Fall 2014

Assessment of color difference between the tooth as a whole and underlying dentin

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Assessment Of Color Difference Between The Tooth As A Whole And Underlying Dentin

by

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A thesis submitted in partial fulfillment
of the requirements for the Master of
Science degree in Oral Science
in the Graduate College of
The University of Iowa

December 2014

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CERTIFICATE OF APPROVAL

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MASTER'S THESIS

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To my parents, for their unconditional love, endless support, making me who I am today

To my Abdulrahman, for his love and support.

To all my family and friends, who in one way or another participated in this journey.

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my mentor, Dr. Marcos Vargas, I wouldn't have been able to do this without his guidance and expertise. There was no obstacle encountered that he could not help me find a way around it. He is an example of an expert and a professional whom I had an immense pleasure to work with. My sincere thankfulness also goes to my thesis committee, which support, encouragement and insightful comments were fundamental for the completion of my work. I would like to deeply thank to Dr. Cobb for her unconditional support throughout the course of my work on the thesis and every aspect of the program . No words can explain my gratitude for everything she has done to facilitate this project. Special thanks goes to Dr. Fang Qian for providing excellent and detailed statistical analysis. Thanks for the significant guidance on how to report the results in my thesis and suggestions on my presentation. Dr. Justine Kolker for her constant availability and sharing her knowledge and her guidance on the thesis structuring. Thanks also to Dr. Marcela Hernandez for her input and advice. And thanks to Dr.Peter Lund for allowing me to use his instrument used in this study

My gratitude is also due to all members of the Operative Dentistry Department, faculty, staff and graduate students, who direct or indirectly helped me going through the master program and finish my thesis. Thanks for making my life easier and my time in Iowa enjoyable.

Finally, I would like to thank my family and my fiancé Abdulrahman, for the unconditional support, I am here because of you, you always believed in me and been there for me when things where not going right, I love you, and I owe all of this to you.

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CHAPTER I

INTRODUCTION

Color is a key element that helps us perceive our surroundings. What is the world without colors? Beauty is defined in terms of colors: a clear blue sky, a fresh green field, and the golden sands on the edge of a turquoise sea. Our perception of color is what makes us appreciate what is beautiful.

We usually refer to colors with general names such as red, blue, green etc. But not all reds are the same, nor are all blues the same. Color is complex, with primary and secondary components. Primary components are hue, chroma or saturation, and value or brightness (Zhang, Sokhansanj et al. 1998, Vichi, Fraioli et al. 2007, Xiong, Chao et al. 2008, Arimoto, Nakajima et al. 2010). The hue is the main component of color; it is what is usually referred to by the name of a color. It is derived from the three main or primary colors: red, yellow, and blue. Chroma refers to the saturation of the color. High chroma refers to color that is intense and rich; low chroma to color that appears faded and dull. Value refers to the lightness or darkness of the color. Think of it as adding white or black paint to a red or blue or yellow paint. That's how the color will be defined in terms of value.

Another aspect of color perception and the optical properties of an object has to do with light, specifically, the ability of an object to absorb or reflect light. A transparent object allows light to pass through so it appears clear. A translucent object allows light to pass diffusely or incompletely. In the other hand, an opaque object reflects light and does not allow it to pass through (Villarroel, Fahl et al. 2011). The secondary color components are: translucency, opacity, surface gloss, and fluorescence. Translucency is the most important of the secondary color components (Winter 1993, Kelly, Nishimura et al. 1996, Xiong, Chao et al. 2008).

"You are not fully dressed until you wear a smile." Almost everyone seeks a

beautiful smile (Chu 2002). And what is more beautiful than nature? Restoring and achieving smiles that are defined as beautiful is the main focus of esthetic dentistry. This is achieved by restoring what is natural; this is the ultimate challenge of esthetic dentistry. Therefore, the understanding of the optical properties that affect our perception of teeth color is critical.

A tooth consists of multiple layers. Enamel and dentin have different optical properties. Dentin is high in value, chroma, and fluorescence, and enamel is translucent and is low in chroma and value. Generally speaking, enamel allows light to pass through and then it hits the dentin where dentin will reflect, absorb, or refract it. Therefore the color of a tooth is affected by both of these two structures but predominantly by dentin (Vichi, Fraioli et al. 2007, Vieira, Arakaki et al. 2008, Xiong, Chao et al. 2008, Li, Xu et al. 2010).

There are different methods for measuring teeth color and shade matching. The most common method for shade matching is visual (Browning, Chan et al. 2009). Other digital methods are available, digital imaging using a camera is possible now with the aid of color-interpreting software (Yamanel, Caglar et al. 2010). Colorimeters and spectrophotometer are also used for color measurement and quality control (Vieira, Arakaki et al. 2008, Browning, Chan et al. 2009, Ryan, Tam et al. 2010)

Reproduction of the color and characteristics of natural oral structures is the ultimate goal for color specification measurement and shade matching (Johnston 2009). Manufacturers over the years have tried to develop dental materials that have the biological, mechanical, and optical properties of a natural tooth structure. So far, no material is a perfect substitute for tooth structure, but many materials provide satisfactory results in terms of restoring the natural tooth structure. Understanding the optical properties of the tissues that compose natural teeth is essential for the development of esthetic tooth-colored materials (Winter 1993). Dental porcelain powders are developed and used in a manner to mimic the layers of a natural tooth (Dietschi, Ardu et al. 2006).

Similarly, when composite resins are used to restore lost tooth structure that involves enamel and dentin, replacement material that mimics the optical properties of dentin is used to replace the lost dentin structure, and an enamel replacement material is then layered on top, with the possible use of other optical-effects composites or stains to produce the translucency and the halo effect at the incisal edge (Dietschi 2001). The shade of the enamel replacement material is determined with matching the shade of the remaining tooth structure or the adjacent tooth; the dentin replacement material is selected as one shade darker. This method is based on clinical experience rather than scientific evidence. Therefore, understanding the difference between the color of the tooth and the color of the underlying dentin is essential.

Problem

Comparative work on tooth color in relation to underlying dentin is rare. Most studies compare tooth color to shade guides or restorative materials, or measure the translucency of enamel or dentin of natural teeth. The difference in color between the tooth and the underlying dentin has not yet been studied.

Purpose Of The Study

The aim of this observational study is to investigate the difference between the dentin color and the tooth color as a whole of maxillary anterior teeth at the incisal, middle, and cervical thirds of the crown.

CHAPTER II

LITERATURE REVIEW

Color Science

Color is the psychophysical sensation that results when the human visual system responds to light reflected or omitted from objects in a scene. (Chu, Devigus et al. 2010). To understand the principles of color it has to be broken down to its basic dimensions: hue, value, chroma, and translucency.

Color Dimensions

Hue

This is what we refer to as "color" in our daily life. It could also be described as the "tone" of the color (red, blue, green, etc). Each hue is defined by a range of wavelengths (Chu 2002).

Chroma

Namely, the saturation or intensity of the hue (e.g. how reddish is a red object) (Chu 2002).

Value

The brightness of a color (sometimes expressed as the "lightness" or "darkness" of a color) (Chu 2002).

Translucency

Translucency is the ability of a medium or an object to transmit light through itself. Translucency is inversely related to opacity (i.e., the more translucent an object is, the less opaque it is) (Chu 2002).

Chromaticity

Chromaticity refers to a color's character without considering the value. It is determined by the hue and the chroma together. Colors can be classified into "chromatic" or "achromatic" based on whether they have or don't have a hue. Grey, black, and white are considered achromatic colors since they don't exhibit hues (Clark 1931, Vanini and Mangani 2001).

Color Basics

In order to understand color, it is important to understand how colors interact. To improve the outcomes of an esthetic restoration, it is essential to know about primary, secondary, and complementary colors (Chu 2002).

Primary colors

Primary colors are naturally occurring colors that cannot be created by mixing other colors. The only primary colors are red, blue, and yellow.

Secondary colors

Secondary colors are colors formed by mixing two primary colors. These are orange (red plus yellow), green (blue plus yellow), and violet (red plus blue) (Chu 2002, Bieicher 2011).

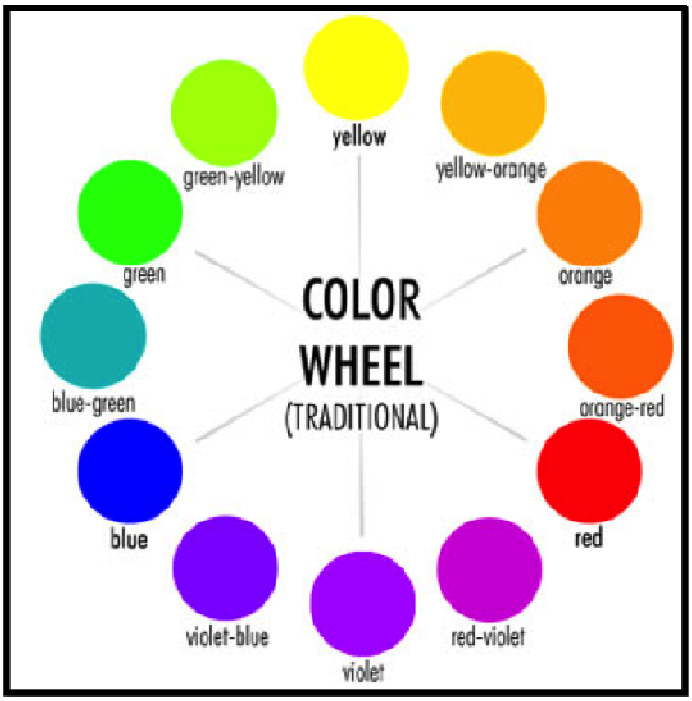

Figure 1:Color Wheel

Adapted from http://www.nhsdesigns.com/graphic/color/color-wheel.php

Complementary colors

Complementary colors appear opposite one another in the color wheel (Chu 2002, Bieicher 2011) (Figure 1). They are created by mixing two primary colors (e.g. Orange is the result of mixing Red and Yellow). Complementary colors enhance the appearance of one another. The mixing of two complements creates a "neutral" or gray color. This is

useful when there is a need to drop the value of a restoration or to give the effect of translucency at the incisal edge of an esthetic restoration.

Color Perception

Color is the result of an interaction between three elements: Light, object, and the observer (Chu 2002). Each of these elements has to exist in order for color to be seen. Factors associated with each of these elements will affect how color is perceived. Therefore color perception is considered individual and subjective (Chu 2002).

Light

Light is a form of electromagnetic radiation. The human eye is sensitive to a narrow range of this form of radiation, which is termed "visible light"(Chu 2002, Joiner 2004). Other forms of electromagnetic radiation include x-rays, infrared waves, and ultraviolet waves, but the wavelengths of these forms of radiation fall out of the human eye's visibility range, which is approximately between 360 to 780 nm (Joiner 2004). When white visible light passes through a prism, it is dispersed to its composing wavelengths. That is because the refraction index is different for each wavelength (Chu 2002, Chu, Devigus et al. 2010). The colors of the spectrum are defined by their relative wavelengths in the following order (from longest to shortest): red, orange, yellow, green, blue, violet (Chu 2002).

Metamerism

Each light source is characterized by the set of wavelengths it emits. And therefore color perception by the same observer of the same object could be different under different light sources. Metamerism is the "phenomenon of two objects appearing to match in color under one condition but showing apparent differences under another condition (lighting)." For example, two colors that appear to be a perfect match under fluorescent light would not match in natural light (Chu, Devigus et al. 2010). Shade matching should be done under different lighting conditions to avoid or minimize the problem of metamerism (Baltzer and Jinoian 2004).

Manufacturers of dental materials have tried to overcome metamerism by creating materials that have a chameleon effect, or take the color of their surroundings.

Observer

Wavelengths reflected by an object or emitted by a source reach the eye and are received by the rods and cones, which are the sensory cells (photoreceptors) in the retina (Chu, Devigus et al. 2010).

The rods perceive the brightness while the cones perceive the hue. There are more rods than cones (about 120 million), and they are extremely sensitive to light. That's why a small shift in the brightness of a restoration will be more noticeable than a shift in color. There are three cone types in the retina; each is responsible for the perception of red, blue, or green wavelengths. The stimulation of these cones at various degrees is responsible for the perception of different hues. The photoreceptors will send signals to the brain through the optic nerve, where the stimulus is translated as color perception (Williamson and Cummins 1983, Hecht 2006, Chu, Devigus et al. 2010, Bieicher 2011).

Viewer-associated factors that affect color perception include color blindness, age, fatigue, nutrition, emotions, medications, and binocular difference (Chu, Devigus et al. 2010, Sikri 2010).

Object/medium

When light hits an object it can be reflected, absorbed, refracted or scattered. The translucency/opacity, composition, surface texture, thickness of the object are factors that dictate the behavior of light within that medium (Wyszecki and Stiles 2000, Chu, Devigus et al. 2010).

Color Matching And Reproduction

As mentioned before, color perception is relatively subjective, depending on many factors related to the main elements discussed before: the observer, the light source, and the object. But advances in color science have provided means to quantify and communicate color in a standardized manner to eliminate the subjectivity and provide a scientific basis for specification and reproduction of any color. The two main methods for color specification are: Color order system and colorimetry (Paravina and Powers 2004).

Color Order Systems

A color order system is a systematic arrangement of all object colors ordered in a three-dimensional space based on three primary attributes. It is usually represented as a large set of physical specimens that display all the colors under consideration based on attributes such as the hue, saturation, and lightness. This system has been used broadly to

specify colors for educational and industrial purposes. The physical specimens (usually displayed as chips) are viewed by designers under standard viewing conditions, and then the desired colors are communicated with known notations of the chips rather than with the specimen itself. There are several color order systems; each was developed with a different set of principles based on color perception. Some of the color order systems developed during the early to middle 20th century include the Munsell system, the Ostwald system, and the Natural Color System. However, each of them had limitations and none of them was universally accepted (Paravina and Powers 2004).

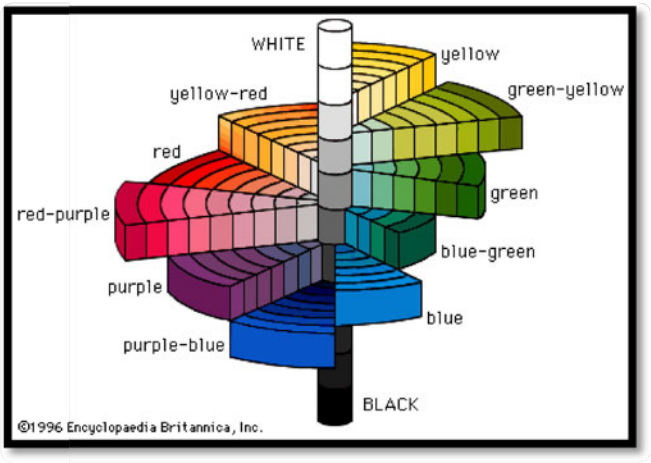

Figure 2: An illustration of the Munsell color order system.

