delta E^*$, whereas OJ consistently showed the lowest $\Delta E^*$ values for all materials.

*Conclusions:* Significant change in color can be seen between the different pink composites after what would be equivalent to eight months of exposure to the immersion media in the clinical setting. Also the pink composites stored in water show a clinically detectable color difference ($\Delta E^*>2.7$) by the end of the study.

## 9.1 Introduction

Cervical lesions (Class V) have been found to be present in 85% of the population (1) and providing an esthetic restoration can prove to be a clinical challenge. The esthetic appearance of such cervical lesions can be quite disturbing for many patients, especially when combined with the recession of the surrounding gingival tissue. Although the progression of gingival recession may be asymptomatic, these areas still concern patients esthetically, and lead them to seek dental care. Patients become aware of the apical migration of the gingival tissues (2), which results in the teeth appearing longer and unattractive (3).

Due to the many advances in adhesive dentistry, a more cost-effective and less invasive way to treat gingival recession is to restore the surface with composite (4). Tooth-colored resin composite Class V restorations have shown promising results for restoring the effects of gingival recessions (5). The more understanding there is of the natural tooth morphology, the more success is achieved with the esthetic outcome. However, tooth-colored resin composites are also used in locations where there was once gingiva. The teeth still appear excessively long (2), therefore reducing the esthetic value of the restoration. To solve this problem gingival-shaded resin composites have been used (1, 6). This has resulted in an increase in availability of pink colored resin composites provided by several manufacturers. Aside from the functional advantage of a minimally invasive treatment to cover exposed tooth structure, the esthetics of the natural gingival tissue is restored albeit the irreversible process of the gingival recession.

Though there have been studies in the past evaluating the success, adhesion and esthetic outcome at the marginal gingiva of tooth-colored resin composites (5, 7) and that of pink gingival-colored resin composites (1, 6, 8); no study has evaluated the color stability of pink resin composites. While the pink resin composites solve the esthetic challenge due to gingival recession, it is important to determine whether the color remains stable overtime despite the use of different immersion media. The aim of this study is to evaluate the color stability of four different pink resin composites when immersed into different immersion media. There were two null hypotheses for this study: 1) The type of immersion media does not influence the color of the pink resin composite; 2) The color stability of all four pink resin composites is the same over time.

## 9.3 Materials and Methods

*Specimen preparation*

Forty-eight identical preparations were made in the cervical area of denture teeth (Portrait ™ IPN® Dentsply Trubyte) and restored with four different brands of pink resin composites (Table 9.1), two of which were pink resin composites: Venus Pearl® (shade: GUM, Heraeus Kulzer, Hanau, Germany) and Epricord™ (shade: Gingival P1, Kuraray Noritake Dental Inc. Okayama, Japan) and two were pink flowable resin composites: Revolution Formula 2 (Kerr USA, California, USA) and PermaFlo® Pink (Ultradent Products, INC, Utah, USA). Each preparation had a diameter of 3 mm and a depth of 1 mm. All four materials were placed after etching (Ultra-etch, 35% phosphoric acid, Ultradent Products, INC, Utah, USA), and bonding (Optibond solo plus, Kerr USA, California, USA); and light cured (Bluephase C8, Vivadent, Schaan, Liechtenstein) all according to their manufacturer's instructions. All specimens were polished in the same manner to imitate the clinical situation with rubberized abrasive finishing burs (Jiffy® Polishers, Ultradent Products, inc, Utah, USA) as directed by the manufacturers.

**Table 9.1** Material properties according to manufacturer's data.

| Name | Manufacturer | Type of resin | Composition | Filler size | Vol% |
|---|---|---|---|---|---|
| PermaFlo® Pink | Ultradent | Flowable | Bis-GMA, and TEGDMA | 0.7 µm | 60 |
| Revolution Formula 2 | Kerr | Flowable | Bis-GMA and TEGDMA | 0.6 µm | 60 |
| Epricord™ | Kuraray | Microhybrid | Urethane tetramethacrylate, and TEGDMA | 0.6 µm | 80 |
| Pearl® | Venus | Nanohybrid | Crosslinker monomer TCD-DI-HEA and UDMA | 5 nm - 5 µm | 59 |

Bis-GMA: Bis-phenol-A-diglycidyl ether methacrylate; TEGDMA: Triethylene Glycol Dimethacrylate; UDMA: 7,7,9-trimethyl-4, 13-dioxo-3, 14-dioxa-5, 12-diazahexadecane-1, 16-diyl-bis-methacrylate; TCD-DI-HEA: Bis-(acryloyloxymethyl) tricyclo (5.2.1.02,6) decane

*Immersion media*

Red wine (bag-in-a-box wine, Carlo Rossi Cabernet Sauvignon California "Reserve" wine), orange juice (Florida's Natural®, Citrus World Inc, Florida, USA), coffee (café Estima Blend™ Starbucks Coffee Company, USA) and tap water (control) were used in this study. Three specimens of each resin composite were immersed in 250 ml of each of the immersion media, and stored at 37 $^{0}$C in an incubator. The immersion schedule was made based on the daily drinking habits of the average American (9). Hence the specimens were immersed in the immersion media for seven hours per day, for seven weeks. During the seven hours the specimens were removed from the immersion media, rinsed with water, and brushed with an electric toothbrush (Oral-B complete CrossAction, The Procter and Gamble Company, Ohio, USA) for 10 seconds at every hour, before being placed back into the incubator. The immersion media were refreshed every seven days.

*Color Measurement*

Color measurement of each restoration was taken using a dental spectrophotometer, Crystaleye® (10) (Olympus, Tokyo, Japan) under standardized conditions. The spectrophotometer was calibrated according to the manufacturer’s instructions. The color system used for the output of the color measurements was the CIE L*a*b* color system (11, 12). This system has a lightness scale, L*, from 0 (black) to 100 (white), and two opponent color axes: axis a* for redness (+) and greenness (-) and axis b* for yellowness (+) and blueness (-). Baseline color measurements were taken before immersing the specimens into the immersion media. The color measurements were then taken at an interval of one day, one week, three weeks and seven weeks. Prior to color measurement, the specimens were removed from the immersion media, rinsed with tap water, and brushed with an electrical toothbrush for 10 seconds. For each measurement the color of the restoration (diameter of 3 mm) was captured three times, after which the average was taken.

*Data evaluation and Statistical Analysis*

Using the CIE L*a*b* values obtained from each measurement, the color difference values ΔL*, Δa*, Δb* and ΔE* were calculated using the following Equation (9.1) (12):

$$\Delta E^{*} = \sqrt{((\Delta L^{*})^{2} + (\Delta a^{*})^{2} + (\Delta b^{*})^{2})} \qquad \text{Eq (9.1)}$$

For the color evaluation of this study a ΔE* value of 2.7 was considered as the acceptability threshold (10, 13). Fisher's exact tests were used to determine if the color change of the resin composite specimens was statistically significant. The statistical tests were two-sided at the 5% level of significance without adjustment for multiple testing.

