The Optical Effect of Zirconia Background, Ceramic Thickness, and Cement on All-Ceramic Material

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THESIS

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DEDICATION

This thesis is truly dedicated to two people in my life: my father, Masaki Sakai, without whom I'd never have had the inspiration to start, and my husband, Andrew Lee, without whom I'd never have had the determination to finish. This is also dedicated to my family, friends, colleagues, and mentors who have been supportive through this process.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
Bis-GMA	Bis-Glycidydimethacrylate
CIE	Commission International de l'Eclairage
CVD	Color Vision Deficiency
HEMA	Hydroxyethyl Methacrylate
HSD	Honestly Significant Difference
HT	High Translucency
4-META	4-Methacryloxyethyl-Trimellitate Anhydride
MDP	10-Methacryloyloxydecyl Dihydrogen Phosphate
MPa	Mega Pascal
LED	Light Emitting Diode
SD	Standard Deviation
TC	Tooth Color

Summary

This study aimed to investigate the optical influence of various all-ceramic restoration material thicknesses, zirconia abutment background shades and resin cement on the resultant esthetic outcome using a dental spectrophotometer.

Heat-pressed high translucency (HT) lithium disilicate glass ceramic disks (IPS E.max) were fabricated in 4 different thicknesses, ranging from 0.5 to 2.0 mm, and zirconia abutment material disks (Atlantis) with 3.0 mm thickness were fabricated in 3 different shades including the original white shade and 2 newly introduced tooth-colored shades. The all-ceramic disks were placed over zirconia abutment background disks with glycerin, and color measurements were made using a dental spectrophotometer (CrystalEye) for all the crown-abutment combinations with varying lithium disilicate ceramic thickness and varying zirconia shades. For the evaluation of the optical effect of cement, all-ceramic disks were luted to the lightly shaded zirconia abutment disks using tooth-colored resin cement recommended clinically for porcelain restorations by the manufacturer (PANAVIA 21 TC) using 0.1 mm cement film thickness. Color measurements were made for each one of four different ceramic thicknesses, and the color differences were compared to the ceramic-zirconia combinations without resin cement. Three measurements were taken each time, and color differences, ΔE, ΔL^*, Δa^*, and Δb^* values, were calculated with the white zirconia abutment as a control. The mean ΔE, ΔL^*, Δa^*, and Δb^* values were analyzed using two-way ANOVA and the Tukey HSD post hoc test ($p \leq 0.05$).

The mean ΔE values were significantly different for different zirconia abutments shades, ceramic thickness, and the presence of resin cement. Within the limitations of this study, underlying zirconia abutment background shade, lithium disilicate ceramic thickness, and use of resin cement all influence the resultant optical color of all-ceramic restoration material ($p<0.05$). The zirconia abutment background with the darker shade, thinner all-ceramic material, and the presence of tooth-colored resin cement resulted in larger ΔE values with statistical significance ($p<0.05$). Lithium disilicate all-ceramic material with both tooth-colored underlying zirconia abutments demonstrated the color differences at thinner all-ceramic material to be well beyond the clinically acceptable threshold ($\Delta E > 3.7$), and the color differences diminished with increasing overlaying ceramic thickness. The same trend was observed for the ceramic-zirconia combination with resin cement.

Careful selection of the zirconia abutment shade and luting agent at any given ceramic thickness is critical in predicting and obtaining optimal esthetics when using lithium disilicate all-ceramic crowns.

1. INTRODUCTION

1.1 **Background**

Matching the color of artificial teeth to a patient's natural dentition still remains one of the most challenging aspects in aesthetic dentistry. All-ceramic systems offer a new esthetic dimension, particularly in the restoration of anterior teeth, for the reproduction of the natural appearance of teeth with their inherent superior light transmission and depth of translucency.[1-2] Clinicians are then faced with the task of using an all-ceramic restoration to reproduce the desirable shade in conjunction with any existing underlying structures. This task has become more complex as dental materials continue to improve, and patients' demands and expectations for dental esthetics have increased.

Contemporary all-ceramic systems combine high-strength properties with improved esthetics and translucency of the dental restorations.[3-7] Since they allow more light to enter and scatter, their final esthetic results may be significantly affected by discolored dentin, core material, implant abutments, or many choices of luting agents. Several studies have reported the importance of understanding the optical influence of underlying color on the final appearance of all-ceramic restorations.[8-16] Vichi et al. [11] demonstrated that the Empress ceramic crown with a 2 mm thickness was not affected by the color of substrates, but when ceramic thickness was 1.5 mm or less, visually appreciable color differences were observed. Li et al. [10] showed that the color of underlying composite core build-up has a significant optical influence on the resultant color of an all-ceramic restoration. Furthermore, composite cements have been found to create perceptible color differences with particular combinations of die material, cement and ceramic crown.[17]

Today, dental implant restoration is becoming a predictable therapy approach to replace missing teeth with success.[18-26] For some implant sites, titanium metal abutments create a grayish shade that alters the clinical appearance of all-ceramic restorations and the soft tissue complex because of the translucency of all-ceramic restorations or the thin surrounding periimplant tissues.[27-28] Dentin-like shaded zirconia abutments have been recently introduced to provide better light transmission and reflectance through an all-ceramic restoration or thin gingival tissue, thus giving more natural appearance to the restoration. The use of all-ceramic crowns with those zirconia implant abutments may be indicated for esthetically demanding areas.[29-32] However, very few scientific papers are available at present on the optical properties of the shaded zirconia abutments. Their optical performance with varying all-ceramic material thicknesses and luting agents require more investigation for optimizing the resultant esthetics of all-ceramic crowns.

1.2 **Significance**

Several studies have investigated the optical behavior of all-ceramic restorative material. The optical effects of the underlying tooth structure color, the thickness of the ceramic layers, and the color of the cement on all-ceramic material have been demonstrated.[10-12, 16-17, 33-34]

Implant-supported crowns are an established treatment option for tooth replacements with high success rates.[18-20] For esthetically demanding anterior implant situations, clinicians now face the challenge of using an all-ceramic restoration to reproduce the desirable shade in conjunction with implant abutments. Recently, zirconia implant abutments with various dentin-like shades have been introduced to provide enhanced esthetics. However, the popularity of zirconia seems to be progressing, and there is no scientific data available in the literature with regard to the optical properties of the newly introduced shaded zirconia abutments and their optical effect in combination with different thicknesses of all-ceramic material and cement.

This study evaluated the influence of the different zirconia abutment shades with various overlaying all-ceramic restoration thicknesses on the spectrophotometrically measured color of the overlaying ceramic. The optical effect of widely used resin cement with the combination of zirconia abutment and all-ceramic material was also investigated. Furthermore, a sophisticated spectrophotometer designed specifically for dentistry was utilized in this study. This non-contact type spectrophotometer made it possible to measure and analyze the absolute accuracy of ceramic dental restorations by eliminating the effects of edge-loss error.[35-36] The dental spectrophotometer can provide more systematic and precise measurements than colorimeters used in some previous studies.[9, 37-38]

Clinical implications from this study may provide a more methodical approach to better control the material selection and optimize color matching for achieving desired final esthetics. Better understanding of the optical properties and effects of the combination of zirconia abutment shades, overlaying all-ceramic material thickness, and cement may also result in improved communication with dental laboratories, fewer restoration remakes, efficient usage of chair time and better patient satisfaction.

1.3 **Specific Aims**

All-ceramic systems improve color and translucency of dental restorations, and they have been widely used, particularly for anterior restorations requiring optimal esthetics. Lithium disilicate all-ceramic restorations can be fabricated with different levels of translucencies, and it is very versatile for a variety of indications and esthetics needs. Yet, a perfect color match is still a challenge with much complexity. The final color of esthetic all-ceramic restoration is primarily affected by both the thickness of the material and the underlying color.[10-12, 16-17, 33-34] The background colors include the shades of any underlying abutment or substrate and luting cement. Those colors may influence the resultant color of all-ceramic material to different degrees depending on its various thickness, especially when the translucency of overlaying all-ceramic crown is high. Despite the increasing popularity of zirconia abutment and all-ceramic restoration today, the impact of using these different shades of zirconia abutments has not been fully investigated. Therefore, the purpose of this study was to evaluate the optical influence of different zirconia background colors, various ceramic thicknesses, and the presence of cement on the optical color of heat-pressed high translucency (HT) glass-ceramic lithium disilicate-reinforced materials using a dental spectrophotometer.

1.4 **Hypotheses**

The null hypotheses were: (1) the color difference (ΔE, ΔL^*, Δa^*, Δb^*) of the all-ceramic material specimens will not be affected relative to the different zirconia background shades; (2) the color difference (ΔE, ΔL^*, Δa^*, Δb^*) of the all-ceramic material specimens will not be affected relative to various all-ceramic material thicknesses; and (3) a cement will not affect the optical color.

It may be hypothesized that the overall color difference would be increased relative to different zirconia background shades for the thinner all-ceramic material specimens. It may be also hypothesized that the overall color would be affected by the presence of cement for the thinner all-ceramic material specimens.

2. REVIEW OF LITERATURE

2.1 <u>Color Perception in Dentistry</u>

The perception of color is a complicated process affected by a light source, the surface of an object viewed, and the individual observer.[39] The visual system of the human observer responds to the image of an object based on a multitude of features including the wavelength composition of a visual stimulus, size, shape, surface texture, surrounding background, the state of adaptation of the observer's visual system, and the observer's past experiences. Color perception is achieved through the absorption of light by color receptors containing pigments with different spectral sensitivities. There are three classes of color receptors known as cone cells, and consequently, "normal" color vision is described as being trichromatic. The most common form of color vision deficiencies (CVDs), a congenital X-chromosome-linked defect, affects approximately 8% to 10% of males and 0.4% to 0.5% of females.[40] CVDs are classified into three groups; monochromasy, dichromasy and anomalous trichromasy, depending on the number and type of affected cone photopigments. Several studies have reported that 8% to 14% of male dental professionals and students have been found to be color deficient, similar to the findings for general male population.[41-44]

In dentistry, many diagnoses are performed by color perception. The gingival index was developed by Loe and Silness in 1963 to describe the clinical severity of gingival inflammation as well as its location based on color observations.[45] In oral medicine, some oral lesions are associated with particular color changes which may raise a clinician's suspicion for malignancy. For instance, leukoplakia and erythroplakia appear as adherent white mucosal macules and red macules, respectively, and smokeless tobacco keratosis usually presents as a white or gray area. In cariology, white spot lesions on tooth surfaces are known to be areas of decalcified enamel that often progress to decay. Thus, this opaque lesion is useful in detecting early caries, and various protein dyes have been marketed as caries-detection agents. These dyes are purported to stain only infected tissues with different colors. In restorative dentistry, the final color matching of a restoration is as important as its form and function.[46] Esthetically pleasing outcome is crucial in today's dentistry, and it has been shown to positively influence a patients' self-esteem.[47] Color perception truly plays an important role in the final evaluation of restorations.

2.2 **Color Measurement**

Almost eighty years ago, Clark said, "Color, like form, has three dimensions, but they are not in general use. Many of us have not been taught their names, nor the scales of their measurement. In other words, we as dentists are not educationally equipped to approach a color problem."[48] The concept of color is not easy to define, and color matching still to this day is often seen as a matter related more to art than science. However, over several decades with dramatic improvements in scientific knowledge, color order systems to define color in a specific organized matter have been introduced, and many efforts have been made to rationalize color matching between natural teeth and restorative materials.

The first attempt to organize dental colors was made by Clark based mainly on the Munsell color system.[49] The Munsell color system was created by Albert H. Munsell in the first decade of the 20th century.[50] It classifies each color in three attributes, the Hue, Value, and Chroma, and has become the standard for describing the colors of teeth. Hue indicates the name of the colors, such as red, orange, or green, and each hue is related to a specific wavelength band of the visible spectrum. Value is the lightness or darkness of a color. The third dimension, Chroma, refers to the saturation of a color.