Adapted from http://natashabillington.wordpress.com/2014/02/17/investigating-the-history-of-colour-part-four-munsell-hue-chroma-and-value/

Munsell Color Order System

One of the oldest available color order systems is the Munsell color order system. It was created by in 1905 by Albert H. Munsell, who is considered the father of modern

color classification. He was the first to separate color uniformly and independently into the three dimensions of hue, value, and chroma and illustrate it systematically into a three-dimensional space (Kuehni 2002, Chu, Devigus et al. 2010, Bieicher 2011). It is arranged based on equal visual spaces between adjacent specimens according to three visual attributes, which are the hue (H), value (V), and chroma (C) (Figure 2). Each specimen is identified based on its notation of H/V/C.

The (H) represents the color group of which the specimens fall into (e.g. blue, red, orange, yellow). The Munsell hue is divided into five primary hues (5Y, 5R, 5P, 5B, 5G), which are further divided into 100 subsets. The (C) represents the chroma with an open-ended scale from 0 (achromatic colors) to the maximum depending on the hue group. The (V) represents the brightness/darkness of a specimen, it runs from 0 (black) which absorbs all wavelengths of incident light to 10 (white) which reflects all wavelengths of incident light (Kuehni 2002, Paravina and Powers 2004, Della Bona, Barrett et al. 2009).

An example of the Munsell color notation is: 5Y7/9, where 5Y represents the hue, 7 represents the value, and 9 represents the chroma (Clark 1931). Munsell color order system does not address the translucency dimension, which could be considered a limitation (Chu 2002, Bieicher 2011).

The CIE System

This system is developed by the International Commission on Illumination (abbreviated CIE for its French name, Commission internationale de l'éclairage) (Wyszecki and Stiles 2000). It is the most widely used system for color specification. Its principles are used for designing color measurement instruments and conversion of spectrophotometric readings to color parameters (Smith and J. 1932, (CIE) 2004). The first CIE color specification was introduced in 1931. The system principles remain the

same although the system has been refined over the years. It is based on the three basic elements for color perception: the observer, light, and the object. The light component is represented as the illuminant, and the observer is represented as a standard observer function (Paravina and Powers 2004, Bieicher 2011)

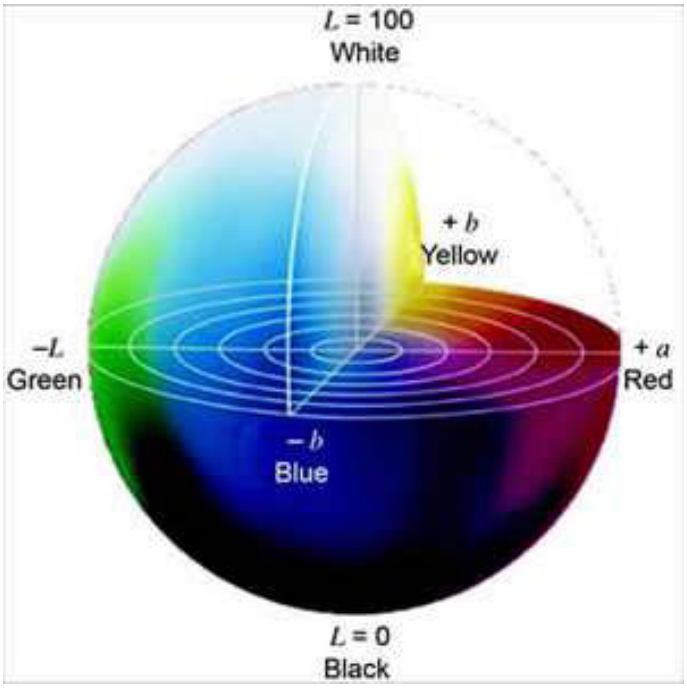

Figure 3: CIE LAB color space.

Adapted from http://wiki.nuaj.net/index.php?title=Colorimetry

CIE illuminants

Various standard illuminants were introduced by the CIE. In 1931 three standard illuminants were introduced: A (representing incandescent light), B (representing direct sunlight), and C (representing indirect sunlight). The D standard illuminants series was introduced in 1964 when the B and C illuminants were found to be unsatisfactory for

fluorescent measurement applications. The standard illuminants D65 (better representation of indirect sunlight with an ultraviolet component), and D50 are the most commonly used illuminants in the industry.(Paravina and Powers 2004)

CIE LAB

One of the most-used color spaces introduced by the CIE in 1976 is the CIE L*a*b* (Figure 3). Three axes of the CIE LAB color space are the L* vertical axis and the a* and b* horizontal axes with the neutral scale located in the center of the space. The L* represents the lightness/darkness of a color. It ranges from 0-100, where 0 is black and 100 is white. The a* axis represents the relative redness-greenness of the color. A positive value represents a shift towards red, and a negative value represents a shift towards green. The b* axis represents the relative yellowness-blueness of the color. A positive value represents a shift towards yellow, and a negative value represents a shift towards blue. Any color could be plotted in the color space by values of its three attributes. (Paravina and Powers 2004, Yuan, Brewer et al. 2007, Sikri 2010)

Color Difference Evaluation

The CIE LAB attributes can be used to calculate the color difference (ΔE) between two specimens. It can be calculated using the following equation:

$$(\Delta E) = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

Where ΔL* is the difference in L values between the two specimens, Δa* is the difference in a values between the two specimens, and Δb* is the difference in b values between the two specimens (Paul, Peter et al. 2002, Paravina and Powers 2004, Karamouzos,

Papadopoulos et al. 2007, Yuan, Brewer et al. 2007, Joiner, Hopkinson et al. 2008, Chu, Devigus et al. 2010).

Color Matching

With the increased demand for natural-looking restorations and rapid development of esthetic restorative materials, shade matching has become an everyday practice in the dental office. Shade matching can be done either visually using shade guides or digitally with color measurement devices. Although visual shade matching is the most common method for shade matching (Browning, Chan et al. 2009), digital methods are gaining more popularity with the continuous improvement and simplification of chairside color measurement devices (Vieira, Arakaki et al. 2008, Browning, Chan et al. 2009, Ryan, Tam et al. 2010, Yamanel, Caglar et al. 2010).

Conventional shade matching

Due to the huge variation in color, one of the most challenging aspects of esthetic dentistry is the accurate matching and reproduction of natural tooth color (Yuan, Brewer et al. 2007). Therefore, dental field professionals should have an understanding about color science concepts and how light interacts with dental tissues and restorative materials.

Dental professionals have used shade guides for almost a century. It is the most widely used method for shade selection (Paravina 2009, Yoshida, Miller et al. 2010). A shade guide is a set of physical standards made of a certain material and arranged based on a specific criteria. They are used for visual shade matching of natural tooth structure or a restoration (Paravina and Powers 2004). It is a low-cost, widely accepted, easy to use

visual assessment tool, where hue and chroma can be relatively easy to match but matching value is more challenging (Chu 2002). As a matter of fact, incorrect value matching is responsible for 75% of improper shade selection (Sagars 2002), and as discussed earlier, a slight shift in value is more noticeable than a slight deviation in chroma or hue due to the human's eyes high sensitivity to brightness.

The first shade guide was developed by Clark around the year of 1933 (Clark 1931, Clark 1933). Several products have been introduced since then, but not until 20 years later a breakthrough through occurred with the development of the Vitapan Classical (Vita Zahnfabrik, Bad Säckingen, Germany), which despite its limitations is still used today (Paravina 2009).

Vitapan Classical shade guide

The Vitapan Classical shade guide consists of 16 tabs arranged into four groups based on hues. The A group represents the orange hue and consists of five tabs. The B group represents the yellow hue and consists of four tabs. The C group represents the yellow/grey hue and consists of four tabs as well. The D group represents the orange/grey hue and consists of three tabs. Within each groups the tabs are arranged based on increasing chroma from 1 to 4. The value decreases as the chroma increases (Paravina and Powers 2004, Paravina 2009). Another variation introduced by the manufacturer is the "value-scale" arrangement where the tabs are arranged according to value from the highest on the far left to the lowest on the far right (Paravina and Powers 2004).

Limitations

It has been reported that shade guides provide 30% of the answer (Chu 2002); because they rely on subjective perception, results vary from one individual to another (Chu 2002). Several problems have been pointed out with the Vitapan Classical shade guide such as inconsistent color range between tabs (Paravina 2009, Yoshida, Miller et al. 2010), lack of logical distribution in relation to the color space of human teeth (Sproull 1973, Preston 1985), and that the color space into which natural teeth fall is much larger than that measured by shade guides since they were initially developed to meet the demand for matching denture teeth (Lemire and Burk 1975, Schwabacher and Goodkind 1990). In addition, issues of quality control, mismatch between different batches, and material difference between the shade tabs and restorative materials have been noted (Preston 1985, Miller 1993). These limitations were realized decades ago, and the need to develop a new systematic shade guide was expressed in a 1985 survey of faculty involved in teaching of color science in dentistry (Goodkind and Loupe 1992, Yuan, Brewer et al. 2007).

As an answer to all the concerns associated with the Vita classical shade guide, the Toothguide 3D-Master (TG, Vita Zahnfabrik, Bad Säckingen, Germany) was introduced in the late 1990s (Baltzer and Kaufmann-Jinoian 2005, Paravina 2009).

Toothguide 3D-Master shade guide

The Toothguide 3D-Master shade guide consists of 29 tabs and represents an application of the lightness-chroma-hue concept of shade matching. The Tabs are identified with a sequence of letter-number-letter. The first number represents the lightness, the letter represents the hue, and the second number represents the chroma

(Paravina 2009). There are six main groups based on value (lightness), from 0 (lightest) to 6 (darkest). Within each of the 6 groups, the tabs are arranged into three chroma levels (except for group 1 which has only two levels), from 1 (least chromatic) to 3 (most chromatic). The levels within the groups are represented by letters, with L (left) being yellowish, M (middle) being of middle hue, and R (Right) being reddish (Paravina and Powers 2004, Yuan, Brewer et al. 2007, Paravina 2009, Chu, Devigus et al. 2010).

Advantages compared to Vita classical shade guide

The Toothguide provides a better match to natural teeth, with wider color range and uniform distribution between tabs. However, clinicians with average knowledge of color find it confusing and difficult to understand and use the Toothguide 3D Master because of the larger number of shade tabs (Paravina and Powers 2004, Yuan, Brewer et al. 2007, Paravina 2009, Chu, Devigus et al. 2010).

Linearguide 3D Master shade guide

Linearguide 3D Master shade guide was introduced as a new modified, simplified version of the Toothguide 3D Master shade guide. It consists of the same tabs but it is a two-step shade matching procedure (Paravina and Powers 2004, Yuan, Brewer et al. 2007, Paravina 2009, Chu, Devigus et al. 2010).

In a study by Paravina et al. where the three shade guides (Vita classical, Toothguide 3D Master, and the Linearguide 3D Master were compared in terms of efficacy and user satisfaction, they found that the Linearguide 3D Master enabled a better shade matching (Paravina 2009).

Shade selection principles

When shade matching is performed the patient should be seated in an upright position so the target tooth can be viewed at eye level (Sikri 2010). Shade matching should be done at the beginning of the appointment and teeth should be fully hydrated and clean (Sikri 2010). Shade matching should be done under a variety of lighting conditions to minimize the problem of metamerism (Dagg, O'Connell et al. 2004, Sikri 2010). Any contrasting surroundings should be controlled; lipstick should be removed and bright clothes covered.

In addition, shade matching should be done quickly (don't stare at the target tooth for more than five seconds) to avoid eye fatigue. Rest the eye by looking at a blue or preferably a neutral grey card to avoid the desensitization of the photoreceptors in the retina to the teeth hues (Sikri 2010). The shade tab should be aligned with the target tooth so that it is subject to the same environmental influence (Clark 1931).

Color Measurement Methods

Generally speaking, color analysis falls into two main approaches. The first is spectral reflectance measurement, or the measurement of the amount of light reflected or transmitted through the object. The second method is to specify the measurement in terms of the three dimensions of color. The choice of method depends on the purpose for which the color measurement is to be used (Clark 1931).

Spectral reflectance measurement

Spectral reflectance measurement quantifies the amount of light energy or the reflecting power of the color at each wavelength of the spectrum. This method is useful to

determine the behavior of colors under different illumination sources (Troland , Clark 1931). Two colors that match under a certain source of illumination but don't match under another source are called metamers (displaying metamerism) (Wyszecki and Stiles 2000). On the other hand, two colors that have the same spectral power will be a perfect match under any source of illumination (Clark 1931).

Three-dimensional measurement:

Three-dimensional measurement quantifies the color sensation as it is perceived rather than the stimulus. It defines color in terms of the three dimensions of hue, brightness and saturation as seen by the eye (Troland , Clark 1931, Paravina and Powers 2004).

The design and performance of the color-measuring instrument largely determines the results (Paravina and Powers 2004). The four major types are: tristimulus colorimeters (Yuan, Brewer et al. 2007, Xiong, Chao et al. 2008, Ryan, Tam et al. 2010, Yamanel, Caglar et al. 2010), spectroradiometers (Paravina and Powers 2004, Gozalo-Diaz, Johnston et al. 2008, Lim, Yu et al. 2010), spectrophotometers (Paravina and Powers 2004, Vichi, Fraioli et al. 2007, Vieira, Arakaki et al. 2008, Browning, Chan et al. 2009, Arimoto, Nakajima et al. 2010, Li, Xu et al. 2010), and digital cameras (Paravina and Powers 2004, Yamanel, Caglar et al. 2010) with the aid of a software analysis of color. A color-measuring instrument contains optical element components. These may include all or some of the following parts: a light source, receptor, an integrating sphere, filters, and a wavelength selection device. The arrangement of optical elements within the instruments vary between different types (Paravina and Powers 2004).

Color Measuring Devices

Devices have been developed to provide a technical, objective method for color measurement (Seghi, Johnston et al. 1986, Chu 2002, Yamanel, Caglar et al. 2010, Yoshida, Miller et al. 2010). They provide a more standardized objective method for color measurement that is not affected by changing conditions that can influence the visual color measurement method (Okubo, Kanawati et al. 1998, Paul, Peter et al. 2004, Da Silva, Park et al. 2008, Yoshida, Miller et al. 2010).

Figure 4: Tristimulus colorimeter (CR-221 Chroma Meter, Minolta, Osaka, Japan).

Tristimulus colorimeters

Tristimulus colorimeters are so named because they only measure color using a

tristimulus value (specific wavelengths, not the whole spectrum). In addition, they measure color under fixed conditions (set illuminant and observer function) (Paravina and Powers 2004). They are easy to use, less expensive than the more sophisticated spectrophotometers and spectroradiometers, and are suitable for measuring the color difference between two objects (Paravina and Powers 2004). However, due to the fact that they use tristimulus values, they cannot measure metamerism. Colorimeters are designed to measure a flat surface (Yu, Ahn et al. 2009). In addition, due to the filters aging and poor reproducibility, the reliability of the instrument is poor (Paravina and Powers 2004).