## 9.4 Results

The average ΔE* value for each of the four materials, for the four individual immersion media, at the final measurement was calculated (Figure 9.1). The color change in the immersion media ranked in the same increasing order for Epricord™ and Pearl®: water < orange juice < red wine < coffee. The color change ranked differently for Revolution Formula 2™: water < orange juice < coffee < wine; and also differently for PermaFlo®: orange juice < water < wine < coffee. Additionally, the mean ΔE* values for each material immersed into the four immersion media over time were calculated (Table 9.2). Looking at the mean ΔE* after the full seven weeks; coffee caused the highest mean change in color (ΔE* =8.5) for the material PermaFlo®. Fisher's exact test was used to further analyze the data, providing the percentage of specimens showing a noticeable change in color (ΔE* > 2.7) for each of the immersion media over a period of time (Table 9.3). Considering only the immersion media, there was a clear influence of the medium on the color change of the material. According to the statistical analysis, at Day 1, Weeks 1 and 7 there were significant changes in color between the different immersion media. The immersion medium that caused the most color change was coffee, as it resulted in a noticeable color change (ΔE* > 2.7) for all the specimens of all four materials, as early as the first week of immersion. The Fisher's exact test for the four resin composites (Table 9.4) shows the percentage of specimens showing a noticeable change in color for each resin composite separately over time. The statistical analysis revealed that all the materials behaved similarly up to the $7^{th}$ week in terms of color stability. However at the $7^{th}$ week there is a statistically significant difference in noticeable color change (ΔE* > 2.7) between all four materials for each of the immersion media. Furthermore, though not statistically significant, it can be seen that all of the Revolution Formula 2™ specimens showed noticeable (ΔE* > 2.7) color changes from the third week onwards.

**Table 9.2** Mean ΔE* values and standard deviation in parenthesis for each material for each of the immersion media over time.

| | | Day 1 | Week 1 | Week 3 | Week 5 | Week 7 | Total |
|---|---|---|---|---|---|---|---|
| Epricord™ | Coffee | 7.1 (2.5) | 7.4 (1.6) | 11.9 (4.4) | 12.9 (5.4) | 14.7 (4.4) | 8.4 (3.7) |
| | Wine | 2.6 (2.5) | 4.4 (2.5) | 4.8 (2.6) | 4.7 (2.1) | 7.6 (0.4) | 4.8 (2.0) |
| | Orange | 0.9 (0.5) | 3.3 (0.4) | 3.6 (0.4) | 4.3 (0.3) | 4.6 (0.6) | 3.3 (0.4) |
| | Water | 1.1 (0.4) | 2.7 (0.3) | 3.9 (0.1) | 3.6 (0.2) | 3.6 (0.6) | 3.0 (0.3) |
| PermaFlo® | Coffee | 7.4 (0.6) | 8.2 (0.5) | 9.1 (1.7) | 8.9 (1.6) | 8.9 (1.5) | 8.5 (1.2) |
| | Wine | 3.4 (0.4) | 4.8 (1.2) | 6.2 (1.2) | 5.9 (1.0) | 5.8 (1.4) | 5.2 (1.0) |
| | Orange | 1.3 (1.0) | 2.4 (0.9) | 2.8 (0.9) | 2.5 (0.8) | 2.3 (0.6) | 2.2 (0.8) |
| | Water | 2.3 (0.7) | 4.4 (1.6) | 5.3 (0.2) | 4.9 (0.4) | 4.2 (0.9) | 4.2 (0.8) |
| Revolution F2 | Coffee | 2.7 (0.7) | 5.4 (1.4) | 5.7 (0.4) | 5.8 (0.7) | 5.8 (0.9) | 5.1 (0.8) |
| | Wine | 2.8 (1.1) | 5.8 (1.4) | 7.7 (0.6) | 6.8 (1.3) | 8.9 (0.7) | 6.4 (1.0) |
| | Orange | 1.9 (0.2) | 3.1 (0.1) | 3.6 (0.3) | 3.8 (0.6) | 4.3 (0.4) | 3.3 (0.3) |
| | Water | 1.4 (0.4) | 2.1 (0.9) | 2.7 (0.4) | 3.1 (0.5) | 3.4 (0.2) | 2.5 (0.5) |
| Pearl® | Coffee | 5.5 (0.6) | 6.5 (1.6) | 9.3 (1.0) | 8.5 (1.3) | 9.7 (1.1) | 7.9 (1.2) |
| | Wine | 2.7 (1.0) | 4.8 (2.2) | 6.7 (0.2) | 8.0 (0.2) | 7.1 (0.3) | 5.9 (0.8) |
| | Orange | 1.6 (1.1) | 2.6 (1.3) | 3.0 (1.8) | 2.8 (1.9) | 3.0 (1.4) | 2.6 (1.5) |
| | Water | 0.6 (0.6) | 2.4 (0.9) | 2.7 (0.7) | 2.5 (0.5) | 2.6 (0.2) | 2.2 (1.1) |

**Table 9.3** Percentage of all specimens showing a noticeable change in color (ΔE* >2.7) for each immersion media over a period of time.

| | **Day 1 *** | **Week 1*** | **Week 3** | **Week 5*** | **Week 7*** |
|---|---|---|---|---|---|
| Coffee | 11/12 (92%) | 12/12 (100%) | 12/12 (100%) | 12/12 (100%) | 12/12 (100%) |
| Wine | 7/12 (58%) | 10/12 (83%) | 11/12 (92%) | 11/12 (92%) | 12/12 (100%) |
| Orange | 1/12 (8%) | 6/12 (50%) | 9/12 (75%) | 8/12 (67%) | 7/12 (58%) |
| Water | 1/12 (8%) | 6/12 (50%) | 9/12 (75%) | 10/12 (83%) | 10/12 (83%) |

* Statistically significant according to Fisher's exact test.

**Table 9.4** Percentage of specimens showing a noticeable change in color (ΔE* >2.7) for each material separately over a period of time.

| | Day 1 | Week 1 | Week 3 | Week 5 | Week 7* |
|---|---|---|---|---|---|
| Epricord™ | 4/12 (33%) | 9/12 (75%) | 11/12 (92%) | 11/12 (92%) | 12/12 (100%) |
| PermaFlo® | 7/12 (58%) | 9/12 (75%) | 11/12 (92%) | 10/12 (83%) | 10/12 (83%) |
| Revolution F2 | 4/12 (33%) | 9/12 (75%) | 12/12 (100%) | 12/12 (100%) | 12/12 (100%) |
| Pearl® | 5/12 (42%) | 7/12 (58%) | 8/12 (67%) | 8/12 (67%) | 8/12 (67%) |

* Statistically significant according to Fisher's exact test.