In 1931, the Commission International de l'Eclairage (CIE) published the standards for color matching, establishing some scientific parameters for color evaluation.[51] There were few advancements due to the absence of valid scientific instruments available for color measurements. Later, in 1970's, Sproull published a series of articles and described the three dimensional nature of color and its relationship with dental color matching.[39, 52-53] He suggested that the shade guides were inadequate for the complexity given by the appearance of the teeth and there is much room for improvements in dental color application. Mainly led by industrial interests, science of color continued to develop, and in 1976, the CIE developed a new system named CIELAB system.[54-55] CIELAB system was derived to correlate two colors and express color differences numerically. It made it possible to calculate the differences in colors in a way that corresponded to visual perception, since the Munsell color system and the previous CIE specifications were unable to do so due to their irregular space distribution.

The CIELAB colorimetric system has become an accepted method and is widely used for color measurement in dentistry. In this system, color is expressed in terms of three coordinates values, L*, a*, and b*. The L* axis represents the lightness of an object, with values ranging from 0 (completely black) to 100 (completely white). The a* axis represents chromaticity with negative coordinates indicating green and positive coordinates indicating red. The b* axis also represents chromaticity with negative coordinates indicating blue and positive coordinates indicating yellow. The color difference, ΔE, of two objects is constructed by comparing the differences between the respective 3 coordinate values of each object as shown in the following formulas:

$$\Delta L^* = L^*_1 - L^*_2$$

$$\Delta a^* = a^*_1 - a^*_2$$

$$\Delta b^* = b^*_1 - b^*_2$$

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

The value of ΔE indicates the magnitude of the color difference, but it does not show the direction of the color difference. The introduction of the CIELAB system enabled the quantification of color differences which can be corresponded to visual perception, and it is a benchmark tool for colorimetric assessments of natural teeth and dental restorative materials.

2.3 Color Measurement Instruments

In order to reduce color mismatch due to rather subjective visual assessment, two main categories of electronic devices have been developed for dental color analysis, colorimeters and spectrophotometers. Colorimeters are designed to measure color on the basis of three axes in X, Y, and Z tristimulus terms or in CIELAB values by using a filter that simulates the human eye.[56] Spectrophotometers are built to measure the reflectance or transmittance factors of an object for the entire spectral curve with color measurements within the visible spectrum ranging from 350 nm to 800 nm. Colorimeters do not register spectral reflectance by wavelength and thus can be less accurate than spectrophotometers. However, they are relatively simple to use and usually low-cost instruments. Commercially available colorimeters include ShadeVision (X-Rite, Grandville, MI), ShadeEye (Shofu Dental, Menlo Park, CA), and ShadeScan (Cynovad, Montreal, Canada).[57-58] Spectrophotometers are more sophisticated instruments for color matching in dentistry because they can generally provide more systematic and precise measurements than colorimeters.[59] The main components of a spectrophotometer include a source of optical radiation, a means of dispersing light, an optical system for measuring, a photodetector and a means of converting light obtained to a signal that can be analyzed.[56] Spectrophotometers are quite complex devices and used to be too bulky and difficult to handle and correctly calibrate for intraoral in vivo usage. However, recent advances in electronics have resulted in the very latest developments of color measurement devices in which digital images are combined with a portable handheld spectrophotometer. Table I shows the list of commercially available color matching instruments.[57-58] Those devices vary significantly in terms of capable features, measurement area, and cost.

TABLE I

COMMERCIALLY AVAILABLE DENTAL COLOR MATCHING DEVICES

Instrument	Manufacturer	Device Type
ClearMatch	Clarity Dental, Salt Lake City, UT	Software for digital image analysis
CrystalEye	Olympus America, Center Valley, PA	Digital color imaging, Spectrophotometer
EasyShade	Vident, Brea, CA	Spectrophotometer
EasyShade Compact	Vident, Brea, CA	Spectrophotometer
ShadeEye	Shofu Dental, Menlo Park, CA	Colorimeter
ShadeScan	Cynovad, Montreal, Canada	Digital color imaging, Colorimeter
Shade-X	X-Rite, Grandville, CA	Spectrophotometer
ShadeVision	X-Rite, Grandville, CA	Digital color imaging, Colorimeter
SpectroShade Micro	MHT, Niederhasli, Switzerland	Digital color imaging, Spectrophotometer

CrystalEye (Olympus, Tokyo, Japan) is amongst the most accurate and useful new dental spectrophotometers.[58] It can capture entire tooth images and includes an easy-to-use color analysis system and a built-in virtual trial assessment function.[60] The digital images are produced by this device with a 7-band light emitting diodes (LEDs) light source, and the images can depict the tooth color more precisely than conventional systems used with digital cameras. Moreover, the images captured from inside the oral cavity with a small non-contact type cap eliminate external light that can cause discrepancies and the effect of edge-loss error. Edge-loss error caused by the use of a contact type measuring device is often one of the problems resulting in a lower value reading.[61] When color is measured with an instrument that has a relatively small window, a considerable fraction of the light entering the tooth is lost, because it emerges at the surface outside of the window of measurement.[35] This spectrophotometer also utilizes a 45/0° geometry, which is one of the four geometries the CIE recommends for instrumental color measurements of reflecting specimens.[62] The geometry represents the angles of the illuminating light path and the measured light path from the normal to the surface of the object whose color is being determined. The effects of measurements using various geometries have been analyzed, this 45°/0° bidirectional geometry was the most appropriate for measuring the teeth and gingiva.[63] This geometry is reportedly superior for correlation with visual estimates of color and color difference.[56]

The new and advanced dental color measuring instruments with computerized color analysis features may not entirely substitute conventional visual assessment. Many dentists are more familiar with visual color matching using traditional shade guides, and shade matching is still seen as more of art than science with digital instruments. However, these instruments certainly aid clinicians with more standardized and accurate color matching. They also enhance communication with dental laboratories for the reproduction of natural tooth color especially with measuring difficult parameters such as translucency, hue, chroma, and value. Furthermore, these instruments allow for improved understanding of color perception and its correlation with clinical aspects.

2.4 Visual Threshold and Color Perception

Although a human visual system is very adept at recognizing small color differences, the objects viewed in dentistry present many complex factors that make accurate color perception difficult. The color perception of teeth is highly influenced by their shape, size, location, and unique environment of the oral cavity. In addition, the intrinsic color gradation present in teeth from the incisal edge to the cervical area creates intricate color scenes. When evaluating a pair, including a natural tooth and a restoration, translucency and heterogeneous surface characteristics also affect visual judgment. Thus, accurate color assessment in clinical dentistry is a very complex task.

With recent advances in instrumental color measurement technology, it has finally become possible to measure tooth color accurately in the oral environment. Combined visual and instrumental assessments are required to quantify the perceptibility and acceptability visual thresholds in order to interpret color differences and perception in clinical dentistry.[64] The numerical color thresholds would be helpful scientific tools for color judgment.

There are many studies regarding color perception and color matching tolerances in vitro.[37, 65-70] However, their results vary depending on individual methodology with different color measurement instruments and dental materials. Some perceptibility thresholds reported in those in vitro studies ranged from ΔE of 0.7 to 2.0.[66-67, 70] Acceptability thresholds ranged from ΔE of 1.1 to 3.3 for color differences.[68-70] Thresholds for perceptibility judgments have been established to be lower than thresholds for acceptability judgments for color difference in dentistry.[65, 70]

However, the threshold values previously reported may have a limited clinical significance since in vitro experiments do not simulate color matching and visual assessments in an actual intraoral setting. Only a few studies to date have attempted to determine perceptibility and acceptability visual thresholds in vivo. Johnston and Kao used a colorimeter with a fitted metal mouthpiece and measured intraoral color differences between composite resin veneers and adjacent, contralateral, or opposing teeth that were natural or restored. This resulted in the mean perceptibility tolerance ΔE of 3.7.[37] In another clinical study, a spectroradiometer which was not designed for intraoral use was utilized to evaluate color differences between an interchangeable maxillary denture tooth and the rest of the complete denture appearance.[71] It was found that 50% of their dentist observers could perceive a color difference at ΔE of 2.6 and would remake the restoration at ΔE of 5.6. Common limitations of those studies include the size and area of the tooth used for the calculation of ΔE values, as well as the dental materials and colorimetric instruments used in such studies. A recent study utilized a dental spectrophotometer with very specific features, such as measuring geometry, a design to avoid any edge-loss error, and specifications for intra oral use to obtain accurate tooth color measurements.[72] The study concluded that ΔE of 1.6 represented the color difference that could not be detected by the human eye when evaluating the color match of all-ceramic crowns against natural teeth clinically.

Today, the clinical implementation of advanced colorimetric technology with the ability to accurately quantify perceived color and color differences necessitates the further clarification and establishment of human color discrimination thresholds.

2.5 **Ceramics in Dentistry**

The evolution of dental ceramics has been tremendous over the past few decades. The remarkable progress from feldspathic porcelain to the development of zirconia-based all-ceramic material has expanded the range of application of ceramics in dentistry.

Ceramics can be classified by their clinical application, processing technique, or their microstructure.[73] Clinically, ceramics have been used to veneer metallic frameworks for metal-ceramic dental restorations since 1960's.[74] Veneering ceramics fired to metals are processed generally by sintering, and they are usually leucite-based and commonly known as feldspathic porcelains.[75]

Driven by the need for more esthetic materials and metal-free ceramic systems by patients and dentists, all-ceramic systems have been continuously evolving to achieve adequate strength and optimal esthetics. All-ceramic materials encompass a wide range of processing techniques including sintering, heat-pressing, slip-casting, and machining.[73] All-ceramic materials use a broad variety of crystalline phases as reinforcing agents, ranging from 35% to approximately 99% by volume. This increased amount of crystalline phase compared to metal-ceramics is responsible for an improvement in mechanical properties. Their optical properties are influenced by the nature, size and dentistry of particle, refractive indexes of the crystalline phase and glassy matrix, as well as porosity.[75]

Heat-pressing applies external pressure to sinter and shape the ceramic at high temperature, and the mechanical properties of many ceramic systems are maximized with high density and small crystal size.[76] The first generation heat-pressed ceramics are leucite-based with the amounts of crystalline reinforcing phase varying from 35% to 55% by volume.[75] The second generation heat-pressed ceramics contain about 70% lithium disilicate as the major crystalline phase. They are heat-pressed at 920°C which is lower than for the leucite glass ceramic. During the crystallization cycle, a controlled growth of the grain size (0.5–5μm) leads to a glass ceramic that is made up of prismatic lithium disilicate dispersed in a glassy matrix.[75] Lithium disilicate has a unique microstructure consisted of many small interlocking plate-like crystals that are randomly oriented.[77] These crystals cause cracks to deflect, branch or blunt, arresting any potential propagation of cracks through this material. This alteration provide a substantial increase in the flexural strength to 360 MPa and good fracture toughness, which are more than twice that of first generation leucite-based ceramic material.[78] In addition, this material can be highly translucent due to the optical compatibility between the glassy matrix and the crystalline phase by minimizing internal scattering of the light by voids within the material.[79] Lithium disilicate's desirable performance and strength also have led to their expanded use to restorations produced by machining.

2.6 **Resin Cements**

Resin cements are mainly used for the permanent cementation of full coverage all-ceramic restorations, porcelain laminate veneers, indirect composite resin restorations, "Maryland" bridges, and cast restorations in some cases with less than ideal resistance and retention features. Resin cements can be categorized by their polymerization method into 3 groups. Three groups include self-cured, light-cured, and dual-cured materials.[75] Self-cured resin cements are indicated for resin-bonded fixed partial dentures and all-ceramic and composite resin restorations where light may be unable to penetrate fully. Light-cured cements are indicated for all-ceramic and veneer restorations that are thin or translucent enough to allow the light penetration and adequate polymerization of the cement. Lastly, dual-cured cements contain both light-cure and self-cure systems that polymerize the cement with the help of chemical catalysts where light penetration may be limited.

The performance of all-ceramic restorations has been enhanced with the use of resin cements based on laboratory and clinical studies.[80] Resin cements are generally microfilled or hybrid composites formulated primarily from bis-glycidydimethacrylate (Bis-GMA) or urethane dimethacrylate resins and fumed silica or glass filler particles with 20% to 75% by weight.[75] Rein cements provide high compressive strength and low solubility. However, the disadvantages may include possible irritating effects on the pulp and high film thickness, and resin cements may be technique-sensitive with multiple steps.