Some examples of tristimulus colorimeters in the market are: Minolta colorimeter (CR-221 Chroma Meter, Minolta, Osaka, Japan) shown in (Figure 4), ShadeVision (X-Rite, Grand Rapids, MI, USA) (Yoshida, Miller et al. 2010). The ShadeRite Dental Vision System, and ShadeScan are instruments that combine digital color analysis with colorimetric analysis (Sikri 2010).

Spectroradiometer

These instruments are designed to measure irradiance or radiance (radiometric energy). The radiometric quantities are measured at intervals of 5, 10, or 20 nm of the visible spectrum. One of the spectroradiometer's advantages is that it provides simulation of human perception as it measures the color of objects at the same position as a human observer would perceive them in the same viewing condition. In addition, it has the capability of measuring the color of surface color and self-luminous sources. However, the position of the measured object or source is very critical, since a slight change will produce a change in the results (Paravina and Powers 2004). In a study that was done by Lim et al. in 2010 to compare the translucency parameter for different ceramic systems measured by a spectrophotometer and a spectroradiometer, they found that the

measurement results were significantly different but highly correlated (Lim, Yu et al. 2010).

Spectrophotometers

Spectrophotometers are widely used to measure surface colors. The spectrophotometer measures colors based on reflectance by calculating the ratio of reflected wavelengths of the target object to the wavelengths reflected from a white standard reference at intervals of 5, 10, or 20 nm of the visible spectrum. They are more stable and are the instruments of choice for surface color measurements. They can be used for evaluation of color difference and absolute color measurements in addition to metamerism evaluation (Paravina and Powers 2004).

They have an advantage over spectroradiometers in that they include a stable light source (Cal, Guneri et al. 2006). In a study done in 2009 by Browning WD et al. where the color measurements by human raters were compared with color measurements of the an intraoral spectrophotometer (VITA EasyShade-Vident), it was found that measurements of L* a* and b* are more accurate and precise using the spectrophotometer (Browning, Chan et al. 2009). These results are in agreement with a study done by Paul S. in 2002 (Paul, Peter et al. 2002). However, the spectrophotometer was found to show variations based on the method, the measuring geometry and the illuminant employed.

Colorimeters and spectrophotometers are designed for measurements of flat surfaces (Ryan, Tam et al. 2010). Colorimeters are used to measure red, green, and blue points. On the other hand, spectrophotometers measure the full light spectrum (Browning, Chan et al. 2009, Yoshida, Miller et al. 2010), and they measure the space coordinates not on one but any standard illuminant (Browning, Chan et al. 2009).

Examples of some of the spectrophotometers available in the market are:

Easyshade (Vita Zahnfabrik, Bad Säckingen, Germany), and spectrophotometers that provide images: SpectroShade Micro (MHT, Verona, Italy) and Crystal- eye (Sikri 2010, Yoshida, Miller et al. 2010). Such spectrophotometers that combine digital color imaging of the target tooth in addition to spectrophotometric analysis offer the advantage of improving the communication with the laboratory (Da Silva, Park et al. 2008, Sikri 2010).

Digital imaging

The use of digital cameras for color measurement is becoming more popular. It allows for color measurement based on an image rather than an area of color in an object (Cal, Sonugelen et al. 2004, Paravina and Powers 2004, Yoshida, Miller et al. 2010). It is a cheaper way to measure color, where images are taken and then analyzed with computer software, but its reliability is unknown (Browning, Chan et al. 2009).

It is important to obtain a high quality image because lower quality images could lead to errors in the color measurement results (Jarad, Russell et al. 2005, Wee, Lindsey et al. 2006). This can be affected by many factors including the camera type and settings, the size of the image, the position of the teeth and the shade tabs, and the lightning conditions (Yoshida, Miller et al. 2010).

Edge-Loss

When light falls on a translucent material, it will be absorbed, reflected, or scattered, or a combination of all three. When the light passing through the translucent material is scattered and therefore not detected by the sensor of a color measurement device, this is termed “edge-loss” (Bolt, Bosch et al. 1994, Yu, Ahn et al. 2009). This

phenomenon occurs during reflectance measurements (Johnston, Hesse et al. 1996), and could result in loss of accuracy of the color measurement result (Ragain and Johnston 2001).

Variables affecting the amount of edge-loss

Some studies have been conducted to determine the variables that affect the amount of edge-loss and how it affects the accuracy of the color measurement results. In a study done by Bolt et al. in 1994 to quantify the edge-loss associated with tooth color measurements using a small window for illumination they found that edge-loss is wavelength dependent (edge-loss for green light is 85% of the edge loss of red light). In addition, they determined that when color measurement is obtained using a small window for illumination, the L* a* b* coordinates are shifted towards green and blue and lower brightness in comparison with actual coordinates of the object. They determined that edge loss effect could be decreased by using a larger measuring window. However, the measurement window size is limited by the configuration and dimensions of the measured object (Bolt, Bosch et al. 1994). Image based spectrophotometers offer the advantage of minimizing the effect of edge-loss since the measurements are obtained from an image rather than from direct measurement of the reflected light.

In another study done by Johnston et al. in 1996 to analyze the edge-loss in reflectance measurements of pigmented maxillofacial elastomer, they concluded that edge-loss is affected by the following factors: observation geometry of the color measurement device, beam size of the illumination, direction of the illumination, thickness of the translucent medium, optical properties of the translucent medium, and the backing of the translucent medium (Johnston, Hesse et al. 1996)

Color Science And Education In The Dental Field

Color concepts are an intersection between art and science, studied and utilized extensively in many fields. Esthetics has become an important aspect of dental practice today. The development of tooth-colored materials, expansion in tooth-whitening procedures, introduction of new shade guides, and advancement of color matching technologies highlights the shift in the dental practice towards a more esthetic, natural outcome and the importance of a profound knowledge in color science in the field of dentistry (Paravina, O'Neill et al. 2010, Villarroel, Fahl et al. 2011).

Color and appearance is a foundational pillar in the field of esthetic dentistry. The need to shed light on aspects of color science and its relation to the dental practice is clearly understood in the dental research arena (Paravina, O'Neill et al. 2010). A section for research in color and appearance (DM 11) has been incorporated by the Dental Materials Group of the International Association for Dental Research (IADR). In addition, the Society for Color and Appearance in Dentistry (SCAD) has been established, with annual meetings, rapidly increasing membership, and publication of its own journal, the Journal for Color and Appearance in Dentistry (JCAD), which publishes the latest research in the field of color in dentistry (Paravina, O'Neill et al. 2010).

In the past, surveys have been conducted to assess the status of color education in dentistry. Several concerns were raised. Among those was the low number of dental schools that teach color concepts in dentistry, clinics that have been found to lack a color-balanced environment, limitations of the shade guides used, and manufacturers' shortcomings in solving issues that relate to color (O'Keefe, Strickler et al. 1990, Goodkind and Loupe 1992, Sproull 2001). However, in a more recent survey conducted by Paravina et al. in 2009 to assess the status of color education in dental schools in pre and post doctoral levels, it was found that there was a substantial increase in the past

decade in courses in “color” or “color in dentistry” in dental school curricula with an increase in faculty and staff with color expertise (Paravina, O'Neill et al. 2010).

Accurate shade matching remains a challenge for many clinicians. Incorrect shade matching was estimated to be the reason for approximately 50% of the remakes of esthetic restorations (Sagars 2002). Knowledge about color concepts and clinical experience has a significant effect on the clinician’s shade matching ability (Paravina, O'Neill et al. 2010).

Color Measurement Parameters Used In Dental Research

Many color parameters are used for color measurements. As discussed earlier, the color coordinates L*,a*,b* are widely used in dental color research for different color measurement applications. They are defined by the CIE LAB (**International Commission on Illumination***)*. CIE *L** value is a measure of the lightness of an object. A perfect black has a CIE *L** value of 0 and a perfect reflecting diffuser (white) has a CIE *L** value of 100. CIE *a** value is a measure of redness (positive value) or greenness (negative value), and CIE *b** value is a measure of yellowness (positive value) or blueness (negative value) (Browning, Chan et al. 2009; Li, Xu et al. 2010; Yamanel, Caglar et al. 2010).

The color difference between two specimens (Δ□)

Color difference can be calculated using the following equation:

$$(\Delta E) = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{½}$$

(Joiner 2004, Joiner 2006, Li, Xu et al. 2010, Yamanel, Caglar et al. 2010). □It

represents the difference in color but does not specify the direction of the color coordinates difference (Wee, Monaghan et al. 2011).

Translucency Parameter (TP)

One of the most commonly used parameters to measure translucency is the Translucency Parameter (TP) (Xiong, Chao et al. 2008, Yu, Ahn et al. 2009, Arimoto, Nakajima et al. 2010, Li, Xu et al. 2010, Ryan, Tam et al. 2010). It is the color difference of an object or material of a uniform thickness against a black background and a white background. It is a measure of the reflected light and its related directly to the visual assessment of translucency (Yu, Ahn et al. 2009)). It is calculated with the following equation:

$$TP = [(L^*_W - L^*_B)^2 + (a^*_W - a^*_B)^2 + (b^*_W - b^*_B)^2]^{1/2}$$

Subscript W and B refer to the white or black background used to measure the specific color coordinate (Li, Xu et al. 2010; Ryan, Tam et al. 2010).

Another measure of the translucency that is used for the measurement of the transmitted light (transmittance of the material) can be calculated using the following formula:

$$T = (L_{specimen} / L_{source}) \times 100\%$$

Where $L_{specimen}$ is the specimen luminance, and L_{source} is the source luminance (Xiong, Chao et al. 2008)

Contrast Ratio (CR)

Contrast ratio (CR) is another parameter used in some studies to measure the translucency of material (Xiong, Chao et al. 2008, Yu, Ahn et al. 2009, Arimoto,

Nakajima et al. 2010, Li, Xu et al. 2010, Ryan, Tam et al. 2010). CR is also an estimate of the opacity of a 1 mm thick specimen (Yu, Ahn et al. 2009). It is the ratio of the reflectance (Y_B) from an object against a black background to the reflectance (Y_W) obtained for the same object against a white background (Xiong, Chao et al. 2008, Yu, Ahn et al. 2009). The formula used is: $CR=Y_B/Y_W$ (Yu, Ahn et al. 2009, Spyropoulou, Giroux et al. 2011).

Opalescence Parameter

The opalescence of the material could be measured as the difference in blue-yellow and red-green coordinates between the transmitted and reflected colors against a black background using the following equation:

$OP = [(CIE\ a_T - CIE\ a_R)^2 + (CIE\ b_T - CIE\ b_R)^2]^{1/2}$ T refers to the color transmittance and subscript R refers to the color reflectance (Arimoto, Nakajima et al. 2010).

Perceptibility Thresholds Defined

Perceptibility thresholds of color differences have been found to range from ΔE^*= 1.0 to 3.7 (Johnston and Kao 1989, Seghi, Hewlett et al. 1989). Values of ΔE from 0-2 are considered not perceivable by the human eye, 2-3 just perceivable, 3-8 moderately perceivable and $\Delta E > 8$ is distinctly perceivable (Vichi, Fraioli et al. 2007; Yamanel, Caglar et al. 2010). Acceptability thresholds have been reported to be higher than Perceptibility thresholds in dentistry (Johnston and Kao 1989, Douglas and Brewer 1998), they range from $\Delta E^* = 2.72$ to 6.8 (Ruyter, Nilner et al. 1987, Johnston and Kao 1989, Ragain and Johnston 2000, Khashayar, Bain et al. 2013).

Natural Teeth

Tooth color is a complex phenomenon. It results from a combination of several optical properties of multiple structures. Multiple factors affect the perceived tooth color. Translucency, surface texture, compositional structures' thickness, and illumination are some of the factors that affect the color perception of a tooth or a restoration. Tooth color is a result of light interacting with its composing structures. Knowledge of dental tissues is essential in order to understand tooth color, and the optical properties that result from their interaction with light (Paravina and Powers 2004).

Dental Tissues

The tooth is composed of four main tissues: enamel, dentin, cementum, and the pulp. Enamel and dentin are separated by a thin area called the Dentinoenamel Junction, and have the largest effect on a tooth's color (Paravina and Powers 2004).

Enamel

Enamel is the outermost structure of a tooth's crown. It is the hardest tissue in the human body. It's mainly composed of inorganic matter (95% by weight) that is primarily a crystalline lattice of hydroxyapatite. The hydroxyapatite is the building block for enamel rods that are packed tightly and oriented in different directions depending on their position in the tooth crown. Each rod has a head and a tail; the head is oriented towards the incisal or occlusal part while the tail is oriented towards the cervical part of the crown (Paravina and Powers 2004).

Enamel thickness varies in different locations of the tooth. Its greatest thickness is at the incisal or occlusal third, and decreases throughout the middle, until it reaches the cementoenamel junction (CEJ) where enamel is the thinnest (Heymann, Swift et al. 2012).

Dentin

Dentin is the tissue underlying enamel; it forms the bulk of the tooth. It is the second hardest tissue in the body. It is composed of channels called dentinal tubules, which enclose odontoblasts and their processes. The dentinal tubules extend from the pulp and end at the DEJ. Dentin has more organic components than enamel. The main organic component is collagen arranged densely as fibers and soluble proteins. The inorganic component is 75% by weight, which is formed by less organized hydroxyapatite crystals. Dentin is more opaque than enamel. The formation of dentin continues throughout life in response to different stimulus or as part of the natural aging process. (Paravina and Powers 2004).

DEJ

The Dentinoenamel Junction (DEJ) is the 30 μm thick hypermineralized zone between enamel and dentin that serves as a firm attachment between the two tissues.

Optical Properties Of Dental Tissues

Generally speaking, tooth color analysis takes one of two main approaches. The first is to measure the amount of light reflected or transmitted through the tooth; the second is to specify the measurement in terms of the three dimensions of color. Selecting

one of these methods depends on the intended use for the color measurement (Clark 1931). The scattering and absorbing coefficients of a medium can be used to calculate the Kubelka-Munk equations to describe the optical properties of a layer of material.

There are certain criteria that must be met in order to apply the K-M equations. These are:

1) The material is dull at its surface and of a constant finite thickness.

2) Optical effects at its edges may be neglected.

3) Optical homogeneities are uniformly distributed within the specimen and are substantially smaller than the specimen thickness.

4) Illumination is diffuse and homogenous (Paravina and Powers 2004).

Enamel and dentin are natural tissues, with different components and different levels of homogeneity.