## 9.5 Discussion

In general, color stability is an important parameter for modern resin-based filling materials (14, 15). Due to the scarce number of studies overall on pink resin composites, there is little information concerning this issue. Only one study reported a three-year clinical evaluation of a gingival-colored compomer (16), yet the color evaluation was subjective and based on a questionnaire on the patient's satisfaction of the color match. Of the four resin composites in our study, the two flowables, Revolution Formula 2™ and PermaFlo® behaved differently with regard to color stability when compared to the two resin composites Epricord™ and Pearl®. PermaFlo® and Revolution Formula 2™ contain fillers with an average particle size of 0.7µm and 0.6 µm respectively; have low film thicknesses, superior polish-ability, and are methacrylate-based. Epricord™ and Pearl® however, have particle size distributions of 5 nm-5 µm and 0.6 µm, respectively and are urethane based. The present results are surprising because previous studies (17, 18) found that tooth colored resin composites with similar compositions to that of Epricord™ and Pearl® were less stain-resistant than resin composites with a bis-GMA resin matrix, due to their lower water absorption and solubility characteristics. It has also been discussed in the past that the volume percentages of resins correlate with greater levels of discoloration (19-21). In this study Epricord™ which is urethane based, and has the highest percentage volume of resins, proved to have low color stability. Looking further into why pink resin composites have lower color stability than tooth colored resin composites with similar compositions, we looked into the color stability of the pink pigment. As there are no studies discussing the color stability of pink resin composites, we looked at the behavior of pink pigments in prostheses. The greater color change in the red pigments in our study is consistent with a previous investigation (22) showing that the red pigment undergoes significant color changes. All the pink resin composites in our study showed noticeable color changes ($\Delta E^* > 2.7$) even in tap water already after the 3rd week. This is in agreement with Kiat-amnuay *et al.,* who claimed that all pigments but the red remained stable in tap water. It is possible however that water obtained in different locations could contain different chemical and mineral proportions that could affect color stability.

As previously mentioned, the immersion schedule of the present study was based on the daily drinking habits of the average American. The average American drinks 3.1 cups of coffee per day (9). It takes an average of 20 minutes to drink one cup, so per day an average coffee drinker has their teeth and any present restorations exposed to coffee for approximately a period of one hour p/d. The setup of this study was aimed to replicate the habits of an average coffee drinker. This explains why the specimens were brushed after one hour, every hour, as this is equivalent to one day of coffee drinking (three cups x 20 min). Therefore seven weeks of measurements approximates eight months of exposure of the pink restorations to coffee in 'real time'. Looking at these results we can say that pink resin composites have an unacceptable change in color after eight months of exposure to coffee. Previous studies on the discoloration of tooth colored resin composites have conducted evaluations only after a total of 24 hours (18), one week (23), 4 h p/d for one week (24), 7 h p/d for three weeks (25), and 24h p/d for 60 days (14). The strength of the present study is that the drinking habits of the patient are taken into consideration and a clinical situation was simulated. Due to this clinical simulation, we can look at the trends in the results, and say that a clinician should be cautioned against using Epricord™ on a patient who is a coffee drinker; and for example not to use Revolution Formula 2™ on a patient who is mainly a wine drinker.

Since there is no gold standard $\Delta E^*$ threshold yet for clinical color acceptability, in this study the $\Delta E^*$ for clinical acceptance was set at a level of 2.7, based on recent clinical studies (10, 13). This is a lower value than in past studies (26, 27) where acceptability thresholds were determined with inadequate instruments for tooth color measurement which led to a substantial amount of edge-loss error (26) and tooth dehydration (27). Also, in these past studies a very small area of tooth structure was used in color measurements (27), thus making results perhaps less valid (28).

There are different ways in which discoloration of resin composites can be induced. The discoloration induced by immersion media though, occurs internally and depends on: the contents of the resin composite, the light-curing unit used for polymerization, the duration of light-curing; and the surface roughness due to polishing techniques (18). In this study, the polishing technique and the light curing process was standardized for all specimens. However there may have been other limitations concerning the methodology of this study. Even though we tried to mimic the clinical setting, an *in vivo* assessment would have been required to actually evaluate the long term behavior of pink resin composites. Also the frequency of brushing was set to once a day in real time, but in reality patients may brush their teeth more frequently and the use of toothpaste was not taken into consideration either. It should also be taken into consideration that the specimens immersed into coffee, wine and orange juice formed a biofilm like layer which meant that all specimens had to be brushed anyway for correct color measurement. Orange juice consistently had a lower $\Delta E^*$ value, and in the case of PermaFlo® even more so than the control (tap water). Orange juice has a lower pH value than water, and therefore its acidity can cause damage to the surface integrity of the specimen especially during the mechanical movements of brushing. This could limit the validity of the results because this erosion may have been the reason why there were very low $\Delta E^*$ values for the specimens immersed into orange juice.

## 9.6 Conclusions

Within the limitations of this study, the following conclusions were drawn:

1. Among the immersion media, orange juice consistently showed the lowest $\Delta E^*$ values for all materials, whereas coffee showed the highest $\Delta E^*$ values.
2. There is no significant change in color between the four different pink resin composites until the 7th week, which is equivalent to eight months of exposure of the resin composites to the immersion media.
3. There is color change in the pink resin composites stored in water by the end of the study that is clinically evident $\Delta E^* \geq 2.7$.

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# CHAPTER 10

## *General Discussion, Summary and Future Prospects*

*"If we knew what it was we were doing, it would not be called research, would it?"*
***–Albert Einstein***

In 1931 Dr. B. Clark wrote in The Dental Digest: "Almost every writer in the field of dental esthetics and dental ceramics makes mention of the many difficulties encountered in the reproduction of tooth color..". Yet, the research for this thesis started in 2007, 76 years after Clark's words, and still this statement remains valid and still is the manner at which almost all scientific papers begin on this subject. The esthetic appearance of the natural tooth is comprised of many different factors making the tooth a specifically difficult object to determine its color. The subjective perception of color with the human eye is prone to a great many different types of illusions and variables. The fluctuating surrounding illumination and environment at which the human eye, the observer, perceives the color of the natural tooth does not make the process any easier. There are also many ways in which the artificial restorations, made out of dental materials, differ from the natural internal build-up of the human dentition. To end with, the final acceptance or rejection of these dental restorations are almost always based on the observer's response. In short, this is the color problem in dentistry. These influences on tooth color perception, determination and reproduction were considered within the scope of this thesis. This, in order to increase predictability and knowledge on tooth color science, recognizing the difficulty in single tooth color matching in the anterior region and the trends in esthetic dentistry where art is meeting science.