There are many commercially available resin cements.[81] Some resin cements contain adhesive promoters, such as 10-methacryloyloxydecyl dihydrogen phosphate (MDP), hydroxyethyl methacrylate (HEMA), and 4-methacryloxyethyl-trimellitate anhydride (4-META), which have been claimed to chemically bond to both tooth structure and various restorative materials.[76] One adhesive resin cement (Panavia 21, Kuraray America, New York, NY) is formulated based on Bis-GMA and modified with MDP, and this cement has relatively strong shear bond strengths to etched enamel, alloys, and porcelain.[76] Furthermore, the most recent versions incorporate a self-etching primer system (ED Primer, Kuraray America, New York, NY) to improve bond strength to dentin which was low with the prior version. For bonding to lithium disilicate all-ceramic restorations, ceramics are pre-treated with hydrofluoric acid gel before silanation to dissolve the ceramic surface and roughen it, and silane coupling agents are used to achieve good bond strength.[75] Bonding to zirconia restorations may be achieved by mechanical roughening of the surface and chemical bonding with adhesive monomer contained in specific primers or resin cements. An acidic adhesive monomer, such as MDP, has been reported to bond to zirconia-based ceramics by chemical bonding of the phosphate ester group of the acidic monomer to zirconia and form a cohesive bond with resin cements.[82] Zirconia is a non-silica-based ceramic and does not etch using traditional methods. In order to promote bonding, alternative pretreatment techniques for zirconia include air-particle abrasion and tribochemical silica coating to form a roughened surface to increase mechanical retention prior to chemical bonding with the primer or adhesive cement. The use of those phosphate monomer primers seems to be effective in improving zirconia bonding to resin cements.

3. METHODOLOGY

3.1 **Study Design**

The objective of the present study was to assess the optical influence of different zirconia abutment background color, various ceramic thicknesses, and the presence of resin cement on the final color of heat-pressed glass-ceramic lithium disilicate-reinforced materials using a dental spectrophotometer. Therefore, an in-vitro study was conducted involving bench-top color assessments and data comparisons to fulfill the objectives.

3.2 **Materials and Methods**

To simulate the clinical situation in which a single-unit all-ceramic crown can be bonded on different shades of zirconia abutment substrates, and to evaluate whether the abutment color, ceramic thickness, and resin cement would influence the final esthetic appearance of ceramic crowns, disks of those materials were prepared following the manufacturers’ instructions. To make the disks of a uniform diameter and desired thickness, electronic digital calipers (Fowler, Newton, MA) were used. All disks were evaluated for specified thickness and reduced to within 0.02 mm of the designated thickness by grinding and polishing with 400,600, and 800-grit silicon carbide papers (Carbimet 2, Buehler, Lake Bluff, IL) using the grinding and polishing apparatus in running water (Grinder and Polisher, Buehler, Lake Bluff, IL).

Eight disks of heat-pressed glass-ceramic lithium disilicate-reinforced materials (IPS e.max Press HT Shade B1, Ivoclar Vivadent, Schaan, Liechtenstein) were fabricated each in 0.5, 1.0, 1.5, and 2.0 mm thickness. A 3.0 mm thickness disk of yttrium-stabilized zirconium oxide (Atlantis Abutment in Zirconia, Astra Tech, Waltham, MA) was fabricated each in one original shade and two recently commercially available shaded ones; shade 00 (bleach white), shade 10 (lightly shaded), and shade 30 (medium-dark) (Figure 1). For the assessment of color of different zirconia abutment shades at various ceramic thickness on the final esthetics, different thicknesses of IPS e.max disks were placed, one by one, on each of three background shades with glycerin. For the assessment of optical effect of tooth-colored (TC) resin cement (PANAVIA 21 TC, Kuraray America, New York, NY), eight IPS e.max ceramic disks of each thickness were first cleaned ultrasonically in water for two minutes. Then the disks were etched using 40% phosphoric acid gel (PANAVIA Etching Agent V, Kuraray America, New York, NY) for five seconds, washed and dried. They were silanated (Clearfil Porcelain Bond Activator mixed with Clearfil New Bond, Kuraray America, New York, NY) before the application of the cement. The autopolymerizing composite luting agent was dispensed from the syringe, mixed for 20 – 30 seconds, and applied to the conditioned ceramic surface. Different thicknesses of IPS e.max disks were placed, one by one, on the lightly shaded zirconia abutment disks with a pressure of 500 g weight for the setting time to ensure the cement thickness of 0.1 mm. The digital calipers were used to ensure the cement film thickness was within 0.05 mm of the designated thickness by measuring the total thickness of the ceramic-zirconia combinations before and after the cement application.

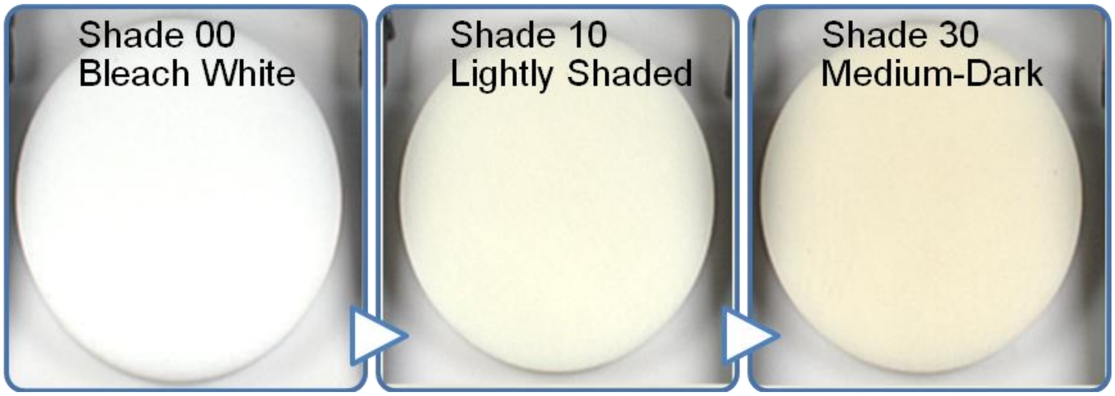

Figure 1. Zirconia Abutment Disk Shades

The color of each ceramic-zirconia combination with or without resin cement was measured three times, and the resultant values were averaged to give the color value of each combination. For color measurement, a dental spectrophotometer (Crystaleye, Olympus, Japan) was used (Figure 2).[28] This spectrophotometer used seven light emitting diodes (LEDs) as an illumination source with 45/0° geometry. At the beginning of each session and prior to data acquisition, the instrument was calibrated using a calibration plate (Olympus, Japan) according to the manufacturer's recommendation. A plastic protective cap which acted as an aperture was placed on the spectrophotometer head, and the spectrophotometer was positioned to capture the sample image. The image capture time was a 0.2 second. The spectral data from the specimen was acquired from the captured image of the specimen. The reflectance values from 400 to 700 nm with 1 nm intervals for each pixel were transferred from the spectrophotometer to a personal computer (Figure 3). The spectrophotometric data was used to calculate the CIELAB color coordinates L*, a* and b*. The color difference, ΔE, was obtained from the L*, a* and b* values, using the following formula, to compare the experimental combination (lightly shaded, medium-dark, lightly shaded zirconia abutment disk with cement) with the control combination (bleach white zirconia abutment disk);

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

$$\Delta L^* = L^*_{control} - L^*_{experiment}$$

$$\Delta a^* = a^*_{control} - a^*_{experiment}$$

$$\Delta b^* = b^*_{control} - b^*_{experiment}$$

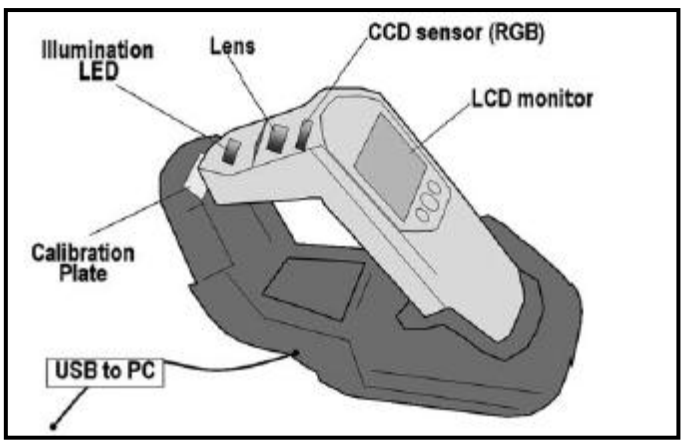

Figure 2. Diagram of Spectrophotometer

Figure 3. Spectrophotometer Device Used to Capture Sample Images

3.3 Statistical Analysis

The means and standard deviations of ∆E values were calculated. For combinations of different zirconia background colors and IPS e.max thicknesses, two-way analysis of variance (ANOVA, $\alpha = 0.05$) was used to analyze the effect of the 2 parameters, zirconia abutment background color and ceramic thickness, for the ∆E values using statistical software (Statistical Package for the Social Sciences, version 15.0; SPSS Inc, Chicago, Ill). When significant difference was found using the two-way ANOVA, the Tukey Honestly Significant Difference (HSD) post hoc test was performed ($\alpha = 0.05$). When a significant interaction effect of the 2 parameters was also found from two-way ANOVA, separate one-way ANOVAs for each zirconia background color were conducted to analyze the main effect of IPS e.max thickness on the ∆E values.

The mean and standard deviation of ∆L*, ∆a*, and ∆b* values were also calculated. Two-way ANOVA was used to analyze the effect of the 2 parameters, zirconia abutment background color and ceramic thickness, for the

ΔL^* and Δb^* values separately. When a significant difference found using the two-way ANOVA, the Tukey HSD post hoc test was performed. When a significant interaction effect of the 2 parameters was also found from two-way ANOVA, separate one-way ANOVAs for each zirconia background color were conducted to analyze the main effect of IPS e.max thickness on the ΔL^* and Δb^* values separately.

In order to compare the specimens with or without resin cement for different IPS e.max thicknesses, the mean and standard deviation of ΔE, ΔL^*, Δa^*, and Δb^* values were calculated and analyzed with the 2 parameters, ceramic thickness and the presence of cement in the same manner as mentioned above.

4. RESULTS

4.1 Optical Properties of Zirconia Abutments

The average L* a* b* values for zirconia abutment background material in three different shades (bleach white, lightly shaded, and medium-dark) are listed in Table II. The L* values varied from 81.54 to 90.81, and the b* values ranged from 1.87 to 15.21. The white zirconia abutment material is "whitest" among the three different shades with the highest value on L*-axis and least "yellow" with the lowest value on b*-axis. The medium-dark zirconia abutment material is least "white" with the lowest value on L*-axis and most "yellow" with the highest value on b*-axis.

TABLE II

AVERAGE L* a* b* VALUES FOR ZIRCONIA ABUTMENT MATERIAL

	L*	a*	b*
Shade 00 (bleach white)	90.81	-1.68	1.87
Shade 10 (lightly shaded)	85.55	-2.50	10.29
Shade 30 (medium dark)	81.54	-1.59	15.21

4.2 Comparison of ∆E Values for Ceramic-Zirconia Combinations

Figure 4 represents the results of mean ∆E values for 4 different IPS e.max specimen thicknesses placed over two different zirconia abutment background shades. The mean ΔE values with a medium-dark zirconia abutment background material were greater than the mean ΔE values with a lightly shaded zirconia background material at all four different overlaying IPS e.max specimen thicknesses (Table III). Comparing within each zirconia background shade, the mean ΔE values were the greatest when the 0.5mm-thick IPS e.max was placed on top. As the thickness of IPS e.max increased, decreases in the mean ΔE values were recorded for both lightly shaded and medium-dark zirconia background specimens.