Dentin may be relatively less homogenous than enamel because as mentioned earlier, it is composed of various types of dentin (primary, reparative, and tertiary dentin) depending on the age of the tooth and the conditions it has been exposed to. Although enamel and dentin are not completely homogenous, studies have shown that the K-M theory can predict enamel's and dentin's reflectance in various thicknesses accurately, due to the low errors associated with applying the K-M theory. However, that is only applicable for an individual enamel or dentin sample. It does not apply when the DEJ interface is included. Studies have shown that the K-M theory cannot predict the reflectance of the Enamel-DEJ-dentin complex, because DEJ is a very inhomogeneous medium with a small thickness (Paravina and Powers 2004).

In dentin, the organic component may be responsible for light absorption while the orientation and size of the tubules cause scattering and absorption of light. Light scattering is caused mainly by hydroxyapatitie crystals in enamel and dentinal tubules in dentin (Paravina and Powers 2004).

Double Layer Effect

Enamel and dentin are turbid structures (Spitzer and Bosch 1975). The color of natural teeth is complex and is a result of a combination of optical properties of dental tissues (O'Brien 1985). Dentin is high in value, chroma, and fluorescence, and enamel is translucent and low in chroma and value. The color of natural teeth is determined by the color and diffuse reflectance of dentin, and the thickness and light scattering effect of enamel. This is termed the "double-layer effect"(O'Brien 1985). Therefore the color of a tooth is affected predominantly by dentin and by the translucency of enamel acting as a color modifier (Vichi, Fraioli et al. 2007, Vieira, Arakaki et al. 2008, Xiong, Chao et al. 2008, Li, Xu et al. 2010).

The Absorption And Scattering Of Light In Human Enamel

In a study done by D.Spitzer et al. in 1974 to evaluate the absorption and scattering coefficients of human and bovine enamel, they found that the light absorption of enamel in the region under 300 nm is fully or partly caused by the absorption of the organic components. In addition, the absorption of aromatic amino acids (tryptophan, tyrosine, and phenylalanine are responsible for the proteins' absorption in the region between 240 and 300 nm (Spitzer and Bosch 1975).

The dentinal tubules are responsible for dentin light scattering while hydroxyapatite crystals are responsible for light scattering in enamel (Vaarkamp, ten Bosch et al. 1995).

Three Dimensions Of Color In Dental Tissues

Hue

As discussed earlier the hue is considered the color family. It is defined by the wavelength range of a color that enables perception of a certain color (Sikri 2010). Teeth fall in the yellow, orange, red hue range. In the Vita Classic shade guide, the hues are represented by the A, B, C, and D, where A group falls in the red-yellow range, B group falls in the yellow range, C group in the grey range, and D in the red-yellow-grey range (Boksman 2007).

Value

It represents the brightness of an object, and it is directly related to reflectivity of an object (Boksman 2007). The more light an object reflects, the higher the value. It is the most important primary attribute when studying tooth color (Clark 1931). The brightness of a composite restoration or a porcelain veneer could be increased by decreasing the chroma, or by decreasing the translucency (leading to increase in the reflectivity thus increase in value) (Sikri 2010). Another way to control the value of a composite restoration is to control the thickness of the outer enamel replacement material, which is more translucent than dentin replacement material, so the greater thickness of enamel composite, the lower the value of a restoration.

Chroma

It is the intensity of a color, or the amount of hue in a color (Boksman 2007). The higher the chroma of an object, the lower the value is (inversely related). In the Vita

shade guide, the numbers within each hue group represent the chroma; with higher numbers denoting higher chroma and lower value (Terry, Geller et al. 2002).

The Optical Triad Of Dental Tissues

Translucency

It is a state between transparency and complete opacity. Transparent mediums allow light to pass through, while opaque mediums will reflect and absorb light. On the other hand, translucent mediums have the ability to transmit, reflect, absorb and scatter light depending on many factors like thickness, surface gloss, texture, underlying structure, dehydration, and degree of translucency and opacity (Fondriest 2003). The greater the translucency, the lower the value since more light is scattered or absorbed through the translucent material (Sikri 2010). Enamel is more translucent than dentin.

Fluorescence

It is the ability of a material to absorb light (electromagnetic radiation) at certain wavelengths and then emit it (Sikri 2010). Because of the higher organic components in dentin, it is responsible for the majority of fluorescence in natural teeth. Although teeth emit fluorescence at all wavelengths it is primarily in the blue range of the spectrum. Fluorescence and chroma are inversely related (Fondriest 2003).

Opalescence

It is a property of translucent materials to appear red-yellow in transmitted light, and blue in reflected light (Fondriest 2003). In natural teeth it mainly occurs in enamel

because of hydroxyapatite crystals acting as prisms, so that when illuminated, enamel will allow the transmittance of longer wavelengths (red, yellow) and scatter shorter wavelengths (blue) (Sikri 2010).

Studies On The Color Of Natural Teeth

One of the foundational studies on tooth color assessment was conducted by Clark in 1931. He analyzed the teeth of 1,000 patients over a period of eight years in an attempt to establish specifications of tooth color and to provide basic records for further research in the applications of color in the dental field. He established limits of the three dimensional attributes (brilliance, saturation, and hue) for natural teeth (Clark 1931). He produced a plot of the distribution of hue, value and chroma of natural teeth based on the Munsell color system, and classified teeth into three categories: dark teeth, medium brilliant teeth, and light teeth with an average brilliance of 5.64, 6.53 and 7.12 respectively. According to Clark, the brilliance of the middle third of a tooth could be considered the average brilliance of that tooth (Clark 1931). In addition, in contrary to the general belief he suggested that the dominant hue of natural teeth is yellow and not yellow-red (orange). However, the yellow hues lie in close proximity to the orange boundary.

He demonstrated that saturation and brilliance are directly related and that both increase from the incisal edge to the gingival third. Furthermore, he suggested that extreme hue differences do not exist in the same tooth and that the distribution of hue throughout the tooth crown does not follow any rule. The color of the middle third of a natural tooth is a result of additive mixing of the incisal and gingival thirds of the tooth (Clark 1931).

In 1987 Goodkind RJ et al. conducted a study where the color of 2,830 maxillary

and mandibular anterior teeth was measured using a fiber-optic colorimeter (Sterndent Corp., Stamford, Conn.) at the incisal, middle, cervical thirds. Five hundred subjects participated in the study. For each subject, teeth 6, 7, 8, 25, 26, and 27 were included. Measurements were repeated three times. The R,G,B numbers obtained by the colorimeter were converted to standard tristimulus values X,Y, and Z which are used to determine the Munsell hue, value, and chroma at each site of each tooth. The mean hues at the incisal third were yellower than those of the middle third. The mean hues for the cervical thirds appeared yellow-red. The values means were similar for all thirds, with higher values at the incisal thirds. The chroma means were almost identical for the incisal and middle thirds, while the cervical third appeared more saturated.

Correlation with sex was analyzed, and a statistically significant difference by sex was found for hue, value, and chroma for all three thirds. Women's teeth were slightly yellower, lighter, and less saturated. Regarding birthplace, they found that the 156 teeth from subjects born outside the U.S were slightly more yellowish at the middle third and cervical thirds. The correlations with hair and eye color were not significant. Results were more consistent for correlations of tooth color with age. After the age of 35, teeth became darker, redder, and more saturated, with the exception of cervical thirds where teeth became yellower. In addition, they found that the maxillary anterior teeth were yellower than the mandibular anterior teeth with the exception of the middle third of the maxillary canines where they were redder than that of the mandibular canines. When individual teeth were compared, the canines were found to be darker, less yellow, and more saturated than the corresponding incisors (Goodkind and Schwabacher 1987).

Gozalo-Diaz et al. evaluated the color of central incisors of 120 subjects using a spectroradiometer (PR-705; Photo Research, Inc, Chatsworth, CA, USA) and an assessment of the correlation of the color of maxillary central incisors was made with gender and age. The mean L*, a*, b* values found for the 120 teeth tested was 77.3, 4.2, 19.5 respectively. Additionally they found that 36% of the total variability in L* was

accounted for by the statistically significant predictors of age and gender. Sixteen percent of the total variability in a* was accounted for by the statistically significant predictor of age. The 21% of the variability in b* was accounted for by the statistically significant predictors of age and gender. The mean ΔE (SD) between predicted and observed CIE LAB values for the central incisor was 5.8 (Gozalo-Diaz, Johnston et al. 2008).

As mentioned earlier translucency is one of the most important optical properties that affect the color of natural teeth and the esthetics of a restoration (Winter 1993, Kelly, Nishimura et al. 1996). It is measured by the amount of light transmission or diffuse reflection from a surface of a turbid medium (Brodbelt, O'Brien et al. 1980). In a study done by Brodbelt RH. in 1981 the translucency of human enamel dentin was measured by total transmittance of wavelengths from 400 to 700 nm. He reported that the transmittance coefficient (t_c) of enamel to be $0.481 mm^{-1}$ at 525 nm, and increased with the increase of the wavelength (Brodbelt, O'Brien et al. 1981). In another study conducted by Xiong F. et al. in 2008 the transmittance of the whole tooth was investigated. The translucency of 32 newly extracted maxillary central incisors was measured using a colorimeter (PR-650) at nine locations of the crown. The locations were determined by dividing the tooth crown into nine regions equally, and the relation between the transmittance of natural teeth with age and location was determined. They found that the transmittance of maxillary central incisors ranged from 0.13% to 0.65%, and differed for different regions, and it relatively decreased from incisal to cervical third. In addition, they found that the transmittance of the natural tooth increased with the tooth's age (Xiong, Chao et al. 2008). A summary of CIE L*,a*,b* values reported in studies that have measured the color of maxillary central incisors in vivo is presented in the following tables (Table 1) and (Table 2):

Reference	Method	Subject demographics			Color coordinates		
		Country	Number	Age	L*	a*	b*
Gegauff et al.	Colorimeter	USA	20	20–27	51.1	- 0.1	-0.2
Rubino et al.	Colorimeter	Spain	600	15–50	67.6 ± 7.0	4.3 ± 2.1	12.1 ± 3.3
Zhao and Zhu	Spectrophotometer	China	70	18–70	51.48 ± 8.02	0.62 ± 0.14	0.15 ± 0.02
Odioso et al.	Spectrophotometer	USA	180	13–64	69.3 ±5.92	5.4 ±1.33	18.7 ± 3.37
Russell et al.	Spectrophotometer	Ireland	7	Dental students	48.31	1.35	2.73
Russell et al.	Spectrophotometer	Ireland	7	Dental students	41.31	- 0.91	4.91
Hasegawa et al.	Spectrophotometer	Japan	87	13–84	73.0 ± 5.0	3.5 ± 1.5	16.5 ± 5.0

Table 1: Reported L*a*b* values for central maxillary incisors measured in vivo.

Adapted from Joiner, A. (2004). "Tooth colour: a review of the literature." Journal of Dentistry **32**: 3-12.

Reference	Method	Subject demographics			Color coordinates		
		Country	Number	Age	L*	a*	b*
Cho et al.	Colorimeter	Korea	47	>19	57.8 (3.5) 39.0–65.8	-1.0 (0.9) -5.1 to 4.0	6.7 (3.1) -1.0 to 15.1
Cho et al.	Shade vision system	Korea	47	>19	74.0 (3.4) 64.5–83.2	5.0 (1.5) 1.6–9.8	19.4 (4.0) 10.4–29.0
Zhao and Zhu	Spectrophotometer	China	70	18–70	51.48 (8.02)	0.62 (0.14)	0.15 (0.02)
Zhu et al.	Spectrophotometer	China	162	20–73	54.91 (6.39) 21.89–83.75	-1.69 (1.56) -8.07 to 9.21	9.19 (5.65) -6.53 to 59.89
Zhou et al.	Colorimeter	China	181	15–67	56.0–81.0	-2.5 to 6.0	2.0–28.0
Xiao et al.	Colorimeter	China	405	13–64	70.67 (1.91)	4.29 (2.05)	17.51 (4.13)

Table 2: Reported L*a*b* values for central maxillary incisors measured in vivo.

Joiner, A. (2006). "The bleaching of teeth: a review of the literature." J Dent **34**(7): 412-419.

Effect Of Surroundings On The Color Perception

Colors surrounding the teeth will affect color perception of them (e.g. gingiva, clothing, lipstick). Whenever possible, the surroundings should be neutralized. Additionally, shade matching should be done at intervals of no more than five seconds to avoid the phenomenon of afterimage (Boksman 2007), in which the photoreceptors in the retina will be fatigued and less sensitive to the color one is staring at and more sensitive to the complementary color. And since teeth fall in the yellow-orange hue range, staring at the complementary colors of these hues (blue is the complementary color of orange, while violet is the complementary color of yellow), or preferably a neutral grey card will minimize the afterimage (Sikri 2010).

Some Factors That Affect Tooth Color

Location

The optical properties of a natural tooth may vary at different regions of the crown because of the shape of the tooth and different thicknesses of enamel and dentin (Xiong, Chao et al. 2008). Therefore, multiple measurements are recommended to analyze tooth color (Hasegawa, Ikeda et al. 2000). This appears to increase the reliability of the measurements (Xiong, Chao et al. 2008). The middle third of the tooth has been described as the site that represents the whole tooth's color best, since the incisal edge is more translucent, and the cervical third is affected by the wavelengths reflected from the red gingival tissue (Schwabacher, Goodkind et al. 1994, O'Brien, Hemmendinger et al. 1997). Hasegawa et al. measured the color at five different locations of the labial surface

of tooth using a spectrophotometer, and found a significant variation in the L*a*b* values along the axis. They found that the highest L* values were at the middle, followed by the cervical, and were lowest at the incisal area. For a* and b* the values increased gradually from the incisal to the cervical areas 67 and 87 (Hasegawa, Ikeda et al. 2000, Hasegawa, Motonomi et al. 2000). O'Brien et al. reported similar results when the color of 95 extracted anterior teeth was measured using a spectrophotometer. For the incisal third the mean L*, a*, and b* values reported were 71.4, 0.9 and 12.8 respectively. For the middle third they were 72.4, 1.2 and 16.2, respectively, and for the gingival third they were 72.6, 1.5 and 18.4, respectively (O'Brien, Hemmendinger et al. 1997).

Age

Several reports have described the effect of age on tooth color (Burke and Samarawickrama 1995, Zheng, Nakajima et al. 2005). Some of the changes that may have an effect on tooth color include shrinkage of the pulp, reduction of the blood supply, increase of dentin as a result of deposition of secondary and tertiary dentin, reduced enamel thickness as a result of wear, stain deposition (ten Bosch and Coops 1995, Zijp, ten Bosch et al. 1995, Xiong, Chao et al. 2008), and darkening of teeth with age (Goodkind and Schwabacher 1987, Gozalo-Diaz, Johnston et al. 2008). In addition, it has been reported that natural teeth become more reddish and more yellow with increasing age (Gozalo-Diaz, Johnston et al. 2008). It was demonstrated that the color of teeth shifted towards the yellow color with a range of approximately 0.10 b* for each year of life, and the average lightness decreased by 0.22 L*(Odioso, Gibb et al. 2000).