The general introduction in **Chapter 1** provides background information on tooth color science, lays out the color problem in dentistry and describes the aims of this thesis. In color research, after measuring the reflectance of two objects, the calculated CIE L*a*b* values can be compared between measurements. ΔE* is a measure of this color difference, providing a quantitative representation of the perceived color difference between a pair of colored objects under a given set of experimental conditions. ΔE* has been used extensively in dental research, but there is a lack of agreement on what values of ΔE* are considered to be the perceptibility and acceptability thresholds.  That is why this thesis begins in **Chapter 2** with a systematic review on perceptibility and acceptability thresholds in tooth color perception. The results of this research showed that a new prospective controlled (clinical) study is necessary to quantify a color difference threshold in order to be able to interpret all the aspects related to color research in dentistry and provide a consensus for dental researchers. It was concluded that at the moment most clinical studies refer to the same few papers that have attempted to determine perceptibility and acceptability thresholds from three decades ago under *in vitro* conditions. Such ΔE* values are derived from the CIE L*a*b* color space which are measured electronically with tooth color measuring devices (CMD). There are many different CMDs available for dental clinicians and researchers and therefore before further research was further conducted, **Chapter 3** looked at five different CMDs in order to study their overall performance in terms of repeatability and reliability. It was concluded that when compared to colorimeters and digital cameras, a spectrophotometer can be seen as the gold standard of color measuring devices in tooth color determination. Hereafter two different spectrophotometers were studied in **Chapter 4** in order to evaluate whether the dental clinician can communicate with the dental technician if different spectrophotometers are being used. After the previous conclusion that spectrophotometers are the most repeatable instruments for determining color, the aim was now to see whether data can be exchanged between measurements taken with two different spectrophotometers. It was concluded that the exchange of L*a*b* values between two spectrophotometers cannot be recommended; yet the two devices match each other better when the output of the tooth color is given as the closest corresponding shade tab according to the device’s database.

Even though we have entered an era of digital dentistry, where CMDs have not only been extensively studied, but are also available to the dental clinician, still classical shade-guides are the method of choice in the daily practice. Seventy-six years ago the aforementioned article by Clark stated that the main problem was that a system of color measurement and color specification was lacking. The current commercial shade-guides are still inadequate. However, it would be impractical and commercially impossible to construct a shade-guide covering the entire field of natural tooth color and at the same time differentiating between the body and enamel colors. Furthermore it was acknowledged that a simple method for the measurement and specification of the colors found in teeth was necessary by means of an equipment. Now that we have systems for color measurement that are digital, it is also no longer impractical to construct a digital database with the range of the tooth color space, which is what was evaluated in **Chapter 5**. This chapter acknowledged the problem with contemporary shade-guides, which is that they inadequately cover the tooth color space. It was concluded that the newly developed color determination and color reproduction system, which was logically and systematically arranged and simplified could cover the range of human teeth below the level of perceptibility ($\Delta E^* \leq 1.6$) better than four other available contemporary systems. Before such a new concept can be adopted for general use though, successful clinical use has to be demonstrated in the future. Therefore, clinical research is necessary to show that the measured or visually assessed color match, using the newly developed system, can be precisely reproduced in porcelain restorations. After this study, I was able to see what Clark meant in 1931 with ‘a new and improved shade-guide system being commercially impossible’ as this may be still the very reason why even today the inadequate shade-guides are still being used. It is not only important to research a new shade-guide system, but to also research how to improve the use of the more traditional shade-guide systems already being used. This was investigated in **Chapter 6**. In this chapter the Vita Classical shade-guide system was arranged systematically according to Lightness ($L^*$) in order to test whether clinicians can score more often a correct shade match visually than with a conventional arrangement based on Hue groups. This was based on the theory that the human visual system contains more rods which are more sensitive to light and register brightness. The conclusion of this study was that dental clinicians who used the shade-guide system arranged according to an increase in Lightness were not more or less successful in selecting the correct tooth shade. Although, it was not evaluated within the scope of the study, the observation was made that when the shade tabs were arranged from light to dark, the process of color determination was quicker for the clinician. The evaluation of ease and time would be variables to be tested in the future in a similar study.

Even before Clark, as early as 1924, Dr. Victor Sears wrote an article on “The Art side of Denture Construction’. This article recognized that translucency has an important effect on the eye. Color is known to have three dimensions, hue, value and chroma, but the fourth dimension should be recognized as translucency, especially with teeth as it plays a big role in color matching of restorations with the natural dentition, this is a conclusion also mentioned in **Chapter 6**. Further research on how to measure translucency was, and still is, indeed necessary to solve the color problem in dentistry.

Therefore in **Chapter 7** two different concepts of the natural layering technique were evaluated in order to measure the effect of different thickness layers of composites on the overall translucency and color of a restoration. It was found that with the more modern concept of natural layering, which uses an ‘enamel’ composite and a ‘dentin’ composite of the same shade, but different translucency, more predictable results can be achieved with the final restoration. If a clinician uses a system based on the more modern concept, which always has the same highly translucent enamel layer over the dentin layer, it is more difficult to have control over the final outcome. A natural tooth is build up in different organic layers of different translucencies, and hence composite restorations give the best esthetic results when layered in the same manner. Not only did we look at the effect of layering of composites, but also at other dental materials such as porcelain and different colors of cement layers. **Chapter 8** evaluated such color management when it comes to thin porcelain veneers. The conclusion of this study was that even when different shades of resin cements are used, the underlying tooth color cannot be masked.

Looking further into the behavior esthetic dental materials, the color stability of composite resins has been widely studied within dental research. However, composites are also available in natural gingiva colors and their color stability proves to behave differently as studied in **Chapter 9**. Significant change in color was seen between the different pink composites after what would be equivalent to eight months of exposure to the immersion media in the clinical setting. Looking at such color stability studies on dental materials, it brings light to the discussion on how valid the importance of the correct natural color of materials are, if they do not stand the test of time during function. To create the desired esthetic effect of a restoration is one thing, but it is another thing to be able to successfully maintain the esthetic results throughout a diversity of clinical circumstances and to demonstrate reasonable longevity.

As mentioned before, the evaluation of color differences are necessary within color research, and the CIE L*a*b* based color difference equation is generally and unanimously applied. In a recent PhD thesis of Dr. R.I. Ghinea 2013 (University of Granada, Department of Optics), it was reported that there is still an important gap between the perceived and computed color differences when using the CIE L*a*b* formula, and concluded that the CIE DE2000 color difference formula is better correlated with the visual perception, recommending its use in dental research and for *in vivo* dental color measurements. The present PhD thesis has continuously used the CIE L*a*b* color space as this has been widely used in research and applications in the dental field, yet it is now recognized that future color research should indeed consider using the newer formula CIE 2000 as its better adequacy has now been proven.

> "On the topic of color Dr. Victor Sears also wrote: "For the purpose of laying myself open to attack, let me tell you that my selection for the predominating Hue for full dentures is limited to practically five numbers". He goes on to explain that the five colors are yellow or orange in their foundation, with exception of one which has a faint suggestion of pink. When I started the research for this thesis I would have been one to 'attack' such statements. I believed that the more colors there are available the more coverage there is of the tooth color space and that this in combination with a digital 'recipe' of the amount of pigmentation would be the answer to the color problem within dentistry. Yet towards the end of my research I am seeing that the above idea of Sears in 1924 is wiser than I originally thought. As I deepened my knowledge on color science within dentistry and especially on the phenomenon of the 'blending-effect' (also known as chameleon effect) I can see that the practical solution is to have no more than a few colors for the dental clinician; and that future research must be more towards this direction."