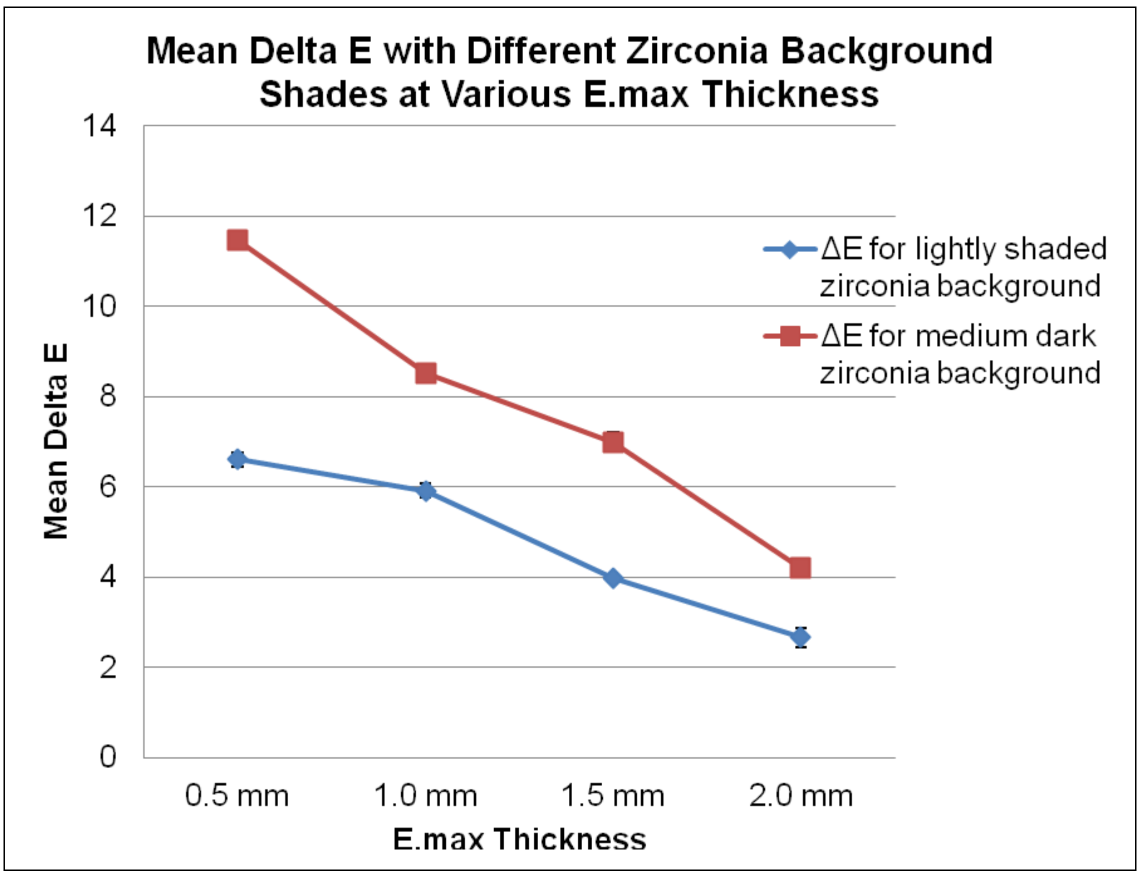

Figure 4. Mean ΔE Values for Ceramic-Zirconia Combinations

TABLE III

ΔE VALUES FOR CERAMIC-ZIRCONIA COMBINATIONS

E.max Thickness	Zirconia Background	Mean Delta E	Std. Deviation
0.5mm	Lightly Shaded	6.60	.16
	Medium Dark	11.46	.12
1.0mm	Lightly Shaded	5.92	.17
	Medium Dark	8.53	.10
1.5mm	Lightly Shaded	3.96	.08
	Medium Dark	6.99	.21
2.0mm	Lightly Shaded	2.66	.21
	Medium Dark	4.21	.20

The results of the two-way ANOVA are presented in Table IV. There were statistically significant differences in ΔE values among different zirconia background shades and IPS e.max material thicknesses ($p < 0.0001$). The ΔE values were influenced by zirconia background shade and ceramic thickness with a significant interaction effect between those two variables. Post-hoc multiple comparisons using Tukey HSD test indicated that all ΔE values were significantly different from each other among 4 different IPS e.max thicknesses with each zirconia background shade (Table V).

TABLE IV

TWO-WAY ANOVA FOR MEAN ΔE VALUES FOR CERAMIC-ZIRCONIA COMBINATIONS

Source	Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	443.130[a]	7	63.304	2436.015	.000
Intercept	2533.819	1	2533.819	97504.000	.000
IPS e.max Thickness	274.981	3	91.660	3527.180	.000
Zirconia Background Shade	145.400	1	145.400	5595.135	.000
IPS e.max Thickness X Zirconia Background Shade	22.750	3	7.583	291.811	.000
Error	1.455	56	.026		
Total	2978.405	64			
Corrected Total	444.585	63			

a. R Squared = .997 (Adjusted R Squared = .996)

TABLE V

POST HOC TUKEY TEST FOR ∆E VALUES FOR CERAMIC-ZIRCONIA COMBINATIONS

	(I) IPS e.max Thickness	(J) IPS e.max Thickness	Mean Difference (I-J)	Std. Error	Sig.
Lightly Shaded Zirconia Background	0.5mm	1.0mm	.68184*	.07970	.000
		1.5mm	2.63949*	.07970	.000
		2.0mm	3.94376*	.07970	.000
	1.0mm	0.5mm	-.68184*	.07970	.000
		1.5mm	1.95765*	.07970	.000
		2.0mm	3.26192*	.07970	.000
	1.5mm	0.5mm	-2.63949*	.07970	.000
		1.0mm	-1.95765*	.07970	.000
		2.0mm	1.30428*	.07970	.000
	2.0mm	0.5mm	-3.94376*	.07970	.000
		1.0mm	-3.26192*	.07970	.000
		1.5mm	-1.30428*	.07970	.000
	(I) IPS e.max Thickness	(J) IPS e.max Thickness	Mean Difference (I-J)	Std. Error	Sig.
Medium Dark Zirconia Background	0.5mm	1.0mm	2.93022*	.08149	.000
		1.5mm	4.46437*	.08149	.000
		2.0mm	7.24489*	.08149	.000
	1.0mm	0.5mm	-2.93022*	.08149	.000
		1.5mm	1.53416*	.08149	.000
		2.0mm	4.31467*	.08149	.000
	1.5mm	0.5mm	-4.46437*	.08149	.000
		1.0mm	-1.53416*	.08149	.000
		2.0mm	2.78051*	.08149	.000
	2.0mm	0.5mm	-7.24489*	.08149	.000
		1.0mm	-4.31467*	.08149	.000
		1.5mm	-2.78051*	.08149	.000

*. The mean difference is significant at the 0.05 level within each zirconia background shade.

4.3 **Comparison of ΔL*, Δa*, and Δb* Values for Ceramic-Zirconia Combinations**

Table VI represents the results of mean ΔL*, Δa*, and Δb* values for four different IPS e.max specimen thicknesses placed over two different zirconia abutment background shades. For the mean ΔL* values, the greatest ΔL* = 7.78 was obtained from the 0.5mm thinnest e.max placed over the darker zirconia background, and the lowest ΔL* = 2.38 was observed with the thickest 2.0mm e.max placed over the lighter zirconia background shade material (Figure 5). The mean Δa* varied from -1.28 to 0.02 with relatively small changes among the different combinations (Figure 6). For the mean Δb* values, the greatest change Δb* = -8.33 was obtained from the 0.5mm thinnest e.max placed over the darker zirconia background. The smallest change Δb* = -0.98 was observed with the thickest 2.0mm e.max placed over the darker zirconia background followed by Δb* = -1.11 with the 2.0mm e.max placed over the lighter zirconia background shade material (Figure 7).

TABLE VI

ΔL*, Δa*, and Δb* VALUES FOR CERAMIC-ZIRCONIA COMBINATIONS

E.max Thickness	Zirconia Background	Delta L*		Delta a*		Delta b*	
		Mean	SD	Mean	SD	Mean	SD
0.5mm	Lightly Shaded	3.75	.20	.02	.13	-5.43	.28
	Medium Dark	7.78	.06	-1.13	.10	-8.33	.20
1.0mm	Lightly Shaded	3.31	.19	-.04	.11	-4.90	.16
	Medium Dark	5.75	.06	-.98	.09	-6.23	.09
1.5mm	Lightly Shaded	3.04	.14	-.32	.10	-2.51	.10
	Medium Dark	6.27	.23	-1.28	.09	-2.81	.11
2.0mm	Lightly Shaded	2.38	.31	-.31	.12	-1.11	.15
	Medium Dark	4.01	.22	-.84	.10	-.98	.13