Bleaching

It has been reported that bleaching of natural teeth increases the value and decreases the chroma (Ishikawa-Nagai, Terui et al. 2004). However, the degree of tooth color change depends on the original tooth color (Ishikawa-Nagai, Terui et al. 2004).

Dehydration

Moisture content has been proven to have an effect on tooth color. Teeth tend to become lighter when dehydrated. The translucency of enamel had been found to decrease with dehydration, and therefore the reflectance is increased (Brodbelt, O'Brien et al. 1981). Russell et al. measured the color of anterior teeth of seven subjects before and after 15 minutes of rubber dam application using a spectrophotometer. They found that the color of teeth become lighter and less saturated with dehydration. The L* and a* significantly increased, while the b* showed no significant difference. The color of teeth returned to the baseline values within 20 minutes of removal of the rubber dam (Russell, Gulfraz et al. 2000)

CHAPTER III

METHODOLOGY

Overview

Dentin is believed to contribute the most to tooth color, while enamel acts as a color modifier. However, there is little information in the literature about the color of enamel and dentin separately and how they contribute to the overall tooth color. No studies have evaluated the difference in color between the tooth as whole and the underlying dentin. The purpose of this in vitro observational study is to evaluate the difference in color between the tooth as a whole and the color of the underlying dentin of maxillary anterior teeth in terms of the color difference value (ΔE), and the three CIE LAB space color coordinates (L*, a*, b*) at three regions of the crown of the tooth (incisal, middle, and cervical thirds). And to define the direction and magnitude of color shift in the CIE LAB color coordinates.

Research Question

What is the difference between the dentin color and the color of the tooth as a whole?

Research Hypotheses

Null Hypothesis (1):

There is no difference between the color of dentin and the color of the tooth as a whole in **L*** at the **incisal third.**

Null Hypothesis (2):

There is no difference between the color of dentin and the color of the tooth as a whole in **L*** at the **middle third.**

Null Hypothesis (3):

There is no difference between the color of dentin and the color of the tooth as a whole in **L*** at the **cervical third.**

Null Hypothesis (4):

There is no difference between the color of dentin and the color of the tooth as a whole in **a*** at the **incisal third.**

Null Hypothesis (5):

There is no difference between the color of dentin and the color of the tooth as a whole in **a*** at the **middle third.**

Null Hypothesis (6):

There is no difference between the color of dentin and the color of the tooth as a whole in **a*** at the **cervical third.**

Null Hypothesis (7):

There is no difference between the color of dentin and the color of the tooth as a whole in **b*** at the **incisal third.**

Null Hypothesis (8):

There is no difference between the color of dentin and the color of the tooth as a whole in **b*** at the **middle third.**

Null Hypothesis (9):

There is no difference between the color of dentin and the color of the tooth as a whole in **b*** at the **cervical third.**

Null Hypothesis (10):

There is no difference between the color of dentin and the color of the tooth as a whole in (ΔE) at the **incisal third.**

Null Hypothesis (11):

There is no difference between the color of dentin and the color of the tooth as a whole in (ΔE) at the **middle third.**

Null Hypothesis (12):

There is no difference between the color of dentin and the color of the tooth as a whole in (ΔE) at the **cervical third.**

Teeth Selection

Eighty nine natural maxillary anterior teeth extracted less than a year prior to the beginning of the study (28 central incisors, 13 lateral incisors, 48 canines) were selected from the pool of extracted teeth at the University of Iowa Dow's Institute for Dental Research where they were stored in 0.2% thymol and distilled water. The teeth selected were sound, with no or minimal wear (no incisal dentin is exposed), and stain free. Age of the extracted teeth was unknown. The surface of the teeth was cleaned with a hand scaler (SH5/33, Hu-Friedy, USA), then placed for five minutes in distilled water in ultrasonic cleaner (Cole-Palmer, Chicago, IL, USA) then cleaned with a toothbrush (Oral-B, USA) under running water. After cleaning, the teeth were placed in a labeled sectioned container and stored in artificial saliva and kept in a refrigerator (Figure 5). Each tooth was randomly assigned a label according to the slot it was randomly placed in in the container. Labels consisted of a letter and a number for future referencing e.g. (A1).

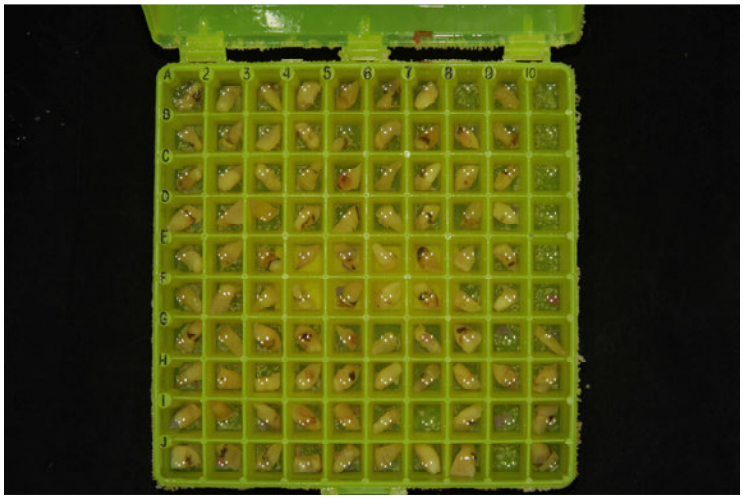

Figure 5: Teeth stored in artificial saliva in a sectioned container.

Radiographs To Determine Enamel Thickness

A digital radiograph was taken at a sagittal plane to determine the enamel thickness for each tooth. Teeth were stabilized on a wooden tongue depressor (Henry Schein Inc., Melville, NY, USA) using rope wax (Modern Materials Inc., Rochester, NY, USA) with the proximal side facing the tongue depressor (Figure 6, a). The tooth on the tongue depressor was submersed in artificial saliva at all times except for moment of taking the radiograph. The radiographs were viewed on a computer screen with MYPACS software (McKesson Technologies Inc., Alpharetta, GA, USA) and a digital ruler was used to measure the thickness of enamel from the facial surface to the DEJ at the incisal, middle, and cervical third (Figure 6, b). Each radiographic image was saved as a .jpg image format with the ruler markings on it and the tooth label was assigned to the image.

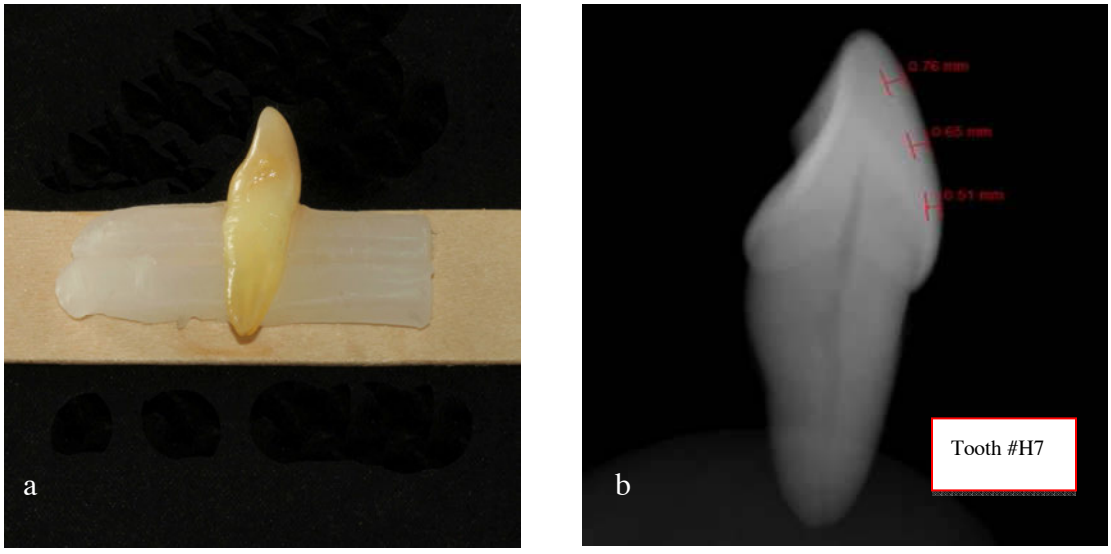

Figure 6: Radiographs to determine enamel thickness.
a) Stabilization of the tooth on a tongue depressor with rope wax.
b) Radiograph of a tooth with measured enamel thicknesses at the incisal, middle and cervical thirds.

Horizontal And Vertical Grooves

Using a diamond disc (Struers Inc.,Cleveland, OH, USA) on a laboratory straight handpiece (KaVo Dental, Charlotte, NC, USA) (Figure 7, a), three horizontal grooves, evenly spaced (2-3mm) with a depth of 1.5 mm were cut through the mesial and distal sides of each tooth. In addition, vertical grooves were cut in the same manner through the incisal edge (Figure 7, b). The grooves were used later as physical reference for the points of measurement. Teeth were kept hydrated at all times until the moment of cutting the grooves and then they were stored back in artificial saliva.

Figure 7: Cutting horizontal and vertical grooves
a) Cutting the grooves on the tooth using a diamond disc.
b) The horizontal and vertical grooves cut into proximal sides, and a incisal edge of the tooth crown.

Mounting

When necessary, the roots were shortened using a diamond bur (Brasseler, Savannah, GA, USA) on a highspeed handpiece (KaVo Dental, Charlotte, NC, USA), to enable the tooth to fit in the typodont (KaVo Dental, Charlotte, NC, USA) slot to be in alignment with the adjacent teeth. Each tooth was mounted in its corresponding position in a typodont, with two artificial teeth adjacent to it at each side (Figure 8). A Vinyl Polysiloxane Bite Registration Material; Regisil (Dentsply Caulk, Milford, DE, USA) was used in the slot and then the tooth was pushed until the Cementoenamel junction (CEJ) was at the same level of the gingival margin of the typodont (Frazier and Dlugokinski 1999) (Figure 9). Teeth were kept hydrated and the typodont was immersed in artificial saliva as soon as the Regisil started setting (Figure 10).

Figure 8: Mounting the teeth on a typodont using polyvinylsiloxane.

Figure 9: Natural tooth mounted on the typodont.

Figure 10: Typodont immersed in artificial saliva.

Color Measurement

Specifications of Spectroshade™ spectrophotometer

The color measurement device used in the current study was Spectroshade™ (MHT Optic Research AG, Zurich, Switzerland) (Figure 11), which is a reflectance spectrophotometer that uses a digital camera/ LED spectrophotometer combination with an internal computer and analysis software. The positioning guide is displayed on an liquid crystal display (LCD) touch screen. Color measurement data can be displayed directly on the device or the data can be transferred to a computer (Chu, Trushkowsky et al. 2010). In the current study the measurements were done directly on the screen.

It employs a 45/0 optical geometry with a D_{65} illuminant source (6500^{o} K) that is transformed to a monochromatic light (λ = 400-720 nm) by means of grating. This light is split in order to illuminate the teeth from two sides at a 45^{o} angle with an intra-oral camera. On both of the system's detector areas (640 · 480 pixels, 8 bit-depth) the reflected light is directed at 0^{o}. Two Charged Couple Devices (CCD) chips are incorporated, one is a color chip responsible for the production of the colored video image, and the other is a white and black CCD image sensor responsible for the determination of the shade value (Paul, Peter et al. 2002).

The computer is able to analyze up to 6 million-reference points every time shade is determined. During a measuring process, light originating from the monochromator of the device is emitted in 20-nm intervals on the target tooth so that 17 photometric spectra of each object are recorded. To eliminate surface gloss caused by the excessive reflection during measurement, polarization filters are used. The resulting images resolution consists of 300,000 pixels (Chu 2003, Karamouzos, Papadopoulos et al. 2007). Within the software, the obtained spectral data are translated into focal images (Dozic, Voit et al. 2010).

Figure 11: Spectroshade spectrophotometer.

Instrument Calibration

Before each measurement session, the instrument was calibrated according to manufacturer's instructions using the white and green calibration tiles. Before calibration, the tiles were cleaned and checked for any dust or debris. When the instrument was powered on, and the image-capturing mode was selected, a note appeared on the screen to place the instrument plastic mouthpiece against the white tile at the base of the instrument mounting-platform (Figure 12). The mouthpiece should cover the white tile that is designed to precisely fit the opening of the mouth piece, and the "capture" button on the handle of the instrument was pressed, then another note appeared to place the mouth

piece in the same manner on the green tile at the base of the instrument mounting platform, and the “capture” button was pressed, then a note appears on the screen indicating calibration of the instrument is complete.

Figure 12: The Spectroshade mounting platform with the white and green calibration tiles.

Capturing Tooth Image With Spectroshade

The plastic mouthpiece provided by the manufacturer was attached; the mouthpiece insures standardized distance between the object (tooth to be captured) and the light source of the Spectroshade. The camera usage bar on the handle was clicked and the camera window appeared automatically, displaying the yellow target box in the center on the LCD screen.

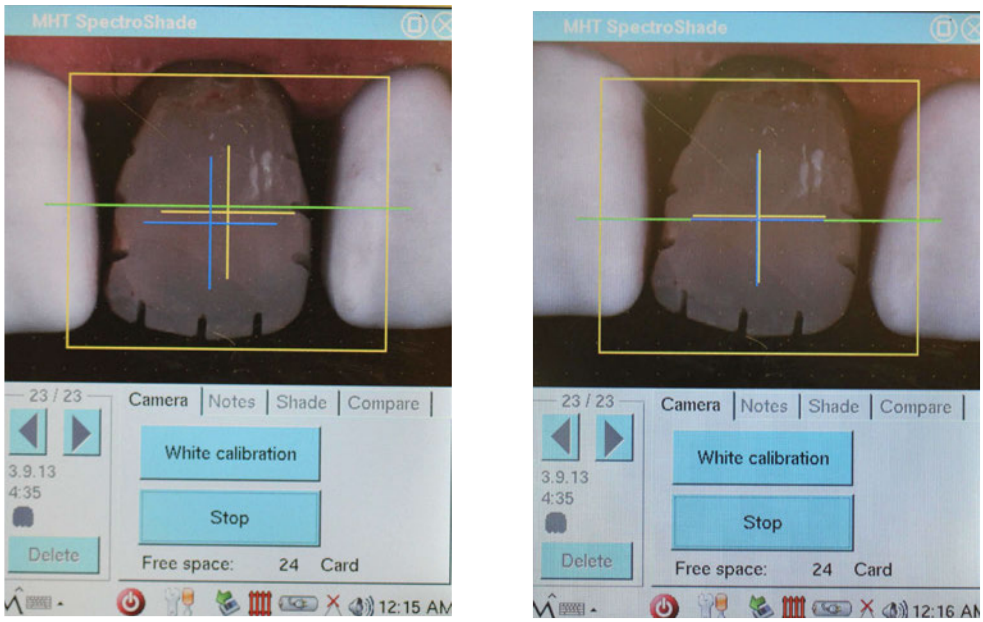

Figure 13: The positing indicators on the LCD screen of Spectroshade. Lines should be overlapped to ensure proper angulation and distance of the target tooth.