Ghazal Khashayar

In 1931 schreef dr. B. Clark in 'The Dental Digest': "Bijna iedere schrijver op het gebied van tandheelkundige esthetiek en tandheelkundige keramiek maakt melding van de vele moeilijkheden bij de reproductie van de tandkleur.". Het onderzoek voor dit proefschrift begon in 2007, 76 jaar na Clark's woorden, en nog steeds blijkt deze verklaring geldig en nog steeds is het de manier waarop bijna alle artikelen in wetenschappelijke tijdschriften over dit onderwerp beginnen. De esthetiek van de natuurlijke tand wordt bepaald door vele verschillende factoren die de tand tot een moeilijk object maken om de kleur er van te bepalen. De subjectieve perceptie van kleur door het menselijk oog is onderhevig aan een groot aantal verschillende soorten van illusies en variabelen. De wisselende lichtomstandigheden en de omgeving waarin het menselijk oog, de waarnemer, de kleuren van de natuurlijke tand waarneemt, maken het proces er niet eenvoudiger op. Er zijn ook vele manieren waarop restauraties, gemaakt van tandheelkundige restauratie materialen, verschillen van de natuurlijke interne opbouw van de menselijke tand. De definitieve acceptatie of afwijzing van deze restauraties is vrijwel altijd gebaseerd op de reactie van de waarnemer. In het kort is dit het probleem bij kleur in de tandheelkunde. Deze invloeden van de mening van de patiënten over de tandkleur (perceptie), de waarneming van kleur en de reproductie van tandkleur vallen binnen het kader van dit proefschrift. Dit met als doel om de voorspelbaarheid van kleur-reproductie en de kennis van kleurwaarneming en -reproductie te vergroten, wat leidt tot het erkennen van de problemen van het bereiken van een niet afwijkende/passende kleur van een voortandrestauratie.

In **Hoofdstuk 1** wordt in een algemene inleiding achtergrondinformatie gegeven over het wetenschapsgebied waar het kleur bepalen en reproduceren van ons gebit onder valt. Het probleem van het kleurbepalen in een klinische tandheelkundige setting wordt toegelicht en de doelen van dit proefschrift worden nader beschreven. In onderzoek naar kleur kan men, na meting van de reflectiecoëfficiënt van twee objecten, de CIE L*a*b*-waarden van twee verschillende metingen vergelijken. Met een berekende $\Delta E^*$ kan het kleurverschil kwantitatief worden weergegeven. $\Delta E^*$ wordt vaak gebruikt in tandheelkundig onderzoek. Er is echter een gebrek aan overeenstemming over de drempelwaarde van $\Delta E^*$ voor met het oog waarneembaar kleurverschil en voor door de patiënt aanvaardbaar kleurverschil. Daarom begint **Hoofdstuk 2** met een literatuuronderzoek, een systematische beoordeling (systematic review) waarin werd onderzocht welke drempelwaarden voor $\Delta E^*$ er internationaal worden gehanteerd voor waarneembaarheid en aanvaardbaarheid van tandkleur-verschillen. De resultaten van dit onderzoek toonden aan dat er nieuw prospectief (klinisch) onderzoek nodig is om alle aspecten van kleuronderzoek in de tandheelkunde te interpreteren en consensus onder tandheelkundige onderzoekers te bereiken over de toe te passen drempelwaarden voor waarneming van kleurverschillen. Er werd geconcludeerd dat op dit moment de meeste klinische studies verwijzen naar dezelfde paar wetenschappelijke publicaties van drie decennia geleden waarin verslag wordt gedaan van in vitro onderzoek om drempelwaarden voor waarneembaarheid en aanvaardbaarheid vast te stellen. Dergelijke ΔE* waarden zijn afgeleid van de CIE L*a*b* kleurenruimte die met elektronische kleurenmeters (color measuring devices; CMD) worden gemeten. Er zijn veel verschillende CMD's beschikbaar voor tandheelkundige clinici en onderzoekers. Daarom is voordat verder onderzoek werd uitgevoerd in **Hoofdstuk 3** gekeken naar vijf verschillende CMD's om hun algemene prestaties in termen van reproduceerbaarheid en betrouwbaarheid te beoordelen. Er werd geconcludeerd dat in vergelijking met colorimeters en digitale camera's, een spectrofotometer kan worden gezien als de gouden standaard van kleurmeetapparatuur. Hierna werden in **Hoofdstuk 4** twee verschillende spectrofotometers bestudeerd om te evalueren of, wanneer verschillende spectrofotometers worden gebruikt, de tandheelkundige behandelaar kan communiceren met de tandtechnicus. Na de eerdere conclusie dat spectrofotometers tot de meest reproduceerbare resultaten voor het bepalen van kleur leiden was het doel nu om te zien of er gegevens kunnen worden uitgewisseld tussen metingen met twee verschillende spectrofotometers. Er werd geconcludeerd dat niet kan worden aangeraden om L*a*b* waarden tussen twee spectrofotometers uit te wisselen, maar de resultaten van de twee apparaten komen beter met elkaar overeen wanneer de tandkleur wordt uitgedrukt als de dichtstbijzijnde bijbehorende ‘kleurstaal’ volgens de database van het apparaat.