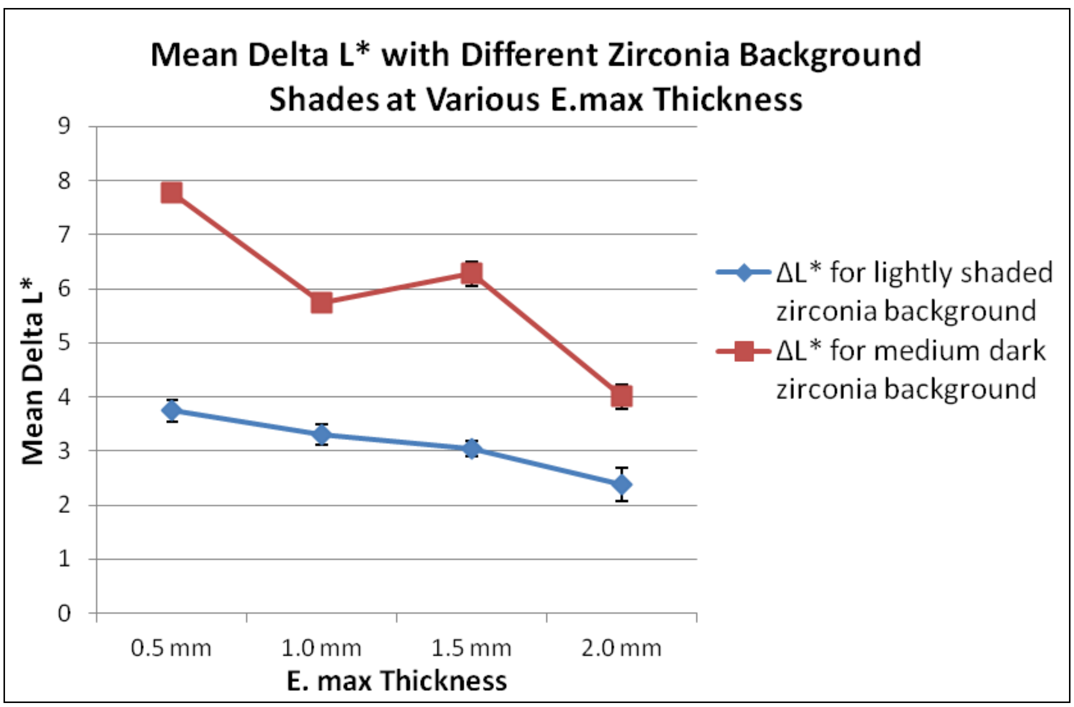

Figure 5. Mean ΔL* Values for Ceramic-Zirconia Combinations

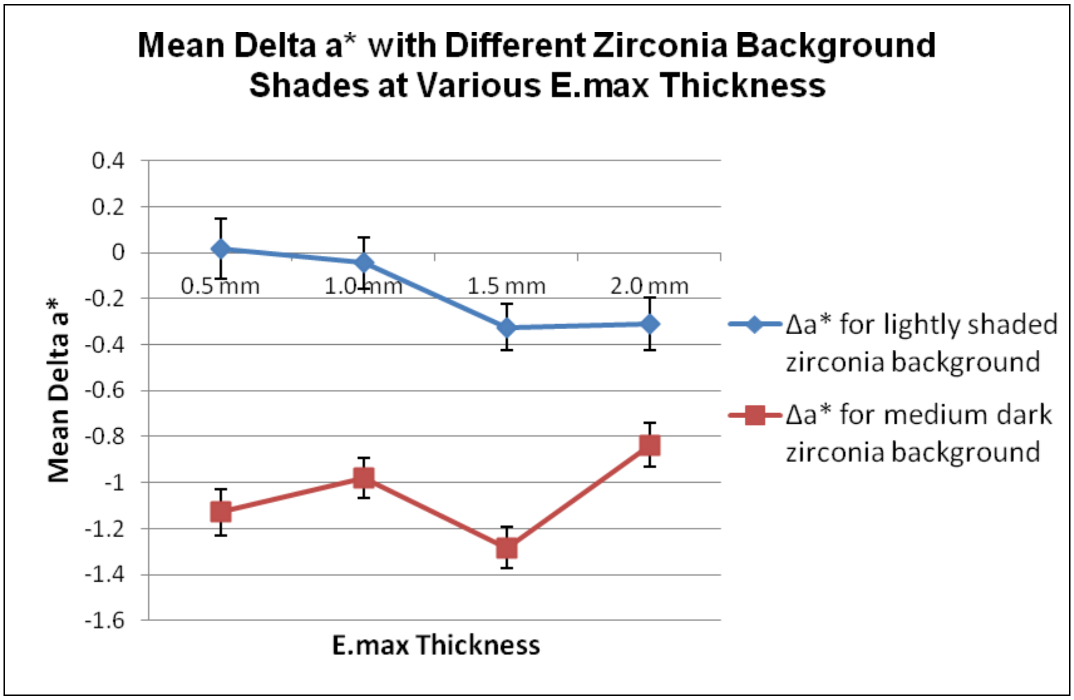

Figure 6. Mean ∆a* Values for Ceramic-Zirconia Combinations

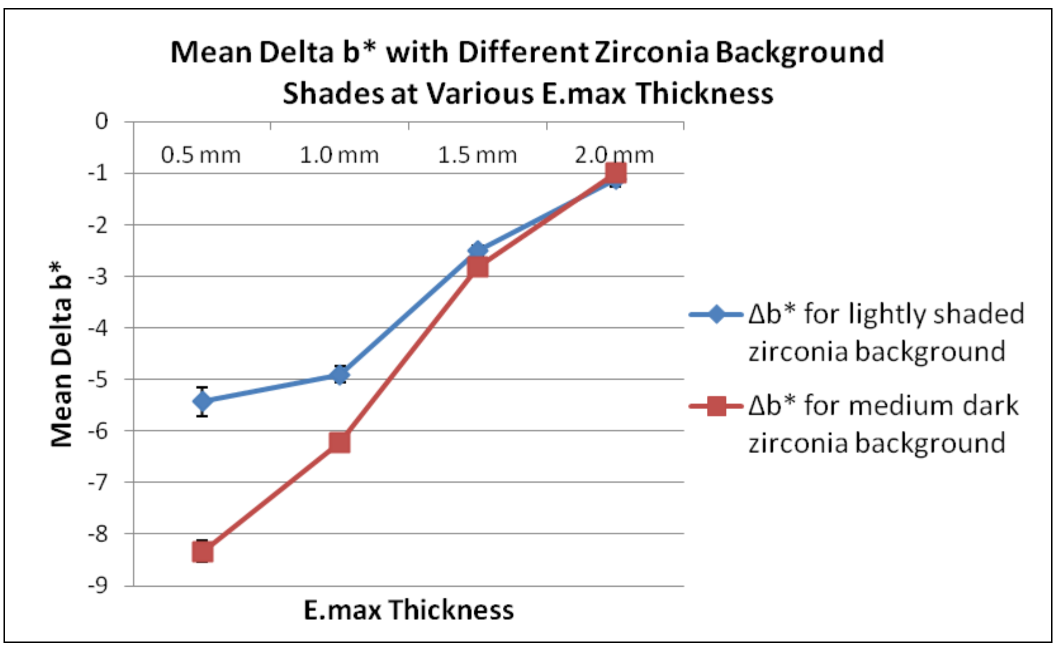

Figure 7. Mean ∆b* Values for Ceramic-Zirconia Combinations

The results of the two-way ANOVA are presented in Table VII and VIII for mean ∆L* and ∆b* values, respectively. There were statistically significant differences within ΔL* and Δb* values among different zirconia background shades and IPS e.max material thicknesses ($p < 0.0001$). The ΔL* and Δb* values were influenced by zirconia background shade and ceramic thickness with a significant interaction effect between those two variables. Tukey HSD post hoc test indicated that all ΔL* values were significantly different from each other among different IPS e.max thicknesses and zirconia background shades except the 1.0mm e.max specimen compared to 1.5mm placed over lightly shaded zirconia background (Table IX). All Δb* values were significantly different from each other among different combinations (Table X).

TABLE VII

TWO-WAY ANOVA FOR MEAN ΔL* VALUES FOR CERAMIC-ZIRCONIA COMBINATIONS

Source	Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	194.584[a]	7	27.798	730.081	.000
Intercept	1316.480	1	1316.480	34576.201	.000
IPS e.max Thickness	53.202	3	17.734	465.766	.000
Zirconia Background Shade	128.539	1	128.539	3375.962	.000
IPS e.max Thickness X Zirconia Background Shade	12.843	3	4.281	112.436	.000
Error	2.132	56	.038		
Total	1513.196	64			
Corrected Total	196.716	63			

a. R Squared = .989 (Adjusted R Squared = .988)

TABLE VIII

TWO-WAY ANOVA FOR MEAN Δb^* VALUES FOR CERAMIC-ZIRCONIA COMBINATIONS

Source	Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	381.288[a]	7	54.470	2071.369	.000
Intercept	1043.532	1	1043.532	39683.309	.000
IPS e.max Thickness	340.090	3	113.363	4310.966	.000
Zirconia Background Shade	19.320	1	19.320	734.687	.000
IPS e.max Thickness X Zirconia Background Shade	21.879	3	7.293	277.332	.000
Error	1.473	56	.026		
Total	1426.293	64			
Corrected Total	382.761	63			

a. R Squared = .996 (Adjusted R Squared = .996)

TABLE IX

POST HOC TUKEY TEST FOR ΔL* VALUES FOR CERAMIC-ZIRCONIA COMBINATIONS

	(I) IPS e.max Thickness	(J) IPS e.max Thickness	Mean Difference (I-J)	Std. Error	Sig.
Lightly Shaded Zirconia Background	0.5mm	1.0mm	.43792*	.10957	.002
		1.5mm	.70375*	.10957	.000
		2.0mm	1.36708*	.10957	.000
	1.0mm	0.5mm	-.43792*	.10957	.002
		1.5mm	.26583	.10957	.095
		2.0mm	.92917*	.10957	.000
	1.5mm	0.5mm	-.70375*	.10957	.000
		1.0mm	-.26583	.10957	.095
		2.0mm	.66333*	.10957	.000
	2.0mm	0.5mm	-1.36708*	.10957	.000
		1.0mm	-.92917*	.10957	.000
		1.5mm	-.66333*	.10957	.000
	(I) IPS e.max Thickness	(J) IPS e.max Thickness	Mean Difference (I-J)	Std. Error	Sig.
Medium Dark Zirconia Background	0.5mm	1.0mm	2.03500*	.08386	.000
		1.5mm	1.50750*	.08386	.000
		2.0mm	3.77375*	.08386	.000
	1.0mm	0.5mm	-2.03500*	.08386	.000
		1.5mm	-.52750*	.08386	.000
		2.0mm	1.73875*	.08386	.000
	1.5mm	0.5mm	-1.50750*	.08386	.000
		1.0mm	.52750*	.08386	.000
		2.0mm	2.26625*	.08386	.000
	2.0mm	0.5mm	-3.77375*	.08386	.000
		1.0mm	-1.73875*	.08386	.000
		1.5mm	-2.26625*	.08386	.000

*. The mean difference is significant at the 0.05 level.

TABLE X

POST HOC TUKEY TEST FOR Δb* VALUES FOR CERAMIC-ZIRCONIA COMBINATIONS

	(I) IPS e.max Thickness	(J) IPS e.max Thickness	Mean Difference (I-J)	Std. Error	Sig.
Lightly Shaded Zirconia Background	0.5mm	1.0mm	-.52208*	.09176	.000
		1.5mm	-2.91500*	.09176	.000
		2.0mm	-4.31542*	.09176	.000
	1.0mm	0.5mm	.52208*	.09176	.000
		1.5mm	-2.39292*	.09176	.000
		2.0mm	-3.79333*	.09176	.000
	1.5mm	0.5mm	2.91500*	.09176	.000
		1.0mm	2.39292*	.09176	.000
		2.0mm	-1.40042*	.09176	.000
	2.0mm	0.5mm	4.31542*	.09176	.000
		1.0mm	3.79333*	.09176	.000
		1.5mm	1.40042*	.09176	.000
Medium Dark Zirconia Background	(I) IPS e.max Thickness	(J) IPS e.max Thickness	Mean Difference (I-J)	Std. Error	Sig.
	0.5mm	1.0mm	-2.10875*	.06877	.000
		1.5mm	-5.52500*	.06877	.000
		2.0mm	-7.35167*	.06877	.000
	1.0mm	0.5mm	2.10875*	.06877	.000
		1.5mm	-3.41625*	.06877	.000
		2.0mm	-5.24292*	.06877	.000
	1.5mm	0.5mm	5.52500*	.06877	.000
		1.0mm	3.41625*	.06877	.000
		2.0mm	-1.82667*	.06877	.000
	2.0mm	0.5mm	7.35167*	.06877	.000
		1.0mm	5.24292*	.06877	.000
		1.5mm	1.82667*	.06877	.000

*. The mean difference is significant at the 0.05 level.

4.4 Optical Effects of Resin Cement on Ceramic-Zirconia Combinations

Figure 8 represents the results of mean ΔE values for 4 different IPS e.max specimen thicknesses placed over slightly shaded zirconia abutment background with or without TC PANAVIA resin cement. The mean ΔE values with cement were greater than the mean ΔE values without cement at all four different IPS e.max specimen thicknesses (Table XI). As the thickness of IPS e.max increased, decreases in the mean ΔE values were recorded for both samples with or without cement.

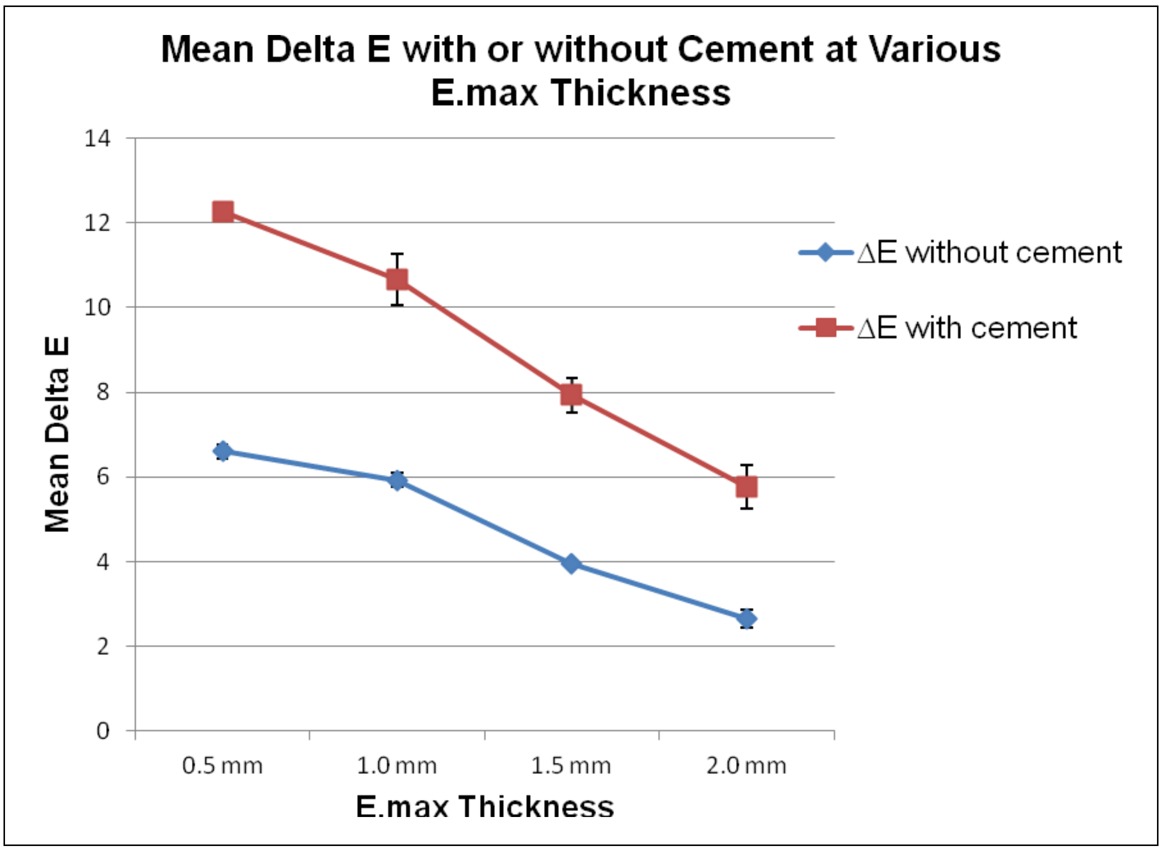

Figure 8. Mean ΔE Values for Ceramic-Zirconia Combinations with or without Cement