The target tooth was centered in the yellow box, and the plus sign in the middle of the target box was centralized on the center of the target tooth. Then, the horizontal alignment indicator (green line) and the vertical alignment indicator (blue line) were aligned with the yellow plus sign in the center of the yellow target box indicating the proper alignment and angulation of the target tooth (Figure 13). When all indicators were overlapped, the "capture" button was pressed. Once the image of the tooth was captured, a color-coded indicator appeared at the lower left corner of the screen. Green color indicates a good image, yellow color indicates an acceptable image, and a red color indicates a bad image. All images were captured with a resulting green color on the indicator to insure good images are captured. If yellow or red colors appeared on the indicator after the image was captured, the image was discarded and another image was taken until the image captured resulted in a green color.

The typodont with the mounted teeth were left immersed in artificial saliva for a week to ensure full hydration before the color measurement. The image of each tooth was

captured with the spectrophotometer (Spectroshade). The vertical and horizontal guiding lines on the screen were used to ensure proper alignment of the tooth.

Grinding Enamel

After the tooth image was captured, the corresponding radiograph (the teeth labels were used to ensure the right image is associated with the right tooth) was magnified on a computer screen using the image viewing software (Preview). Depth grooves were cut at the incisal, middle, cervical thirds of the crown. A periodontal probe was used to measure the depth groves. Then, facial enamel was ground with a diamond bur (Brasseler, Savannah, GA, USA) (Figure 14) in a high speed handpiece (Kavo, Charlotte, NC, USA) with copious water irrigation according to the enamel thickness determined by the radiograph at the incisal, middle, and cervical thirds. Afterwards, the typodonts were immersed back in artificial saliva.

Capturing Dentin Image With Spectroshade

The teeth were left immersed in artificial saliva for another week to ensure full hydration. The dentin image was captured with the spectrophotometer in the same manner as the tooth image was. Vertical and horizontal indicators were used for proper alignment and the image was captured to give a green color indicating a good image.

Figure 14: Mounted tooth after grinding the facial enamel according to the thicknesses obtained from the radiograph.

Color Measurement Of The Tooth And Dentin Images

The "compare" mode was selected in the Spectroshade, which allows the selection of two point on the two images, and automatically displays the L*, a*, and b* values of each of the two points selected and the ΔE values. A square was selected as the shape of the measurement point from the available shapes (round, square, oval), and the diameter of the measurement point selected was 70, which ensures covering the whole facial surface in nine measurements (Figure 15). A grid image with 2mm x 2mm cells was downloaded from a website (http://upload.wikimedia.org/wikipedia/en/b/be/Locator_Grid.png) then printed on a clear sheet, and cut to fit the screen of the device.

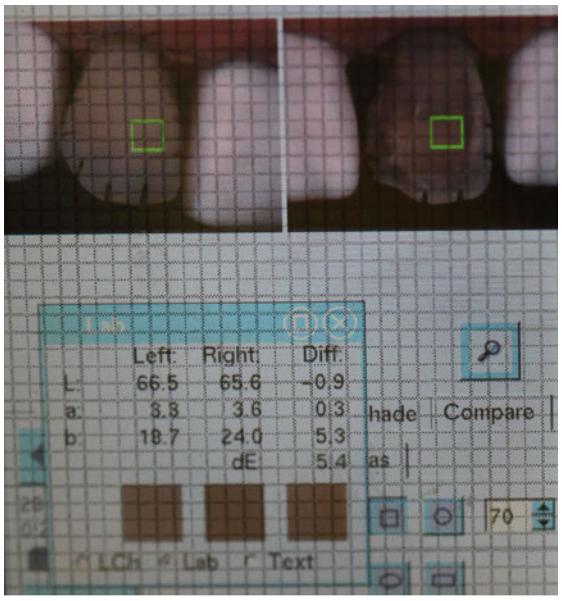

Figure 15: The two images of the tooth and dentin displayed. The clear grid placed on the screen. The same measurement point selected for both images and the color coordinates along with the ΔE values displayed.

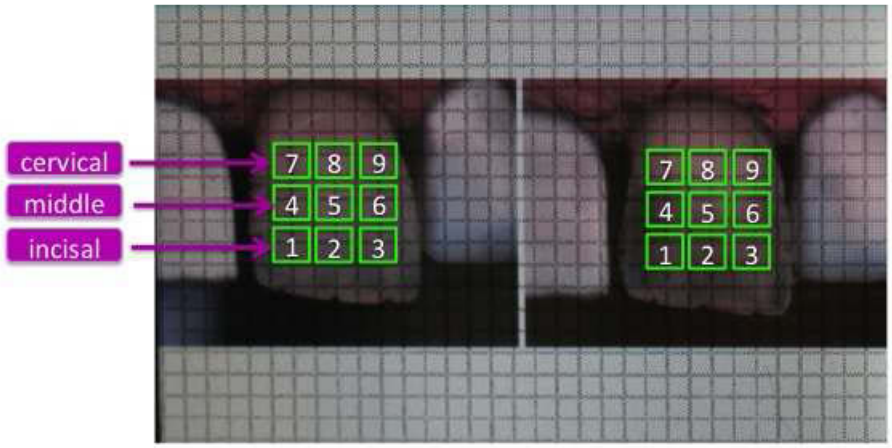

Figure 16: An illustration of the nine measurement points selected at the incisal, middle, and cervical thirds of the tooth

The two images of the tooth, and its corresponding dentin were displayed on the screen and the clear grid was placed on the screen of the spectrophotometer. The grid was

aligned with the previously cut physical horizontal and vertical grooves to ensure that the same point of measurement is selected on both images.

Nine measurement points were selected on each image; three at each third (mesial, middle, and distal sides of the incisal, middle, and the cervical thirds (Figure 16). The readings for each tooth were recorded in a table. An example of the recorded readings of tooth #H7 is presented in table (Table 3).

Tooth # H7				Dentin # H7				ΔE
Third	L	a	b	Third	L	a	b	
Incisal	67.94	3.62	21.71	Incisal	68.9	2.93	23.7	2.31
	68.51	3.45	21.85		69.43	2.67	24.63	3.03
	68.29	3.45	21.62		68.58	2.98	25.17	3.58
Middle	68.14	4.51	26.74	Middle	69.02	3.8	27.49	1.36
	68.68	4.56	26.37		70.67	3.7	27.3	2.37
	68.14	4.74	26.3		69.81	4.07	27.06	1.95
Cervical	66.58	5.89	27.34	Cervical	66.11	5.91	27.23	0.48
	66.53	5.69	27.93		67.18	5.38	28.39	0.86
	64.77	6.29	29.11		65.08	6.09	29.92	0.89

Table 3: An example of the L*, a*, b*, and ΔE values for the nine measurement points at the incisal, middle, and cervical thirds.

And then readings for each third were averaged using excel spreadsheet in the following manner, the ΔE values of each third were averaged as well (Table 4), and then the averaged values were used for the data analyses:

Tooth # H7				Dentin # H7				ΔE
Third	L*	a*	b*	Third	L*	a*	b*	
Incisal	68.2	3.5	21.7	Incisal	69.0	2.9	24.5	3.0
Middle	68.3	4.6	26.5	Middle	69.8	3.9	27.3	1.9
Cervical	66.0	6.0	28.1	Cervical	66.1	5.8	28.5	0.7

Table 4: An example of the averaged L*, a*, b*, and ΔE values for the incisal, middle, and cervical thirds.

Intra-Observer Reliability

Intra-observer reliability tests were performed to verify the reliability of the quantitative measurements made by a single observer for each color measurement. Tooth and dentin images were captured twice by the same blinded observer in a two-week interval for 48 out of the 89 teeth included in the study, then color measurements for the 48 teeth were obtained twice in a two-week interval.

Statistical Analysis

Descriptive statistics were conducted, and a paired-samples t-test was used to determine whether there was a significant difference between the color of dentin and the color of tooth in different thirds of the tooth crown.

Additionally, intraclass correlation coefficient was computed as a measure of agreement between the two duplicate measurements which were made on the same subject by a single observer, and a paired-samples t-test was used to determine whether a significant difference existed between two duplicated measurements made on the same subject by a single observer.

A p-value of less than 0.05 was used as a criterion for statistical significance. Statistical analyses were performed using the statistical package SAS® System version 9.3 (SAS Institute Inc., Cary, NC, USA).

CHAPTER IV

RESULTS

An Overview Of Statistical Methods

Descriptive statistics were conducted, and a paired-samples t-test was used to determine whether there was a significant difference between the color of dentin and the color of tooth in different thirds of the tooth crown.

Additionally, intraclass correlation coefficient was computed as a measure of agreement between the two duplicate measurements which were made on the same subject by a single observer, and a paired-samples t-test was used to determine whether a significant difference existed between two duplicated measurements made on the same subject by a single observer.

All tests utilized a 0.05 level of significance. . Statistical analyses were performed using the statistical package SAS® System version 9.3 (SAS Institute Inc., Cary, NC, USA).

Statistical Results

A total of 89 teeth were included in the study. Descriptive statistics are presented in the following section. The mean difference between the color of dentin and the color of tooth was calculated at the incisal, middle, and cervical thirds. The difference between the color of dentin and the color of tooth is defined as the color of dentin minus the color of tooth.

Intra-Observer Reliability Measurements

Intraobserver agreement was evaluated to assess an agreement on the duplicate measurements made on the same subject by a single observer. Overall, there was very strong evidence that intraclass correlation differed from zero ($p<0.0001$), and the intraclass correlation coefficient of 0.99 indicated strong agreement between the two measurements made by the single observer.

However, the data provided the evidence that there was a significant difference between first and second measurements ($p=0.0074$, a paired-samples t-test). An overall mean difference between the two measurements is: 0.12 ± 1.44. Which is considered not clinically significant.

Descriptive Statistics

Descriptive statistics for the brightness/luminosity (L*) of dentin and the tooth by thirds

The mean values for L* values were calculated individually for the dentin (D) and the tooth (T) at different thirds of the tooth at the incisal (Inc), the middle (Mid), and the cervical thirds (Crv) for all teeth included in the study sample (N) along with their standard deviations (Std Dev), minimums (Min), maximums (Max), and medians, are presented in the following table (Table 5):

Variable	*N*	*Mean*	*Std Dev*	*Min*	*Max*	*Median*
L D Inc	89	69.87	5.47	58.60	81.20	69.40
L T Inc	89	69.84	3.13	64.00	77.00	69.70
L D Mid	89	73.37	5.51	60.30	83.30	73.40
L T Mid	89	71.78	3.57	64.40	79.10	71.90
L D Crv	89	73.49	5.44	51.20	83.10	74.50
L T Crv	89	72.01	3.91	62.40	79.10	73.00

Table 5: Descriptive Statistics of L* at different thirds of the crown.

Note: Luminosity/Value (L), Dentin measurement (D), Tooth measurement (T), Incsial third (Inc), Middle third (Mid), Cervical third (Crv).

Descriptive statistics for the Red-Green axis (a*) of dentin and the tooth by thirds

The mean values for a* values were calculated individually for the dentin (D) and the tooth (T) at different thirds of the tooth at the incisal (Inc) , the middle (Mid), and the cervical thirds (Crv) for all teeth included in the study sample (N) along with their standard deviations (Std Dev), minimums (Min), maximums (Max), and medians presented in the following table (Table 6):

Variable	*N*	*Mean*	*Std Dev*	*Min*	*Max*	*Median*
a D Inc	89	2.14	1.26	-0.10	5.50	1.90
a T Inc	89	2.98	1.36	0.50	7.00	3.00
a D Mid	89	2.48	2.48	1.32	0.30	6.50
a T Mid	89	3.46	3.46	1.45	0.40	7.60
a D Crv	89	3.00	1.29	0.80	6.50	2.90
a T Crv	89	3.93	1.34	0.80	8.10	3.90

Table 6: Descriptive Statistics of a* at different thirds of the crown.

Note: Red-green axis color coordinate (a), Dentin measurement (D), Tooth measurement (T), Incsial third (Inc), Middle third (Mid), Cervical third (Crv).

Descriptive statistics for the Yellow-Blue axis (b*) of dentin and the tooth by thirds

The mean values for b* values were calculated individually for the dentin (D) and the tooth (T) at different thirds of the tooth at the incisal (Inc) , the middle (Mid), and the cervical thirds (Crv) for all teeth included in the study sample (N) along with their

standard deviations (Std Dev), minimums (Min), maximums (Max), and medians presented in the following table (Table 7):

Variable	*N*	*Mean*	*Std Dev*	*Min*	*Max*	*Median*
b D Inc	89	21.26	2.94	14.20	29.50	21.50
b T Inc	89	19.41	3.82	10.50	27.10	19.50
b D Mid	89	23.38	4.56	12.80	52.20	23.50
b T Mid	89	21.92	3.95	11.30	29.60	21.70
b D Crv	89	23.95	3.43	15.80	33.40	23.80
b T Crv	89	23.31	3.34	14.70	30.00	23.40

Table 7: Descriptive Statistics of b* at different thirds of the crown.

Note: Yellow-blue axis color coordinate (b), Dentin measurement (D), Tooth measurement (T), Incsial third (Inc), Middle third (Mid), Cervical third (Crv)

Testing The Difference Between The Color Of Dentin And The Color Of Tooth For Each Parameter By Each third

Difference in L* between the dentin and the tooth at different thirds of the crown

A paired-samples t-test was used to determine whether there was a significant difference between the color in the L*, a*, b* color coordinates and in ΔE of dentin and the color of tooth at different thirds.

The difference in L* between the tooth and the dentin at the incisal, middle and cervical thirds along with the mean, standard deviation, minimum, maximum, median , t-value and p-value are presented in the following table (Table 8):

Variable	*N*	*Mean*	*Std Dev*	*Min*	*Max*	*Median*	*t-Value*	*P-Value*
Diff L DT Inc	89	0.04	3.60	-7.20	8.90	-0.30	0.09	0.9251
Diff L DT Mid	89	1.58	3.08	-6.80	8.00	1.30	4.86	<0.000
Diff L DT Crv	89	1.47	2.46	-12.30	7.50	1.40	5.63	<0.0001

Table 8: Difference in L* at different thirds of the crown.

Note: Difference (Diff), Luminosity/ Value (L), Dentin (D), Tooth (T), Incsial third (Inc), Middle third (Mid), Cervical third (Crv).