Ondanks het feit dat wij in een tijdperk van digitale tandheelkunde leven, waarin CMD’s niet alleen uitgebreid bestudeerd worden maar ook beschikbaar zijn voor de tandarts, zijn nog steeds de klassieke kleurenstalen de methode van eerste keuze in de dagelijkse praktijk. Zesenzeventig jaar geleden in het eerder genoemde artikel van Clark werd reeds geconstateerd dat het grootste probleem was dat de professie geen beschikking heeft over een systeem van kleurmeting en kleurspecificatie. De huidige commerciële kleurenstalen zijn ontoereikend. Het zou echter onpraktisch en commercieel onmogelijk zijn om een kleurenstaal te ontwikkelen die het hele gebied van de natuurlijke tandkleur bestrijkt en tegelijkertijd een onderscheid maakt tussen dentinebasis- en glazuurkleuren. Bovendien werd onderkend dat er een noodzaak bestaat voor een eenvoudige methode voor de meting en specificatie van de kleuren van tanden. Nu er digitale systemen voor kleurmeting zijn is het mogelijk om een digitale databank te ontwikkelen die de hele tand kleurruimte bestrijkt. Dit wordt in **Hoofdstuk 5** beschreven. In dit hoofdstuk wordt het probleem van hedendaagse kleurenstalen onderkend dat zij de kleurruimte van tanden onvoldoende bestrijken. Het nieuw ontwikkelde kleurbepaling- en kleurweergavesysteem, dat logisch en systematisch was ingericht en vereenvoudigd, bleek in staat om het kleurbereik van menselijke tanden onder het niveau van waarneembaarheid te detecteren ($\Delta E^* \leq 1{,}6$) en dat ook beter kon in vergelijking tot vier andere beschikbare hedendaagse systemen. Alvorens een dergelijk nieuw concept kan worden geïmplementeerd voor algemeen gebruik zal succesvol klinisch gebruik nog moeten worden aangetoond. Daarom is klinisch onderzoek nodig om aan te tonen dat de gemeten of visueel beoordeelde kleur, met behulp van het nieuw ontwikkelde systeem, nauwkeurig kan worden gereproduceerd in porseleinen restauraties. Na deze studie, was ik in staat om te zien wat Clark in 1931 bedoelde met “a new and improved shade-guide system being commercially impossible”, omdat dit nog steeds de reden is waarom zelfs vandaag de dag de ontoereikende kleurstalen nog gebruikt worden. Het is niet alleen belangrijk om een nieuwe kleurstaalsysteem te onderzoeken, maar ook om te onderzoeken hoe het gebruik van de meer traditionele kleurstaal systemen kan worden verbeterd. Dit werd onderzocht in **Hoofdstuk 6**. In dit hoofdstuk werd het Vita Classical shade guide systeem systematisch geordend volgens Lightness ($L^*$) om te onderzoeken of de clinicus hierbij visueel vaker een juiste kleur kiest dan met een conventionele ordening op basis van Hue-groepen. Dit was gebaseerd op de theorie dat het menselijk oog meer staafjes bevat welke gevoeliger zijn voor licht en helderheid. De conclusie van deze studie was dat tandartsen die kleurstalen toepassen welke zijn geordend volgens een toename van lichtheid niet meer of minder de juiste tandkleur kiezen. Hoewel niet onderzocht, leek het dat als de kleurstalen waren gerangschikt van licht naar donker, het proces van kleurbepalen sneller verliep. De evaluatie van gemak en tijd zou in een toekomstig onderzoek in een soortgelijke studie kunnen worden uitgevoerd.

Zelfs vóór Clark, al in 1924, schreef dr. Victor Sears een artikel over 'The Art side of Denture Construction’. Dit artikel erkent dat translucentie een belangrijke invloed op de kleurwaarneming van het oog heeft. Van kleur zijn drie dimensies hue, chroma en value bekend, maar een vierde dimensie zou translucentie moeten zijn. Vooral voor de kleurbepaling van restauraties van de voortanden speelt translucentie een grote rol. Dit is de conclusie genoemd in **Hoofdstuk 6**. Verder onderzoek over hoe translucentie te meten is, is noodzakelijk om het kleurprobleem in de tandheelkunde op te lossen. Daarom werden in **Hoofdstuk 7** twee verschillende concepten van laagsgewijs opbouwen van de restauratie met composiet geëvalueerd. Hierbij werd het effect van verschillende laagdikten van composieten op de translucentie en de kleur van een restauratie gemeten. Gevonden werd dat met het moderne concept van ‘natural layering’, waarbij een "glazuur" composiet en een "dentine" composiet van dezelfde kleur, maar andere translucentie worden gebruikt, meer voorspelbare resultaten worden bereikt. Als een tandarts een systeem gebaseerd op dit moderne concept toepast, is het moeilijker om de controle te hebben over de uiteindelijke uitkomst. Een natuurlijke tand is opgebouwd uit verschillende organische lagen die verschillende translucenties hebben, daarom verkrijgt men met composietrestauraties die op een vergelijkbare wijze in lagen worden opgebouwd de beste esthetische resultaten. Niet alleen hebben we gekeken naar het effect van het gelaagd aanbrengen van composieten, maar naar andere tandheelkundige materialen zoals porselein en verschillende kleuren van cementlagen. In **Hoofdstuk 8** is dit onderzocht op dunne porseleinen schildjes. De conclusie van deze studie was dat zelfs wanneer verschillende tinten kunststofcementen gebruikt worden, de onderliggende tandkleur niet kan worden gemaskeerd.

Ook de kleurstabiliteit van composieten blijkt uitgebreid bestudeerd te worden in tandheelkundig onderzoek. Echter, composieten zijn ook beschikbaar in de kleur van het tandvlees, de kleurstabiliteit blijkt zich dan afwijkend te gedragen (**Hoofdstuk 9**). Significante kleurverandering werd waargenomen tussen de verschillende roze composieten na blootstelling aan water, vergelijkbaar aan een periode van acht maanden in de klinische setting. Als de kleurstabiliteit van tandheelkundige materialen niet goed is dan werpen deze studies een nieuw licht op de discussie over hoe valide het belang van de juiste natuurlijke kleurselectie van materialen is, aangezien ze de tand des tijds niet doorstaan. Om het gewenste esthetische effect van een restauratie te realiseren is één, maar het is een andere uitdaging om het esthetisch resultaat succesvol gedurende een redelijke levensduur te realiseren, terwijl deze aan een groot scala aan klinische omstandigheden wordt blootgesteld. Zoals eerder vermeld is de evaluatie van kleurverschillen noodzakelijk in kleuronderzoek, de kleurverschil-vergelijking gebaseerd op het CIE L*a*b* systeem wordt algemeen en unaniem toegepast. In een recent proefschrift van dr. RI Ghinea 2013 (Universiteit van Granada, afdeling Optics), werd gemeld dat er nog een belangrijke kloof bestaat tussen de waargenomen en berekende kleurverschillen bij gebruik van de CIE L*a*b*-formule, en concludeerde dat de CIE DE2000 kleurverschil-formule beter correleert met de visuele perceptie en beveelt het gebruik ervan aan in tandheelkundig onderzoek en voor in vivo tandheelkundige kleurmetingen. Het huidige proefschrift heeft de CIE L*a*b* kleurruimte systematisch toegepast omdat deze op grote schaal wordt gebruikt in onderzoek in het tandheelkundig veld. Op basis van nieuwe inzichten wordt nu onderkend dat in toekomstige kleuronderzoek men het gebruik van de nieuwere formule CIE 2000 zou moeten overwegen.

Over het onderwerp van kleur schreef dr. Victor Sears ook: "For the purpose of laying myself open to attack, let me tell you that my selection for the predominating Hue for full dentures is limited to practically five numbers". Hij legt verder uit dat de vijf tandkleuren in hun basis geel of oranje zijn, met uitzondering van één die een vage suggestie van roze heeft. Toen ik begon met het onderzoek voor dit proefschrift zou ik één van de mensen zijn geweest die een dergelijke verklaring zou hebben aangevallen. Ik geloofde toen dat hoe meer kleuren beschikbaar zouden zijn binnen de kleurenruimte van de tand, in combinatie met een digitaal 'recept' van de hoeveelheid pigment, het antwoord op het kleurprobleem binnen de tandheelkunde zou zijn. Nu tegen het einde van mijn onderzoek zie ik dat het bovenstaande idee van Sears in 1924 wijzer is dan ik oorspronkelijk dacht. Ik heb mijn kennis in kleurwetenschap binnen de tandheelkunde verdiept en vooral de kennis over het fenomeen van het 'blending - effect' (ook wel bekend als kameleoneffect) en zie nu in dat het een praktische oplossing is om niet meer dan een paar kleuren beschikbaar voor de tandheelkundige behandelaar te hebben. Toekomstig onderzoek zou zich meer in deze richting moeten toespitsen.