TABLE XI

ΔE VALUES FOR CERAMIC-ZIRCONIA COMBINATIONS WITH OR WITHOUT CEMENT

E.max Thickness	Lightly Shaded Zirconia Background	Mean Delta E	Std. Deviation
0.5mm	No Cement	6.60	.16
	With Cement	12.28	.18
1.0mm	No Cement	5.92	.17
	With Cement	10.66	.61
1.5mm	No Cement	3.96	.08
	With Cement	7.93	.41
2.0mm	No Cement	2.66	.21
	With Cement	5.77	.51

The results of the two-way ANOVA are presented in Table XII. There were statistically significant differences in ΔE values among IPS e.max material thicknesses and the samples with or without cement ($p < 0.0001$). The ΔE values were influenced by ceramic thickness and the presence of cement with a significant interaction effect between those two variables. Post-hoc multiple comparisons using Tukey HSD test indicated that all ΔE values were significantly different from each other among four different IPS e.max thicknesses with or without cement (TableXIII).

TABLE XII

TWO-WAY ANOVA FOR MEAN ∆E VALUES FOR CERAMIC-ZIRCONIA COMBINATIONS WITH OR WITHOUT CEMENT

Source	Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	583.896[a]	7	83.414	715.995	.000
Intercept	3110.608	1	3110.608	26700.381	.000
IPS e.max Thickness	263.554	3	87.851	754.087	.000
Presence of Resin Cement	306.038	1	306.038	2626.927	.000
IPS e.max Thickness X Presence of Resin Cement	14.304	3	4.768	40.926	.000
Error	6.524	56	.117		
Total	3701.028	64			
Corrected Total	590.420	63			

a. R Squared = .989 (Adjusted R Squared = .988)

TABLE XIII

POST HOC TUKEY TEST FOR ΔE VALUES FOR CERAMIC-ZIRCONIA COMBINATIONS WITH OR WITHOUT CEMENT

	(I) IPS e.max Thickness	(J) IPS e.max Thickness	Mean Difference (I-J)	Std. Error	Sig.
Without Cement	0.5mm	1.0mm	.68184*	.07970	.000
		1.5mm	2.63949*	.07970	.000
		2.0mm	3.94376*	.07970	.000
	1.0mm	0.5mm	-.68184*	.07970	.000
		1.5mm	1.95765*	.07970	.000
		2.0mm	3.26192*	.07970	.000
	1.5mm	0.5mm	-2.63949*	.07970	.000
		1.0mm	-1.95765*	.07970	.000
		2.0mm	1.30428*	.07970	.000
	2.0mm	0.5mm	-3.94376*	.07970	.000
		1.0mm	-3.26192*	.07970	.000
		1.5mm	-1.30428*	.07970	.000
With Cement	(I) IPS e.max Thickness	(J) IPS e.max Thickness	Mean Difference (I-J)	Std. Error	Sig.
	0.5mm	1.0mm	1.62014*	.22781	.000
		1.5mm	4.34467*	.22781	.000
		2.0mm	6.50509*	.22781	.000
	1.0mm	0.5mm	-1.62014*	.22781	.000
		1.5mm	2.72453*	.22781	.000
		2.0mm	4.88495*	.22781	.000
	1.5mm	0.5mm	-4.34467*	.22781	.000
		1.0mm	-2.72453*	.22781	.000
		2.0mm	2.16041*	.22781	.000
	2.0mm	0.5mm	-6.50509*	.22781	.000
		1.0mm	-4.88495*	.22781	.000
		1.5mm	-2.16041*	.22781	.000

*. The mean difference is significant at the 0.05 level.

Table XIV represents the results of mean ΔL*, Δa*, and Δb* values for 4 different IPS e.max specimen thicknesses placed over the lightly shaded zirconia abutment background with or without resin cement. For the mean ΔL* values, the greatest ΔL* = 6.41 was obtained from the 0.5mm thinnest e.max placed over the zirconia background with cement, and the lowest ΔL* = 2.38 was observed with the thickest 2.0mm e.max placed without cement. The changes on a*-axis, described by the mean Δa* values, with cement were greater than the ones without cement at all 4 different IPS e.max specimen thicknesses. For the mean Δb* values, the greatest change Δb* = -10.31 was obtained from the 0.5mm thinnest e.max with cement, and the smallest change Δb* = -1.11 was observed with the thickest 2.0mm e.max without cement.

TABLE XIV

ΔL*, Δa*, AND Δb* VALUES FOR CERAMIC-ZIRCONIA COMBINATIONS WITH OR WITHOUT CEMENT

E.max Thickness	Zirconia Background	Delta L*		Delta a*		Delta b*	
		Mean	SD	Mean	SD	Mean	SD
0.5mm	No Cement	3.75	.20	.02	.13	-5.43	.28
	With Cement	6.41	.12	-1.84	.12	-10.31	.16
1.0mm	No Cement	3.31	.19	-.04	.11	-4.90	.16
	With Cement	5.88	.48	-1.99	.23	-8.66	.39
1.5mm	No Cement	3.04	.14	-.32	.10	-2.51	.10
	With Cement	5.79	.30	-2.70	.33	-4.68	.34
2.0mm	No Cement	2.38	.31	-.31	.12	-1.11	.15
	With Cement	4.89	.34	-2.26	.35	-2.04	.41

5. DISCUSSION

5.1 Optical Effect of Zirconia Background and Ceramic Thickness

Demands for highly esthetic restorations with advances in prosthetic fabrication processes and techniques have led to the introduction of tooth-colored zirconia implant abutments. This yttrium-stabilized zirconium oxide alternative material for implant abutments is reported to have improved mechanical strength and reliability due to its unique stress-induced transformation toughening mechanism and proven biocompatibility.[83-86] Despite its growing popularity, no scientific data are available with regard to the esthetic performance of those newly introduced tooth-colored zirconia abutments in combination with all-ceramic restorative crowns and dental cement.

The present study investigated the optical effect of two newly introduced zirconia abutment shades and different thicknesses of overlay all-ceramic crown material on the final measurable color in comparison to the original white zirconia abutment shade control. The color differences expressed in CIELAB colorimetric system were determined and analyzed to investigate their optical properties.

Both shaded zirconia abutment materials created significant color changes in the final all-ceramic color, and the overall color differences expressed in ΔE values were significantly greater with the medium-dark zirconia material compared to the lightly shaded zirconia material. This significant optical influence of underlying substrate color on the final appearance of all-ceramic restoration agreed with the findings of previous reports in the literature.[9, 11, 33] The lightly shaded and medium-dark colors of zirconia abutments were introduced to provide flexibility for the wide range of patient-specific esthetic demands. Those shaded materials were indeed found to have lower L* values and higher b* values with substantial differences among them; therefore, the abutment color differences were visually appreciable from each other as well as from the original bleach white zirconia abutment. This darker and yellower optical property of the medium-dark abutment contributed to significantly larger ΔE values compared to the lightly shaded abutment at all four clinically relevant thicknesses of the evaluated overlay all-ceramic material. This result emphasized the clinically significant impact of the established optical effect of underlying substrate shade on the final esthetics of the all-ceramic crowns.

For both shaded zirconia abutment materials, the greatest ΔE values were observed with the thinnest 0.5 mm overlay all-ceramic material tested, and the ΔE values decreased as the thickness of all-ceramic material increased. The overall color differences in the final all-ceramic assembly was found to be significantly influenced by ceramic thickness as previously indicated in several previous studies.[9, 11, 33] Increased thickness of all-ceramic material leads to greater absorption of incident light and more diffused reflection within the ceramic with increased internal scattering and opacity. As a consequence, the underlying abutment material has lessened diffused reflection effects, and the optical effect of abutment shade is diminished. The diminishing optical influence of dentin-colored zirconia abutment with increasing overlay ceramic thickness was demonstrated in steadily decreasing ΔE values. In fact, with 2.0 mm all-ceramic ceramic thickness, the lightly shaded zirconia abutment was observed with a mean ΔE value of 2.66, which would be a color difference within the acceptable range for dental restoration color matching (ΔE < 3.7).[37] This finding is consistent with the past study that suggested all-ceramic crowns with a 2.0 mm thickness did not show significantly appreciable color difference for the final esthetics with various underlying substrate, resin cement and thickness.[11] The present study showed high ΔE values ranging from 3.96 to 11.46 for all other ceramic-zirconia combinations with varying ceramic thickness and abutment shade. Those ΔE values were above the threshold for clinically acceptable color difference with especially high ΔE values obtained with 0.5 mm and 1.0 mm ceramic thicknesses. This was mainly due to the optical property of the all-ceramic material used in this study having high translucency. In IPS e.max HT, the lithium disilicate crystals and the glass matrix have similar refractive indices of light, and this reduces internal scattering of the light which normally causes a higher opacity in order to achieve a very high translucency.[75] As a result, this all-ceramic material is highly sensitive to any change in the underlying color.

The optical effects of varying zirconia abutment shades and overlay ceramic thicknesses on the final color were further investigated for any changes in three color coordinate L*, a*, and b* values. Both shaded zirconia abutments showed a significant darkening effect compared to the control white zirconia abutment at all four clinically relevant overlay ceramic thicknesses. In addition, the ΔL* values with the medium-dark zirconia abutment were considerably greater than the ΔL* values with the lightly shaded zirconia abutment at all ceramic thicknesses. At each ceramic thickness, the lower L* values compared to the control can be explained by the markedly lower L* value of the shaded zirconia abutments and the high translucency property of IPS e.max. This overlay all-ceramic material seems to inherently reflect any changes in L* values of the underlying shades and result in large ΔL* values of the final color. The largest ΔL* value, 7.78, was observed for the final color with the thinnest 0.5 mm ceramic and the medium-dark abutment, and the smallest ΔL* value, 2.38, was observed for the final color of the thickest 2.0 mm and the lightly shaded zirconia abutment. For each shaded zirconia abutment, the mean ΔL* values with 2.0 mm ceramic thickness were significantly reduced compared to those with 0.5 mm ceramic thickness. The thicker all-ceramic material with translucency can absorb more incident light and reflect reduced quantity of light, thus resulting in substantially lower L* values.