Based on the paired-samples t-test, the data provided evidence that there was a significant difference in L* parameter between the dentin and the tooth at the middle and cervical thirds ($p<0.05$ in all instances). Therefore, Hypotheses (2) and (3) were rejected. However, the difference in L* was not statistically different at the incisal third ($p=0.9251$). Therefore, Hypothesis (1) stating that there is no difference in L* between the tooth and dentin at the incisal third, was accepted. For parameter L* results indicate that the mean values of dentin were significantly greater than the mean values of the tooth at the middle and gingival thirds, but not for the incisal third. Comparing the three thirds, the mean L* values for the tooth were the least at the incisal third (69.84), followed by the middle (71.78), and the cervical (72.01) thirds. Similarly, the mean L*

values for dentin were the least at the incisal third (69.87), followed by the middle (73.37), and the cervical (73.49) thirds. However, the difference is negligible.

Difference in a* between the dentin and the tooth at different thirds of the crown

The difference in a* between the tooth and the dentin at the incisal, middle and cervical thirds along with the mean, standard deviation, minimum, maximum, medians ,t-value values and p-value are presented in the following table (Table 9):

For the a* coordinate, the data provided evidence that there was a significant difference between the dentin and the tooth at all thirds ($p<0.05$ in all instances). Therefore, hypotheses (4), (5), and (6) were rejected. The results indicate that the a* mean values of dentin were significantly lower than the a* mean values of the tooth at all three thirds, with the most difference at the middle third. Comparing the three thirds, the mean a* values for the tooth were the least at the incisal third (2.98), followed by the middle (3.46), and the cervical (3.93) thirds. Similarly, the mean a* values for dentin were the least at the incisal third (2.14), followed by the middle (2.48), and the cervical (3.00) thirds.

Variable	*N*	*Mean*	*Std Dev*	*Min*	*Max*	*Median*	*t-Value*	*P-Value*
Diff a DT Inc	89	-0.84	1.18	-4.50	1.50	-0.70	-6.73	<0.0001
Diff a DT Mid	89	-0.98	1.21	-4.70	1.00	-0.80	-7.63	<0.0001
Diff a DT Crv	89	-0.93	0.99	-4.00	0.60	-0.80	-8.83	<0.0001

Table 9: Difference in a* at different thirds of the crown.

Note: Difference (Diff), Red-green axis color coordinate (a), Dentin (D), Tooth (T), Incsial third (Inc), Middle third (Mid), Cervical third (Crv).

Difference in b* between the dentin and the tooth at different thirds of the crown

The difference in b* between the tooth and the dentin at the incisal, middle and cervical thirds along with the mean, standard deviation, minimum, maximum, median,t-value values and p-value are presented in (Table 10).

Similarly, for the b* coordinate, the data provided evidence that there was a significant difference between the dentin and the tooth at all thirds ($p<0.05$ in all instances). Therefore, the hypotheses (7), (8) and (9) were rejected. Furthermore, the results indicate that the b* mean values of dentin were significantly higher than the mean values of the tooth at all three thirds, with the highest difference at the incisal third, followed by the middle and cervical third. Comparing the three thirds, the mean b* values for the tooth were the least at the incisal third (19.41), followed by the middle (21.92), and the cervical (23.31) thirds of the tooth. Similarly, the mean b* values for dentin were

the least at the incisal third (21.26), followed by the middle (23.38), and the cervical (23.95) thirds. However, the difference is negligible

Variable	*N*	*Mean*	*Std Dev*	*Min*	*Max*	*Median*	*t-Value*	*P-Value*
Diff b DT Inc	89	1.85	3.08	-4.80	7.80	2.30	5.66	<0.0001
Diff b DT Mid	89	1.46	4.23	-5.30	32.10	1.40	3.25	0.0016
Diff b DT Crv	89	0.64	2.30	-6.40	7.50	0.50	2.61	0.0107

Table 10: Difference in b* at different thirds of the crown.

Note: Difference (Diff), Yellow-blue axis color coordinate (b), Dentin (D), Tooth (T), Incsial third (Inc), Middle third (Mid), Cervical third (Crv).

Total Color Difference Between The Dentin And The Tooth At Different Thirds Of The Crown

The data indicated that there was a significant difference in color between the dentin and the color at all three locations of the crown (P <0.0001 in all instances) (Table 11). Hypotheses (10), (11), and (12) were rejected. The mean difference was highest at the incisal third (4.88), followed by the middle third (4.32), and the cervical third (3.30) where the difference was the least.

Variable	*N*	*Mean*	*Std Dev*	*Min*	*Max*	*Median*	*t-Value*	*P-Value*
ΔE Inc	89	4.88	2.15	1.70	9.50	4.60	21.38	<0.0001
ΔE Mid	89	4.32	2.11	1.30	9.10	3.70	19.35	<0.0001
ΔE Crv	89	3.30	1.85	0.70	10.50	2.80	16.85	<0.0001

Table 11: Total color difference between the dentin and tooth at different thirds of the crown.

Note: Color difference (ΔE),Dentin (D), Tooth (T), Incsial third (Inc), Middle third (Mid), Cervical third (Crv).

Testing The Difference Between The Color Of Dentin And The Color Of tooth By Each Third For Each Tooth Type

Central incisors

A total of 28 maxillary central incisors were used in the study. The descriptive data for the difference in the color ΔE for the incisal, middle, and cervical thirds are presented in (Table 12).

The mean difference was highest at the incisal third (5.58), followed by the middle third, (3.87) and the cervical third (2.89) where the difference was the least (Table

12). There was a significant difference in color between the dentin and the color at all three locations of the crown of central incisors (P<.0001 in all instances).

Variable	*N*	*Mean*	*Std Dev*	*Min*	*Max*	*Median*	*t-Value*	*P-Value*
ΔE Inc	28	5.58	1.98	2.70	8.50	5.05	14.92	<.0001
ΔE Mid	28	3.87	1.64	1.30	7.60	3.70	12.51	<.0001
ΔE Crv	28	2.89	1.94	0.90	10.50	2.30	7.88	<.0001

Table 12: Total color difference between the dentin and tooth at different thirds of the crown of central incisors.

Note: Color difference (ΔE), Dentin (D), Tooth (T), Incsial third (Inc), Middle third (Mid), Cervical third (Crv).

Lateral incisors

A total of 13 lateral incisors were included in this study. The mean overall color difference was highest at the incisal third (4.02), followed by the middle third, (3.36) and the cervical third (2.42) where the difference was the least (Table 13). There was a significant difference in color between the dentin and the color at all three locations of the crown of lateral incisors (P<.0001 in all instances).

Variable	*N*	*Mean*	*Std Dev*	*Min*	*Max*	*Median*	*t-Value*	*P-Value*
ΔE Inc	13	4.02	1.76	1.70	7.90	3.60	8.24	<.0001
ΔE Mid	13	3.36	1.23	1.60	5.50	3.60	9.89	<.0001
ΔE Crv	13	2.42	0.66	1.40	3.60	2.50	13.32	<.0001

Table 13: Total color difference between the dentin and tooth at different thirds of the crown of lateral incisors.

Note: Color difference (ΔE),Dentin (D), Tooth (T), Incsial third (Inc), Middle third (Mid), Cervical third (Crv).

Canines

A total of 48 lateral incisors were included in this study.

Variable	*N*	*Mean*	*Std Dev*	*Min*	*Max*	*Median*	*t-Value*	*P-Value*
ΔE Inc	48	4.70	2.26	1.70	9.50	4.40	14.41	<.0001
ΔE Mid	48	4.85	2.40	1.40	9.10	4.05	14.01	<.0001
ΔE Crv	48	3.78	1.89	0.70	8.20	3.35	13.84	<.0001

Table 14: Total color difference between the dentin and tooth at different thirds of the crown of canines.

Note: Color difference (ΔE),Dentin (D), Tooth (T), Incsial third (Inc), Middle third (Mid), Cervical third (Crv).

The mean overall color difference was highest at the middle third (4.85), followed by the incisal third, (4.70) and the cervical third (3.78) where the difference was the least (Table 14). There was a significant difference in color between the dentin and the color at all three locations of the crown of canines (P<.0001 in all instances).

Statements On Research Hypotheses

Main Hypothesis conditions	*Conclusion*
Ho (1): There is no difference between the color of dentin and the color of the tooth as a whole in **L*** at the **incisal third.**	Accepted
Ho (2): There is no difference between the color of dentin and the color of the tooth as a whole in **L*** at the **middle third.**	Rejected
Ho (3): There is no difference between the color of dentin and the color of the tooth as a whole in **L*** at the **cervical third.**	Rejected
Ho (4): There is no difference between the color of dentin and the color of the tooth as a whole in **a*** at the **incisal third.**	Rejected
Ho (5): There is no difference between the color of dentin and the color of the tooth as a whole in **a*** at the **middle third.**	Rejected
Ho (6): There is no difference between the color of dentin and the color of the tooth as a whole in **a*** at the **cervical third.**	Rejected
Ho (7): There is no difference between the color of dentin and the color of the tooth as a whole in **b*** at the **incisal third.**	Rejected
Ho (8): There is no difference between the color of dentin and the color of the tooth as a whole in **b*** at the **middle third.**	Rejected
Ho (9): There is no difference between the color of dentin and the color of the tooth as a whole in **b*** at the **cervical third.**	Rejected
Ho (10): There is no difference between the color of dentin and the color of the tooth as a whole in **ΔE** at the **incisal third.**	Rejected
Ho (11): There is no difference between the color of dentin and the color of the tooth as a whole in **ΔE** at the **middle third.**	Rejected
Ho (12): There is no difference between the color of dentin and the color of the tooth as a whole in **ΔE** at the **cervical third.**	Rejected

Table 15: List of study hypothesis with the resulting conclusions.

CHAPTER V
DISCUSSION

The color of natural teeth is a complex phenomenon. It is the result of a combination of the optical properties of enamel and dentin; this is termed the "double-layer effect". Dentin is believed to contribute mostly to the color of the tooth, while enamel acts as a color modifier. The identification of enamel and dentin optical properties is of huge interest for the development of tooth-colored restorative materials (Winter 1993, Chiche and Pinault 1994).

When attempting to restore lost tooth structure that involves enamel and dentin, it is necessary to select the appropriate material that mimics the optical properties of each structure (Ardu, Feilzer et al. 2008). The color of the enamel replacement material is usually determined by matching the shade of the remaining tooth structure or the adjacent tooth. The color of the dentin replacement material is assumed to be one shade darker. There have not been studies that assessed the difference in color between the tooth and the underlying dentin.

This in vitro observational study assessed the difference in color between the tooth as a whole and the underlying dentin in terms of CIE LAB color space coordinates, and the ΔE in extracted natural maxillary anterior teeth at each of the three thirds of the tooth crown (incisal, middle, and cervical).

Color Measurement

Color measurement devices are widely used as an objective method for standardizing and quantifying color. Such devices include colorimeters, spectroradiometers, and spectrophotometers. Colorimeters provide color measurements in

terms of three wavelengths of the visible spectrum. On the other hand, spectrophotometers measure color in all wavelengths of the spectrum, which renders them useful for absolute color measurements and color difference measurements. The present study evaluated color measurement according to the CIE LAB color space, as have other studies (Odioso, Gibb et al. 2000, Russell, Gulfraz et al. 2000, Gozalo-Diaz, Johnston et al. 2008).

In the present study the color measurement device used was Spectroshade, which is a spectrophotometer that provides color measurements and images of the target tooth. The instrument allows for color measurement of a selected area providing the values of L* (luminosity, or value), a* (quantity of red-green), b* (quantity of yellow-blue) color coordinates, or the L (luminosity), c (chroma), h (hue). In addition, the instrument's software converts the color measurement data to specific shades of multiple commercially available shade guide options (Ardu, Feilzer et al. 2008). In comparison with other spectrophotometers available in the market, this instrument has the ability to obtain an image of the tooth and select certain points for the color measurement with different diameters and shapes, providing versatility and flexibility. In addition, it limits errors caused by the surface morphology of the tooth since most colorimeters and spectrophotometers are designed for color measurement of flat surface objects. The edge loss effect is minimized by color measurements made on an image. Reliability of the instrument had been reported to be high (Karamouzos, Papadopoulos et al. 2007).

Teeth Selection

The teeth used for the current study were obtained from the extracted natural teeth pool at the University of Iowa Dows Institute for Dental Research. The facility receives a supply of teeth from dentists around the area and from the College of Dentistry. A total of

89 natural maxillary anterior teeth were selected; among those were 28 central incisors, 13 lateral incisors and 48 canines. The teeth included were sound, stain free on the facial surface and with no or minimal wear.

Sound teeth were selected to avoid the effect of caries or restorative material or surface stains on the results of color measurement. The presence of fillings alters the light passing through the tooth or even obstructs it (Clark 1931). The inclusion of anterior teeth seemed more relevant to a color-related study, since shade determination for posterior teeth is less critical because they are not in the esthetic zone. In addition, the enamel thickness and dentin morphology of posterior teeth differs from that of anterior teeth, and including them would have resulted in a difference in the color measurements between the two classes of teeth. Due to the huge variation in the color of natural teeth, a larger sample size would be more representative, but that imposes a challenge due to the limited availability of sound extracted anterior teeth. The age and the exact source of the selected teeth was unknown, which is considered a limitation of this study since as discussed earlier, age does have an effect on the optical properties of enamel and dentin and therefore would have an effect on the overall color of the teeth (Burke and Samarawickrama 1995, Zheng, Nakajima et al. 2005). Studies have demonstrated that extracted teeth do change in color, and no storage medium can prevent the color changes after extraction (Preston 1985). However, in the current study, teeth were kept hydrated and stored in artificial saliva at all times to avoid any further color change induced by dehydration of the teeth.

Mounting the teeth in a typodont was done to simulate the oral environment, since the color of natural teeth in their environment of red gingival and mucous tissue is affected by the simultaneous contrast and environmental effect of the surroundings. In addition, some light enters the tooth through adjacent teeth and gingival tissue (Clark 1931). Nevertheless, measurement might contain some errors since all influencing conditions cannot be accounted for in the measurement.

Color Difference

The results of the current study demonstrated that there was a statistically significant difference between dentin and the whole tooth in all color coordinates at all thirds except for L* at the incisal third. This could be explained by the dentin being thinnest at the incisal third, therefore it would have a less effect on the color and the brightness there. More important than the statistical difference in color measurements is the direction and amount of the color shift in the coordinates, and the amount of color difference (ΔE).

The data demonstrated that the mean L* (Value/ Luminosity) of the teeth tested was 69.84, 71.78, 72.01 for the incisal, middle, and cervical thirds respectively. For the dentin the mean L* was 69.87, 73.37, 73.49 for the incisal, middle, and cervical thirds respectively. These values are in the range of values obtained by Ardu et al. in a study that evaluated the optical properties of central incisors of ten patients. The instrument used in that study was the same instrument used in this study.