Ghazal Khashayar

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*"Mere color,*
*unspoiled by meaning, and unallied with definite form,*
*can speak to the soul in a thousand different ways. "*
***– Oscar Wilde***

Writing up the acknowledgements of one's thesis (otherwise known as the last 4 years of my life -*and then some*-) is not as easy as I would have imagined it to be for a rather emotional and nostalgic PhD candidate such as myself. So, as any other creative minded-internet obsessed-person of my generation would do, I googled it.

Yes… I googled 'how to write your acknowledgement in thesis'.

Soon enough I came across forums on this matter and realized I am not the only researcher who goes straight for the acknowledgements page when looking at somebody else's thesis. The greatest joy is apparently looking back at everyone who has helped you through your PhD years, and it turns out just as in science you can categorize these people as 'the champions', 'the muses', 'the sounding boards' and 'the support teams'. I don't have to think about it too long to know that all these people thankfully do indeed exist in my life.
So here it goes.

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‘*Me without you*
*Is like a*
*Rainbow without hue*.’

## Curriculum Vitae

Born on 1 July 1983 in Tehran, Ghazal Khashayar had always aspired to become a dentist throughout her elementary and high school education at the International School of The Hague. She obtained her Propaedeutic, BSc and MSc degrees in Dentistry at the Academic Centre for Dentistry in Amsterdam from the University of Amsterdam. She first came into contact with scientific research in 2004 as part of her Bachelor of Science thesis, where she co-authored her first research paper on the topic of color science. Until 2009 she was involved in research in her free time, after which she succeeded to receive a scholarship from the Vrije Universiteit of Amsterdam in order to obtain a PhD on the subject of Color Science in Dentistry. Since then she has lectured internationally on the topic of color science and published several articles. Her expertise has also expanded beyond color science as she became involved with digital dentistry and obtained a position as the first female dentist certified trainer for the Lava oral scanner in Europe. With one foot in academia, she also worked as a general dentist in a private practice at The Hague from 2007-2012. In 2012 she left to Harvard School of Dental Medicine for a period of one year, where she gave lectures on color science, worked as a clinical instructor and continued her research for her PhD dissertation.

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Poster session A. Dozic*, G. Khashayar, N. Voit, R. Zwartser, A.J. Feilzer
Robert C. Sproull Poster Prize Awarded

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Digital Scanning
Lecture to postgraduates Prosthodontics program G. Khashayar*

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Lecture G. Khashayar*

## Glossary of color terms used for this thesis

**a* -**Redness-greenness coordinate in the CIE L*a*b* color space. If "a*" is positive, there is more redness than greenness; if "a*" is negative, there is more greenness than redness.

**Absorption** Decrease in directional transmittance of incident radiation (such as light), resulting in a modification or conversion of the absorbed energy. Light incident on a specimen may be partially reflected, partially transmitted, or partially absorbed.

**Acceptability Threshold (AT)** The difference in color that is considered acceptable by 50 % of observers, with the other 50 % of observers replacing or correcting the restoration.

**Accuracy** The closeness of agreement between a test result and an accepted reference value (often used as a color instrument specification).

**Angle of illumination** Angle between the specimen normal and the illuminator axis.

**Aperture** The measurement opening in a typical reflection color instrument. The size of the aperture determines the size and type of sample that can be measured.

**b* -** yellowness-blueness coordinate in the CIE L*a*b* color space. If "b*" is positive, there is more yellowness than blueness; if "b*" is negative, there is more blueness than yellowness.

**Brightness** Attribute of a visual sensation according to which an area appears to emit more or less light. (CIE 45-25-210.) The perceived amount of light coming from an area. "Brightness" is often restricted to apply only to lights and "lightness" is used for the corresponding dimension of the colors of surfaces. One of the three standard elements of color appearance (the other two are hue and saturation). Its colorimetric equivalent is luminance.

**Calibrate** To find and eliminate systematic errors of an instrument scale or method of instrument by use of material standards and techniques traceable to an authorized national or international measurement system.

**Chroma** The saturation and strength of color. It represents the intensity or concentration of a color. It is the difference between the color and a gray having the same brightness. For any given hue, Chroma ranges from 0 percent (neutral gray) to 100% (maximum color saturation). Color appears pure and contains no gray at the maximum level.

**CIE Commission Internationale de l'Eclairage.** An international organization that recommends standards and procedures for light and lighting, including colorimetry.

**Color** Defined by three dimensions, hue, value and chroma (See Munsell, Hue, Value, Chroma). These three dimensions should be matched separately when determining color.

**Color difference** A single number or metric expressing the distance from complete match in colour or shade. A color distance metric defined by the Commission Internationale de l'Eclairage (CIE, International Commission on Illumination) is called delta E ($\Delta E^*$).

**Color shifting** Change in perceived color that is a sum of a blending effect and an effect of physical translucency.

**Color shifting due to blending (Blending Effect)** Change in perceived color of a material due to change in surround; basically an optical illusion – visually perceivable, but not measurable by any instrument.

**Color shifting due to physical translucency** Change in color of translucent dental restorations caused by surround and background (underlying layers of hard dental tissues or other restorative materials).

**Color space** A system for ordering colors that respects the relationships of similarity among them. There are variety of different color spaces, but they are all three dimensional.

**Color Temperature** The temperature, usually expressed in Kelvin, of a full radiator (perfect, theoretical black substance that when heated would not affect the "color" of the light emitted) which emits light of the same chromaticity as the source. For example average daylight color temperature is often expressed as D65, for 6,500 degrees Kevin. See D65.

**Colorant** A dye, pigment, or other agent used to impart a color to a material.

**Colorimeter** A color measuring instrument for psychophysical analysis which provides measurements that correlate with the human eye-brain perception. It uses the tristimulus method, similar to the human eye and expresses colors in numerical form using internationally recognized color systems. It directly measures the XYZ tri-stimulus values for the sample under the illuminant, from which l*a*b* values may be calculated.

**Colorimetry** The science of measuring color and color appearance. Classical colorimetry deals primarily with color matches rather than with color appearance as such. The main focus of colorimetry has been the development of methods for predicting perceptual matches on the basis of physical measurements.

**Cone** One of the two main classes of photoreceptor found in the vertebrate eye. Cones produce usable outputs only at relatively high light levels and provide the main inputs for color vision. There are three types of cones in the human eye, each type having a different spectral sensitivity.