Despite the trend of diminishing ΔL* values with increasing ceramic thickness, for the lightly shaded zirconia abutment, the ΔL* values did not significantly differ between 1.0 mm and 1.5 mm ceramic thicknesses. Furthermore, for the dark-medium zirconia abutment, the ΔL* value increased with 1.5 mm ceramic thickness compared with 1.0 mm ceramic thickness. The increase between those two mean ΔL* values was only 0.52, thus the consequent ΔE = 0.52 caused by this was far below perceptible color difference. This increase in ΔL* may be due to inconsistencies in surface textures, surface finishing, specimen thickness, and measuring errors. Obregon et al demonstrated that the smooth surface porcelain surface texture increased the value particularly in B1 shade used in the present study.[87] Roughness, waviness, and glossiness of surface and possible voids in glycerin between the zirconia abutment and ceramic specimens may also influence reflectance and translucency, potentially affecting ΔL^* values.[88] All specimens, measuring instruments and techniques were standardized, however a compound of subtle discrepancies may be adequate to cause a localized miniscule increase in ΔL^* values seen here without affecting ΔE, Δa^* or Δb^* values. Lastly, regarding the ΔL^* values, for the medium-dark abutment, its darkening effect stretched over a large range ($\Delta L^* = 4.01 \sim 7.78$), whereas the ΔL^* values for the lightly shaded zirconia abutment extended over a noticeably narrower range ($\Delta L^* = 2.38 \sim 3.75$). The ΔL^* values changed in different manners at varying ceramic thickness depending on the zirconia abutment shade, and this was confirmed by a significant interaction effect of those two parameters from the statistical analysis. Overall, the lightness of the final ceramic color was certainly affected by both the ceramic thickness and zirconia abutment shade.

As far as the specific effect of varying ceramic thickness and zirconia abutment shade on the yellowness of the final color was concerned, all the Δb^* values for both shaded zirconia abutments were significantly different from the control at all four ceramic thicknesses evaluated. The largest color changes in the b*-axis compared to the control white zirconia abutment were observed with 0.5 mm ceramic thickness for each of the shaded zirconia abutments, and the amounts of color differences towards yellowness diminished with increasing ceramic thickness. The largest color difference, Δb^* = -8.33, observed with 0.5 mm ceramic thickness for the medium-dark abutment appeared as a significantly prominent yellowing effect compared to Δb^* = -5.43 for the lightly shaded abutment. This was due to the markedly higher b* value of medium-dark zirconia abutment itself and the high translucency property of IPS e.max that reflected the yellowness of the underlying abutment shade as a component of the final ceramic color. However with 2.0 mm ceramic thickness, this medium-dark zirconia abutment demonstrated an approximately equivalent color difference, Δb^* = -0.98, compared to Δb^* = -1.11 for the lightly shaded zirconia abutment. It seems that when the overlay ceramic thickness was increased to 2.0 mm, the Δb^* values of the final color were irrespective of the inherently different b* values of the abutment shades used. Furthermore, with the ceramic thickness of greater than 2.0 mm, the results of the mean Δb^* values may be extrapolated to show nearly no difference from the control white zirconia abutment.

For the mean Δa^* values, no apparent trend or visually appreciable color differences were observed for the ceramic-zirconia combinations with varying ceramic thickness and abutment shade. The lightly shaded abutment material showed no color changes or limited change in the a* values compared to the control white zirconia abutment, and the medium-dark zirconia abutment created a very small shift in the final color towards less “green” negative side of the a*-axis. However, all the Δa^* values only ranged between 0.02 and -1.28, and those relatively small Δa^* values were not associated with any particular pattern with varying ceramic thickness.

The selection of zirconia abutment shades evaluated in this study played a major role in the resultant optical changes seen on the final all-ceramic material. Several unique qualities of zirconia that make it a good material of choice for implant abutments include strength, transformation toughening, and chemical and structural stability, and its main advantage is the more desirable optical properties that can adapt better with an all-ceramic restoration and periimplant soft tissue.[89] However, a few available studies that investigated the optical effect of various types of all-ceramic coping showed visually appreciable color differences after the application of the veneering ceramic.[90] Thus, even though the metal substructure and margin of traditional metal-ceramic crowns are eliminated by the use of zirconia abutments, the innate optical properties of white and shaded zirconia abutments contribute to the final appearance of the all-ceramic restoration. When used in conjunction with highly translucent overlay all-ceramic material as in this study, the color differences were accentuated especially in ΔE, ΔL^*, and Δb^* values with a darker dentin-like zirconia abutment. If those zirconia abutments were evaluated in combination with all-ceramic material with less translucency and more opacity, such as IPS e.max with low translucency or medium opacity, the color differences may be lessened when zirconia abutment shades are varied. Furthermore, the opacity of aluminum or zirconium oxide copings or zirconia monolithic restoration could actually block any optical effect of the underlying abutment shade, making the potential color differences caused by a zirconia abutment insignificant.

The thickness, shade, and level of translucency of overlay all-ceramic material also greatly impacted the results of optical effects on the final esthetics with varying zirconia abutment shades. When light encounters translucent substances such as natural teeth or all-ceramic restorative materials, some light is reflected at the surface, some is scattered in the medium and some is transmitted. With increasing all-ceramic thickness, more incident light was absorbed and scattered internally, and less light was reflected or transmitted through. Thus, as the thickness increases, the influence of the background color decreases, resulting in smaller ΔE values, and the specimen gradually becomes close to its intrinsic color. Then, when the thickness of the specimen reaches or exceeds its infinite optical thickness, the final color will not be influenced by the underlying color.

In this study, the results of the mean ΔE values for ceramic-zirconia combinations with varying zirconia abutments shades and ceramic thicknesses suggest that the infinite optical thickness of IPS e.max is beyond the maximum ceramic thickness of 2.0 mm tested. At 2.0 mm ceramic thickness, the ΔE values were 2.66 and 4.21 for the lightly shaded and medium-dark abutment shades, respectively, and they followed the steadily decreasing trend with increasing ceramic thickness. The infinite optical thickness can be extrapolated to be beyond 2.0 mm thickness, and it may approach the range of 2.7 ~ 3.3 mm thickness reported for IPS e.max B color series in a previous study.[91] No perceptible color difference should be observed theoretically with varying underlying abutment shades at this thickness. However this may provide little clinical relevance because all-ceramic crowns with more than 2.0 mm thickness are not clinically suitable due to the bulkiness of the restoration and inadequate substructure support. In addition to the thickness, the selection of shade and translucency level of all-ceramic restorations would greatly influence the optical effect of tooth-colored zirconia abutments on the final color.

B1 shade was used in this study for IPS e.max ceramic specimens because B1 is one of the most commonly selected shades for highly esthetic cases. IPS e.max has 16 shades categorized in the traditional VITA A, B, C, and D color series and 4 bleached shades available. The color differences in the final esthetics observed relative to both varying zirconia abutment shades and ceramic thicknesses may be altered significantly by the selection of a different overlay all-ceramic shade. The colors of zirconia abutments would emanate through and interact differently with all-ceramic crown when their hue, chroma, and value vary. A darker shade of all-ceramic material, such as B3, may lead to less pronounced final color differences between the two shaded abutments due to some masking effect by utilizing an overlay shade that matches the underlying abutment more closely.

ΔE values reported in this study may present clinically relevant upper limits for potential optical effect possible when utilizing a zirconia abutment whose color is mismatched with all-ceramic restoration. IPS e.max is also offered with multiple translucency levels, including high and low translucency and medium and high opacity. The high translucency selected in this study combined with lightest and relatively uncolored B1 shade maximized the optical influence by the shaded abutments resulting in high ∆E values with significant yellowing and darkening effects. In a clinical situation, the thickness of an all-ceramic full coverage restoration generally ranges from approximately 1.0 mm at the cervical to 2.0 mm near the incisal edge.[76] At those clinically applicable ceramic thicknesses, a critical mismatch between the light and translucent shade of all-ceramic crown material and the darkest available Atlantis custom abutment shade created the color differences beyond the clinically acceptable threshold. This study confirmed that a darker zirconia abutment shade results in increased show-through and significantly alters the final appearance of the all-ceramic restoration. Thus, the proper selection of the abutment shade in harmony with the desired final shade is extremely important, and the manufacturers reinforce this by recommending the usage of darker zirconia abutment shades when similarly dark all-ceramic crown shades are desired.

In summary, the results of the study support the rejection of the null hypotheses because the color difference of the final color of all-ceramic restorative material was affected by varying zirconia abutment shades and ceramic thicknesses. The ΔE values were significantly larger with the darker zirconia abutment compared to the control white and lightly shaded zirconia abutments, and the ΔE values diminished as the thickness of all-ceramic material increased. In addition, when the ceramic thickness was increased to 2.0 mm, the “yellowness” of the shaded zirconia abutments seemed to be masked better, whereas the “darkness” of the abutments may still be prominent. This may be particularly important because the value of dental restorations is critical in color matching. The better understanding of those optical effects would be helpful tools in order to control and predict the final esthetics of all-ceramic material with different dentin-like zirconia implant abutments shades available.

5.2 **Optical Effect of Resin Cement and Ceramic Thickness**

The use of resin cements for bonding of all-ceramic crowns, veneers, inlays and onlays have become popular because of their higher strength, ability to reduce facture of ceramic materials, and low solubility in oral fluid.[80] Their key advantages also include the variety of shades available to maximize the final appearance of translucent restorations. The shade and the thickness of luting agents are critical factors in the final color of all-ceramic crowns.[11, 16-17, 33] In the present study, a resin cement with dentin-like shade, recommended by its manufacturer for esthetic all-ceramic crowns, was used to evaluate its optical effect on the resultant color of all-ceramic restoration with underlying shaded zirconia abutment at varying ceramic thicknesses.

With the white zirconia abutment as a control, the ΔE values for all-ceramic material luted onto the lightly shaded zirconia abutment specimens with resin cement were significantly greater than the ΔE values for the same combinations without resin cement at all four ceramic thicknesses. The presence of the cement had a significant influence on the final color of the ceramic material resulting in high ΔE values. The largest mean ΔE value was observed with 0.5 mm ceramic thickness for the ceramic-zirconia combinations with resin cement, and the ΔE values decreased as the overlay ceramic thickness increased in a similar manner as the specimens without resin cement. The results were attributable to the high translucent characteristic of the all-ceramic material, permitting the immense optical effect of the tooth-colored resin cement.

The optical effect of resin cement on the final ceramic color was influenced by their optical properties. The light transmittance through resin cement is affected by density of the filler, pigments, and the refractive indices of the filler and resin. The resin cements when first developed had poor physical properties with high polymerization shrinkage and excessive leakage because of their low percentage filler content. Since then, modern resin cements have improved in physical properties with more filler content. PANAVIA 21 used in this study is also a modified phosphate ester of Bis-GMA based resin filled up to 75% by weight with quartz particles.[75] The increased density of the filler leads to more light scattering within the material. Darker shades of resin cement, such as the tooth-color (TC) shade in this study, also contain darker pigments that absorb more light, further making the cement layer opaque. Moreover, the refractive indices of the different components in resin cement should not differ very much to prevent light scattering at the resin-filler interface. However, Bis-GMA often has a rather high refractive index compared to filler particles.[92] Thus, this relatively opaque resin cement layer reduced the light transmission and limited the optical effect from the underlying zirconia abutment. The dark tooth-color shade of the resin cement was reflected on the final ceramic color through the highly translucent all-ceramic material, thereby contributing to significantly greater ΔE values at all four ceramic thicknesses.

The color changes in the a*-axis with this tooth-colored cement indicated a larger shift towards slight redness of the final color for the ceramic-zirconia combinations compared to the ones without cement. The natural teeth were reported to become darker and more reddish with advancing age, and this color change may be helpful keeping in mind when color-matching for older populations.[93] The color changes in L* and b* coordinates were also found to be larger than the changes for the ceramic-zirconia combinations without cement at all four ceramic thicknesses. The “darkness” and “yellowness” of the final color with tooth-colored cement were most prominent at thinner ceramic thickness. This was contributed by the apparent low value and high chroma observed in the tooth-color shade of resin cement. The color differences in both L* and b*-axes compared the control white zirconia abutment decreased with increasing ceramic thickness.