They found that the mean values of L* of enamel-dentin complex against a black and white background were 79.6 and 75.4, respectively (Ardu, Feilzer et al. 2008). In another study done by Dietschi et al. in 2006 to evaluate the color of enamel and dentin, eight extracted human molars in the A and B groups of the Vita shade system were selected and sectioned, and the L*, a*, and b* values were obtained using a colorimeter (Minolta CR- 21, Minolta). The mean L* value obtained for enamel was 70.83 and was grouped according to the age/type of the enamel to young/white with a mean L* of 75.89, adult/neutral with a mean L* of 66.77, and old/yellow-gray with a mean L* of 71.84. For dentin, the overall mean of L* was 72.86, overall mean a* of -3.57, and an overall mean b* of 15.67. Values were grouped according to the Vita shade determined with L* values of 76.11, 77.12, 73.88, 74.06, 74.05, 71.52, 67.67, 68.48 for the following shades A1, B1,

A2, B2, A3, B3, A3.4, A4 respectively (Dietschi, Ardu et al. 2006). However, it is hard to compare the findings with the current study due to differences in the color measurement device used and tooth type.

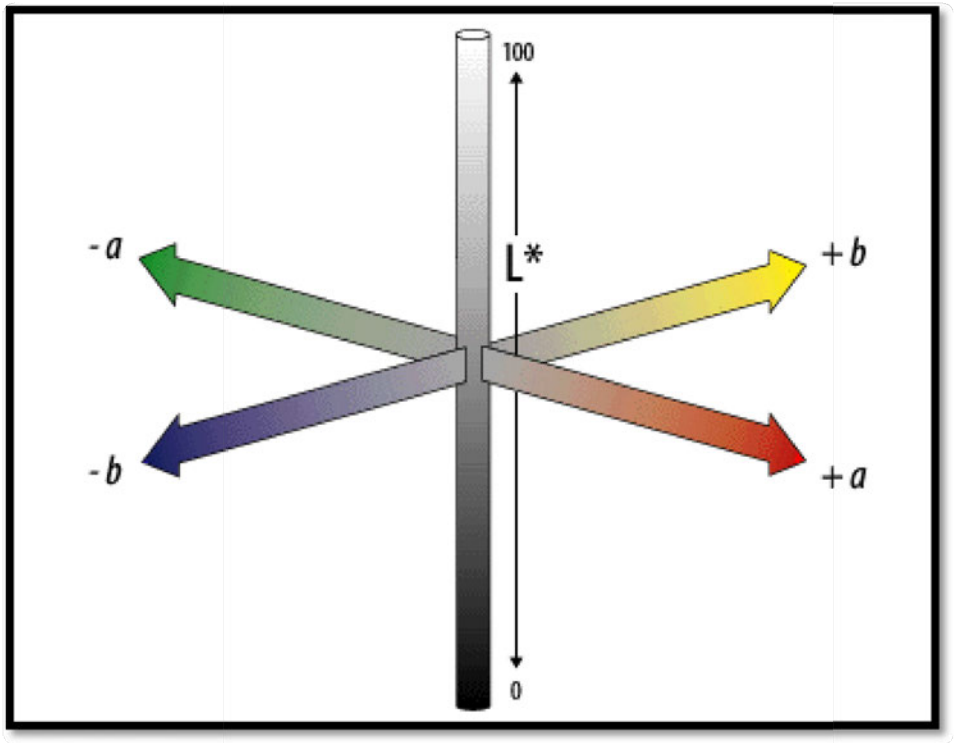

Figure 17: The L, a , b color axes. L* representing the relative lightness/darkness, a* representing the amount of red-green, and b* representing the amount of yellow-blue.

Adapted from http://dba.med.sc.edu/price/irf/Adobe_tg/models/cielab.html

Gozalo-Diaz et al. evaluated the color of central incisors of 120 subjects using a spectroradiometer (PR-705; Photo Research, Inc, Chatsworth, CA, USA) and an assessment of the correlation of the color of maxillary central incisors was made with gender and age. The mean L*, a*, b* values found for the 120 teeth tested was 77.3, 4.2,

19.5 respectively. (Gozalo-Diaz, Johnston et al. 2008).

In the current study, the mean values of L* for dentin were higher than the values for the tooth. This is interpreted as the dentin is lighter than the tooth. This is expected because the dentin is a less translucent structure than enamel. As discussed earlier, when light falls on a translucent medium it could be refracted, absorbed or scattered. The light absorption of a translucent material increases as the thickness increases. Therefore, when the effect of enamel is taken out, the dentin being more opaque reflects more light than when enamel is present, and thus the brightness or reflectivity (luminosity) increases.

For b* there was a statistically significant difference between the tooth and the dentin at all thirds. The mean b* values for the teeth were 19.41, 21.92, 23.31 for the incisal, middle, and cervical thirds respectively, and mean b* values for dentin were 21.26, 23.38, 23.95 for incisal, middle, and cervical thirds respectively. Ardu et al reported mean values of b^* to be 15.2 against black and 8.7 against white background, respectively. The lower b* values obtained in their study could possibly be because of the young age of the patients whose central incisors were measured. Young teeth have thicker and less translucent enamel with less dentin showing through. Another factor could be the fact that only central incisors were measured in their study. Difference between centrals and laterals is so slight, while the cuspids almost always present the same hue and a stronger saturation for all areas with darker gingival thirds and lighter incisal thirds when compared to central and lateral incisors in the same mouth (Clark 1931). Additionally, the teeth in their study were measured in vivo, while in the current study teeth were measured in vitro, and the color of teeth might change after extraction as mentioned previously. In the current study, the mean b* values for dentin were significantly higher than the mean b* values for tooth for all thirds, but the increase is b* was the least in the cervical third. Previous studies had indicated that teeth fall in the yellow hue range, and since dentin is believed to contribute most to the color of the tooth because it is more chromatic than enamel, the results of this study supports that belief. A

higher b* value means there is a shift towards yellow in the yellow-blue axis, meaning that dentin is more yellowish when compared to the tooth as a whole with the enamel overlaying the dentin. The enamel being less chromatic, its acts as a color modifier reducing the show-through of the more yellowish (more chromatic) dentin. The difference in b* is lowest at the cervical third possibly because enamel thickness is lowest at the cervical third (Xiong, Chao et al. 2008, Heymann, Swift et al. 2012), so dentin shows through more at that region of the tooth with less effect of the enamel modification.

Regarding the a* coordinate, there was a statistically significant difference in a* between the tooth and the dentin at all thirds. The mean a* values for tooth were 2.98, 3.46, 3.93 for incisal, middle, and cervical thirds respectively. For the dentin, the mean a* values were 2.14, 2.48, 3.00 for the incisal, middle, and cervical thirds respectively. Similarly, Ardu et al reported mean values of a^* to be 2.1 and -0.3 against black and 8.7 against white background, respectively. Surprisingly, the mean a* values for dentin were lower than the mean a* values for the tooth. Lower a* values indicate a shift away from the red end of the red-green axis. This shift away from the red end could be explained by the opalescence effect of enamel, and that the redness of the tooth comes mainly from enamel. Additionally, this finding supports the belief that teeth fall in the yellow hue range rather than the red hue. The difference was highest in the middle third followed by the cervical third, possibly because of the more thickness of enamel in the middle third of anterior teeth.

In terms of total color difference, the ΔE values show a statistically significant difference between the tooth and the dentin at all thirds. The mean values for ΔE were 4.88, 4.32, 3.30 for the incisal, middle, and cervical thirds respectively. The difference was the least at the cervical third, and this is as expected possibly due to the thinness of enamel at the cervical third of the anterior teeth leading to more dentin showing through at that region, and therefore less difference resulting even when enamel is removed. This

could be used when trying to predict the shade of the underlying dentin for shade matching and selection of a dentin replacement material where the shade of dentin could be matched at the cervical third of the tooth.

For central incisors, the trend is even more pronounced with a mean ΔE values of 5.58 in the incisal third, 3.87 in the middle third, and 2.89 for the cervical third. Similarly, lateral incisors showed mean ΔE values of 4.02, 3.36, 2.42 for incisal, middle, and cervical thirds respectively. However, canines showed the highest overall difference at the middle third with mean ΔE values of 4.70, 4.85, 3.78 for incisal, middle, and cervical thirds respectively. But the difference in ΔE values between the incisal and middle thirds (0.15) is negligible, this is possibly because of the relatively higher thickness of enamel at the middle third of canines where the height of contour in that area. Clark reported that difference between centrals and laterals is slight while the cuspids almost always present the same hue and a stronger saturation for all areas with darker gingival thirds and lighter incisal thirds when compared to central and lateral incisors in the same mouth (Clark 1931).

Perceptibility And Acceptability Of Color Difference

The perceptibility threshold is defined as the color difference value (ΔE) at which the difference in color can be detected by 50% of the observers. Acceptability threshold is the color difference value (ΔE) at which the color difference is acceptable by 50% of the observers, with the other 50% considering it a mismatch (Khashayar, Bain et al. 2013).

Perceptibility thresholds of color differences were found to range from ΔE* = 1.0 to 3.7 (Johnston and Kao 1989, Seghi, Hewlett et al. 1989). Values of ΔE from 0-2 are considered not perceivable by the human eye, 2-3 just perceivable, 3-8 moderately

perceivable and ΔE > 8 is distinctly perceivable (Vichi, Fraioli et al. 2007; Yamanel, Caglar et al. 2010). Acceptability thresholds have been reported to be higher than perceptibility thresholds in dentistry (Johnston and Kao 1989, Douglas and Brewer 1998), they range from ΔE* = 2.72 to 6.8 (Ruyter, Nilner et al. 1987, Johnston and Kao 1989, Ragain and Johnston 2000, Khashayar, Bain et al. 2013).

In this study the color difference between the tooth as a whole and the underlying dentin ΔE values were determined for the different horizontal thirds of the crown. The ΔE was 4.88, 4.32, 3.30 for the incisal, middle, cervical thirds respectively. Based on the perceptibility thresholds defined in the literature the overall color difference between the tooth as a whole and the dentin is considered moderately perceivable at all thirds. However, the values fall within the acceptability thresholds.

For central incisors, the trend is even more pronounced with a mean ΔE values of 5.58 in the incisal third, 3.87 in the middle third, and 2.89 for the cervical third. Similarly, lateral incisors showed mean ΔE values of 4.02, 3.36, 2.42 for incisal, middle, and cervical thirds respectively. However, canines showed the highest overall difference at the middle third with mean ΔE values of 4.70, 4.85, 3.78 for incisal, middle, and cervical thirds respectively.

Evaluating the difference in terms by teeth type, the ΔE values at the incisal (5.58), and middle (3.87) thirds of the central incisors are considered moderately perceivable. However, the ΔE value at the cervical third (2.89) is considered just perceivable. Similarly, in lateral incisors, the ΔE values at the incisal (4.02), and middle (3.36) thirds are considered moderately perceivable, and the ΔE value at the cervical third (2.89) is considered just perceivable. In canines the ΔE values are considered moderately perceivable at all thirds (4.70, 4.85, 3.78). All ΔE values are within the acceptability threshold.

Evaluating The Difference In Color Coordinates By Thirds

Enamel varies in thickness at different regions of the crown. It is thickest at the incisal edge and decrease in thickness gradually until it reaches the CEJ where it terminates. The thickness varies for different classes of teeth; the average thickness of central incisors is 2mm (Heymann, Swift et al. 2012, Xiong, Chao et al. 2008). The means for enamel thickness in this study were 1.07 mm for the incisal third, 0.98 mm for the middle third, and 0.72 mm for the cervical third. Hasegawa et al. reported that both a* and b* of the natural tooth increased when moving in the direction of the cervical third (Hasegawa, Ikeda et al. 2000). This is in agreement with data obtained in the current study, which indicated that the value/luminosity (L*) of the tooth and dentin increased from the incisal to the cervical third. Similarly, the redness (a*) and yellowness (b*) increased from the incisal to the cervical third. Reports that the cervical thirds of the teeth tested were redder and more saturated compared to the incisal, and middle thirds, can be explained by the larger thickness of dentin at the cervical third, in addition to the proximity of the pink gingiva that might scatter some red wavelengths. They also reported the incisal thirds are yellower because of the larger proportion of translucent enamel to pigmented dentin (Goodkind and Schwabacher 1987). This is contrary to the results of this study, possibly because of the difference in the color measurement instrument, and the fact that they used a background to measure the color of the teeth which might have had an effect on the color measurement of the more translucent enamel at the incisal third.

Limitations Of The Study

This in vitro study included extracted maxillary anterior teeth of which the age is unknown. As mentioned earlier, the age has been proven to have an effect on the color of teeth and the optical properties of enamel and dentin. In addition, natural teeth might change in color, and no storage medium can restore that color change. The exact source and extraction time of the teeth are unknown and the media that the teeth had been stored in before they were received by the University of Iowa Dows Institute for Dental Research are unknown as well. In the current study it was impossible to know if any of the teeth included had been previously bleached. Due to the large variation in teeth color, a larger sample size might give more accurate results.

Suggestions For Future Studies

To further improve the knowledge regarding the difference in color between the tooth and the underlying dentin a larger sample size might give more accurate and representative results. To overcome some of the limitations of this current study, color measurements could be done in vivo in teeth that are planned for extraction, where the age, ethnicity of the patient, history of bleaching can be recorded which would have a better representation of the effect of different variables on the optical properties of the enamel and dentin. In addition, the difference in color between the tooth and dentin in bleached teeth could be assessed. Further studies on the relation of tooth color and its comprising structures may allow for creation of a database of esthetic parameters of the teeth, which may be useful for further developments of esthetic restorative materials, and guidelines for more predictability of the outcome of esthetic restorative procedures.

Conclusions

This study assessed the difference in color between the tooth and the underlying dentin in the CIE LAB space color coordinates and the total color difference ΔE at three regions of the crown of maxillary anterior teeth. According to the results of the present study:

- No significant difference in L* exists between the color of tooth and dentin at the incisal third. Therefore, the null hypothesis (1) was accepted.
- A significant difference in L* exists between the color of tooth and dentin at the middle and cervical thirds. Therefore, the null hypotheses (2), (3) were rejected.
- A significant difference in a* exists between the color of tooth and dentin at all thirds. Therefore, the null hypotheses (4), (5), (6) were rejected.
- A significant difference in b* exists between the color of tooth and dentin at all thirds. Therefore, the null hypotheses (7), (8), (9) were rejected.
- A significant difference in ΔE exists between the color of tooth and dentin at all thirds. Therefore, the null hypotheses (10), (11), (12) were rejected.

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

- The dentin is higher in L* than the tooth as a whole.
- The dentin is less reddish than the tooth as a whole.
- The dentin is yellower than the tooth as a whole.
- The overall color difference between the tooth and the dentin is the least at the cervical third.

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