**Contrast ratio** In color measurement, a sample is measured over a white background, then over a black background and the ratio expressed either as a percentage (where 100% = complete opacity) or as a ratio to 1. See Opacity.

**Coverage error** An index that describes the mean of minimal color differences ($\Delta E^*$) among the specimens of one set (e.g., a shade guide) to each specimen of another set (e.g., natural teeth). It is calculated as the mean $\Delta E^*$for all best matches as follows:

$(\Delta E_{COV}= \Sigma\Delta E_{MIN}/n)$

where the mean colour difference of all individual best matches and a number of best matches were denoted as ΣΔEMIN and n, respectively. The smaller the coverage error, the higher are the chances for successful shade matching.

**D65** The CIE positions D65 as the standard daylight illuminant intended to represent average daylight and has a correlated color temperature of approximately 6500 K. CIE standard illuminant D65 should be used in all colorimetric calculations requiring representative daylight, unless there are specific reasons for using a different illuminant. Variations in the relative spectral power distribution of daylight are known to occur, particularly in the ultraviolet spectral region, as a function of season, time of day, and geographic location. D65 corresponds roughly to a midday sun in Western Europe / Northern Europe, hence it is also called a daylight illuminant.

**Fluorescence** The absorption of light at one wavelength and its re-emission at a longer wavelength. Fluorescence plays an important role in the perceived color of many objects.

**Gloss** Associated with the capacity of a surface to reflect more light in some directions than in others. Specular gloss is the ratio of flux reflected in the specular direction to incident flux (i.e., the angle of the reflected light is equal and opposite to the angle of the incident beam) for a specified angle of incidence, source, and receptor angular aperture and these reflections normally have the highest reflectances.

**Hue** The term given to what we commonly call color. It corresponds to the physical wavelength of light and is the term given to the various colors we perceive, e.g. purple, turquoise, yellow, etc.

**Illuminant** Mathematical description of the relative spectral power distribution of a real or imaginary light source, that is, the relative energy emitted by a source at each wavelength in its emission spectrum (the data entered into a color computer, used to predict the effect of different light sources on the perceived color). See D65.

**Ishihara color blindness test** A test for red-green colour deficiencies. It consists of a number of colored plates, each of which contains a circle made of many different sized dots of slightly different colors, spread in a seemingly random manner. Within the dot pattern, and differentiated only by color, is a number.

**L*** Lightness coordinate in the CIE L*a*b* color space. It extends from 0 (black) to 100 (white).

**Lightness** See Brightness.

**Metamerism** Property of two specimens that match under a specified illuminator (illuminant) and to a specified observer and whose spectral reflectances or transmittances differ in the visible wavelengths and may appear to be a miss match under a second specified illuminant to the same specified observer.

**Munsell color system** A widely used system for specifying colors of surfaces illuminated by daylight and viewed by an observer adapted to daylight, in terms of three attributes: hue, value, and chroma, using scales that are perceptually approximately uniform.

**Opacity** The ability of a material to block the passage of light. A material with high opacity is one with low translucency (see Translucency), and vice-versa.

**Perceptibility Threshold (PT)** The difference in color that can be detected by 50 % of observers, with the other 50 % of observers noticing no difference in color between the compared objects.

**Reflectance (of a surface)** The proportion of incident light the surface reflects. (See spectral reflectance).

**Repeatability** The closeness of agreement between the results of successive measurements of the same test specimen, or of test specimens taken at random from a homogeneous supply, carried out on a single laboratory, by the same method of measurement, operator, and measuring instrument, with repetition over a specified period of time. This is the most important aspect of sample presentation technique and one of the most important specifications for a color instrument.

**Reproducibility** The closeness of agreement between the results of successive measurements of the same test specimen, or of test specimens taken at random from a homogeneous supply, but changing conditions such as operator, measuring instrument, laboratory, or time. The changes in conditions must be specified.

**Retina** The inside layer of the back of the eye that contains the photoreceptors and associated neurons. The earliest stages of visual processing take place in the neurons of the retina.

**Rod** One of the two main classes of photoreceptor found in the vertebrate eye. Rods are very sensitive to light but fail to produce a usable signal at high light levels. They mediate night vision and have little effect on color vision in daylight.

**Saturation** Attribute of a visual sensation which permits a judgment to be made of the proportion of pure chromatic color in the total sensation. (CIE 45-25-225.) Pink and red differ in saturation with the red being the more saturated. The spectral colors are all maximally saturated examples of their hues and differ in this respect from pastels which are desaturated. One of the three standard elements of color appearance (the other two are hue and brightness).

**Spectrometer** An instrument for measuring a specified property as a function of a spectral variable. The spectral variable is wavelength or wave number and the measured property is (or is related to) absorbed, emitted, reflected, or transmitted radiant power. This device measures light in distinct bands

**Spectrophotometer** A color measuring instrument for physical analysis which provides wavelength-by-wavelength spectral analysis of the reflecting and/or transmitting properties of objects without interpretation by a human. It captures the full spectrum, consists of 3 principle elements: a light source; a means to direct the light source to an object and receive the light reflected or otherwise returned from the object; and a spectrometer (device that measures light in distinct bands) that determines the intensity of received light as a function of wavelength.

**Spectrophotometry** Quantitative measurement of reflection or transmission properties as a function of wavelength.

**Spectroradiometer** A spectrometer for measuring emitted optical radiant power, normally of a light source.

**Translucency** The ability of the material to allow light to pass through it.

**Transparency** The extreme value of high translucency. A transparent material allows light to pass through undiminished, while a negligible portion of the transmitted light is scattered.

**Tri-stimulus values, match** The amounts of the three specified human response stimuli required to match a color.

**Value** The brightness of a color, or in other words the degree of whiteness and blackness of a color. It is measured in variations of gray. Black is the lowest value, and white is the highest value. To change value, quality of gray is more important than the quantity of gray.

**X** One of the three CIE tristimulus values; the red primary.

**Y** One of the three CIE tristimulus values; equal to the luminous reflectance or transmittance ; the green primary
**Z** One of the three CIE tristimulus values; the blue primary.
**50:50% Perceptibility threshold of color difference ("PT")** Difference in color that can be detected by 50 % of observers. The other 50% of observers will notice no difference in color between the compared objects. A nearly perfect color match in dentistry is a color difference at or below the 50:50% perceptibility threshold.
**50:50% Acceptability threshold of color difference ("AT")** Difference in color that is considered acceptable by 50 % of observers. The other 50% of observers will replacement/correction of restoration. An acceptable color match in dentistry is a color difference at or below the 50:50% acceptability threshold.

This Glossary is intended for the non-specific readers and is based on the Readings on Color, Volume 2: The Science of Color (MIT Press, 1997), the ASTM International Standards on Color and Appearance Measurement: 8th Edition; and the terms and definitions of the International Organization for Standardization ISO Technical report on Dentistry-Dental shade conformity and interconvertibility (ISO/TR 28642: 1999. ISO/TC106/SC2 N788)