The film thicknesses of various commercially available resin cements generally range from 20 to 40 µm, and the film thickness of PANAVIA 21 resin cement was reported to be 19 µm by its manufacturer.[77] Previous studies commonly assessed the optical effect of resin cement using 0.1, 0.2 or 0.3 mm thickness.[11, 33] In the present study, the resin cement was evaluated at 0.1 mm thickness because it approximated the actual cement thickness range for clinical relevance, and assurance of a standardized thickness was easily measured. Increased retention of a restoration using resin cement has been reported with up to approximately 75 µm spacing for cement.[94-95] The optical effect by resin cement may be lessened if cement thickness were reduced. This could allow increased light transmission and approach the ∆E values without cement. More translucent resin cement shade may also results in the ∆E values comparable to those observed without cement. In contrast, a thicker cement layer or the use of more opaque and darker resin cement shades may lead to even larger ∆E values. The other available shades from PANAVIA 21, standard white (EX) and opaque (OP), may also result in significant ∆E values due to their opacities, but they may have varying darkening, yellowing, or reddening effects because of their different inherent optical properties.

The present study demonstrated a significant optical effect of tooth-colored resin cement on the final color when it was used to lute a translucent all-ceramic material onto the lightly shaded zirconia abutment. In the clinical situation, the relatively opaque nature of some resin cement shades could negatively affect the optical characteristics of the final cemented restorations. The main rationale for using these all-ceramic restorations is to match translucency and value to the natural dentition. Thus in situations where translucency is needed, translucent resin cements are indicated. Clinicians must be deliberate in selecting cement during the restoration shade selection and fabrication processes, especially for all-ceramic materials with high translucency.

5.3 Limitations of the Study

There are several limitations in this study, and they are in regards to different aspects of the study, such as the experimental design, specimens, color measurements and statistical analyses.

For data analyses, three measurements were taken for every ceramic-zirconia combination to eliminate any possible outliers in measurements due to unexpected mechanical failure or handling issues. No outliers were observed among any of the measurements, and three consecutive measurements of the same specimens were completely or nearly identical. The average L*, a*, and b* values from those three measurements were recorded as each specimen's coordinates that were subsequently used to perform all the statistical analyses. The limitation of using the average values is the risk of potentially overlooking the variances among the raw individual measurements that may affect the results of the statistical analyses. In this study, the variances among the three measurements were evidently insignificant and small in comparison to the standard deviations of the mean values. Thus, the results of the statistical analyses using the mean values were validated.

The background color of the specimens for all measurements was standardized, and the potential effect was minimized. Yet, a possible limitation still remains that a small fraction of the incident light transmitted beyond the zirconia abutment discs was not captured for spectrophotometric measurements. Neutral colors such as white, grey, and black are, by definition, colors that have no hue. A white background was used for all specimens to minimize the influence of background hue on the color measurement of the discs. Prior to the conduction of the study, all three shades of the zirconia abutments were measured freestanding against various background colors with varying hues, chroma, values and surface finish. At the thickness of 3.0 mm used in this study, no color differences were measured for all three shades among different backgrounds, and this thickness was speculated to be beyond its infinite optical thickness. This arrangement allowed the investigation to focus on the assessment of the optical effect of varying overlay ceramic thickness, abutment shade, and resin cement on the final ceramic appearance with no influence by the background.

Another limitation may rise from possible variations among the disc specimens and resin cement layer. The all-ceramic and zirconia discs were standardized by strictly following the manufacturer's instructions, and the specified thicknesses were ensured with the digital caliper measurements within 0.02 mm of the designated final thickness. However, small discrepancies may have still existed in surface texture, surface finish, batches used for fabrication, and thickness, and those factors may have affected the final ceramic shade. The resin cement layer was also standardized by following the manufacture's guideline, and the film thickness of 0.1 mm was confirmed by the digital caliper measurements before and after its application. The two pastes (Catalyst and Universal) of PANAVIA 21 were dispensed using a custom dispensing unit that ensured convenient and accurate mixes during each use. Yet, small variations may have been present during manipulation and in the final cement thicknesses that affected the depth of cure and complete polymerization. Those factors could influence the final ceramic color. Overall, the results with small standard deviations suggested that the variables were well controlled.

Color measurements were standardized, and the limitations associated with the measurements of translucent dental materials, such as edge-loss error, were avoided by the use of one of the most accurate and reliable dental spectrophotometers.[58] This spectrophotometer used a 45/0° measuring geometry with 7 LEDs as an illumination light source to capture entire tooth images and obtain spectral data. The 45°/0° bidirectional geometry is one of the four geometries the CIE recommends for instrumental color measurements of reflecting specimens, and it has been shown to be the most appropriate for measuring the teeth and gingiva.[62-63] The images were also captured using a small black non-contact type cap that eliminated external light and the effect of edge-loss error. When color is measured with an instrument that has a relatively small window, a considerable fraction of the light entering the tooth is lost, because it emerges at the surface outside of the window of measurement.[35] Edge-loss error caused by the use of a contact type measuring device is a known problem with other color measuring instruments, resulting in a lower value reading.[61]

The biggest limitation of this study is that the results are only applicable to the evaluated dental materials. Heat-pressed lithium disilicate ceramic material with high translucency in B1 shade was used, and the external validity of the results, in evaluating any other ceramic material with different levels of translucency or opacity and shades, is limited. Different shades of the ceramic material may have different optical properties and lead to different optical effects on the final color. Furthermore, in a clinical situation, the abutment shade should be selected similarly to the final desired restoration to avoid the mismatched underlying abutment color from emanating through the all-ceramic translucent material. When the shades of the abutment and all-ceramic crown are in harmony, the optical effect would not be as exaggerated as the ΔE values observed in this study.

Lastly, the nature of the in vitro study is another limitation due lack of simulated intraoral conditions. The current study does not account for any possible changes in the optical effects by different intraoral factors, such as the saliva, gingiva, color stability of resin cement, and texture, shape and size of full contoured restorations. The color differences were assessed on standardized ceramic discs with a flat surface to provide preliminary key information using a dental spectrophotometer that provides accurate and reproducible measurements. The ceramic thicknesses were evaluated in the clinically relevant range. In contrast, curved surfaces of full-contoured restorations with varying ceramic thickness throughout would not provide a standardized system for color measurement. In vivo study to evaluate the optical effect of underlying zirconia abutment shades and cement should be considered in future using all-ceramic restorations under clinical circumstances in order to achieving an esthetically pleasing restoration which satisfactorily integrates with the biological tissues.

5.4 **Clinical Significance**

With the introduction of dentin-colored zirconia abutments, the fabrication of an esthetic all-ceramic restoration with truly individual character may be achieved for single-tooth implant supported restorations. Lithium disilicate all-ceramic restorations, IPS e.max, permit superior light transmission within the crown, thereby improving the color and translucency of the restoration. Because this property does not affect their mechanical properties, IPS e.max can provide restorative options with high strength without compromising the esthetic outcome, a result well- suited for the today's patient pool with increasing demands. Today, combined with the use of the zirconia implant abutment with various shade options, this presents an ideal restorative design with great strength and esthetics. In addition, resin cement with appropriately selected shade can also further enhance those properties.

This study investigated the optical properties and effects of the combination of zirconia abutment shades, all-ceramic material thickness, and resin cement on the final esthetics. The results of the study suggested that zirconia abutment shade, ceramic thickness and resin cement shade all play a key role in the successful reproduction of a final desired shade. In many clinical situations, the thickness of an all-ceramic full coverage restoration in the cervical portion may be relatively thin, and varying zirconia abutment shade and resin cement may have a great optical influence similar to the results seen in this study.

6. CONCLUSION

The combinations of various thicknesses of heat-pressed lithium disilicate ceramic material and different shades of zirconia abutment background were measured for their color differences using a dental spectrophotometer to examine their optical effects on the final color of an all-ceramic restoration. The optical effect of tooth-colored resin cement was also evaluated by comparing their color differences to the ceramic-zirconia combination without cement.

Within the limitations of this study, the results showed that underlying zirconia abutment background shade, ceramic thickness, and resin cement all influence the resulting optical color of all-ceramic restoration material ($p<0.05$). The zirconia abutment background with the darker shade, thinner all-ceramic material, and the presence of the shaded resin cement resulted in larger ΔE values with statistical significance ($p<0.05$). Furthermore, as the thickness of all-ceramic restoration material decreased, the color changes measured increased, leading to ΔE values which were well beyond clinically acceptable threshold and potentially easily noticed by patient and clinician.

Therefore, careful selection of the zirconia abutment shade and luting agent at any given ceramic thickness is very important in controlling and obtaining optimal esthetics when using all-ceramic crowns. Clinical practice implications of the findings from this study may help to provide a more cautious approach in improving or achieving desired color match when using all-ceramic restorations in conjunction with zirconia implant abutments.

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APPENDICES

APPENDIX A

L* a* b* Values for Zirconia Abutment Material

	L*	a*	b*
Shade 00 (bleach white)	90.79 90.84 90.8	-1.69 -1.71 -1.64	1.95 1.83 1.84
Mean	90.81	-1.68	1.873333
SD	0.026458	0.036056	0.066583

	L*	a*	b*
Shade 10 (lightly shaded)	85.56 85.58 85.5	-2.51 -2.49 -2.51	10.2 10.31 10.36
Mean	85.54667	-2.50333	10.29
SD	0.041633	0.011547005	0.081853528

	L*	a*	b*
Shade 30 (medium dark)	81.54 81.55 81.53	-1.61 -1.58 -1.59	15.19 15.2 15.24
Mean	81.54	-1.59333	15.21
SD	0.01	0.015275	0.026457513

APPENDIX B

L* a* b* Values for 0.5mm E.max Over White Zirconia Abutment

	L*	a*	b*
Sample 1	86.62	-1.92	11.14
	86.53	-1.99	11.24
	86.47	-1.83	11.21
Mean	86.54	-1.91333	11.19667
Sample 2	86.26	-2	10.62
	86.15	-2.1	10.74
	86.47	-2.16	10.58
Mean	86.29333	-2.08667	10.64667
Sample 3	86.66	-1.9	11.24
	86.46	-1.91	11.15
	86.61	-2.06	11.22
Mean	86.57667	-1.95667	11.20333
Sample 4	86.58	-1.81	11.13
	86.66	-1.95	11.06
	86.52	-2.02	11.18
Mean	86.58667	-1.92667	11.12333
Sample 5	86.92	-1.97	10.97
	86.84	-1.88	10.9
	86.7	-1.92	10.82
Mean	86.82	-1.92333	10.89667
Sample 6	86.59	-2.01	11.08
	86.57	-1.99	11.01
	86.58	-2	11.04
Mean	86.58	-2	11.04333
Sample 7	86.5	-1.81	11.09
	86.64	-1.88	11.12
	86.69	-1.87	11.18
Mean	86.61	-1.85333	11.13
Sample 8	86.53	-1.91	11.11
	86.61	-1.81	11.13
	86.63	-1.91	11.1
Mean	86.59	-1.87667	11.11333

APPENDIX B (Continued)

L* a* b* Values for 1.0mm E.max Over White Zirconia Abutment

	L*	a*	b*
Sample 1	85.4	-1.9	11.89
	85.4	-1.92	11.81
	85.52	-1.98	12.19
Mean	85.44	-1.93333	11.96333
Sample 2	85.38	-1.93	11.79
	85.4	-1.79	12.02
	85.26	-2.08	11.83
Mean	85.34667	-1.93333	11.88
Sample 3	85.37	-1.81	11.94
	85.23	-1.77	11.94
	85.36	-1.91	12.06
Mean	85.32	-1.83	11.98
Sample 4	85.52	-1.83	11.83
	85.6	-1.88	11.86
	85.51	-1.96	11.93
Mean	85.54333	-1.89	11.87333
Sample 5	85.44	-1.91	11.84
	85.51	-1.91	11.96
	85.57	-1.92	11.85
Mean	85.50667	-1.91333	11.88333
Sample 6	85.41	-2.02	11.97
	85.49	-1.87	11.91
	85.53	-1.84	11.93
Mean	85.47667	-1.91	11.93667
Sample 7	85.4	-2.07	11.75
	85.5	-1.98	11.84
	85.35	-2.08	11.91
Mean	85.41667	-2.04333	11.83333
Sample 8	85.32	-1.95	11.75
	85.42	-1.84	11.92
	85.44	-1.74	11.95
Mean	85.39333	-1.84333	11.87333

APPENDIX B (Continued)

L* a* b* Values for 1.5m E.max Over White Zirconia Abutment

	L*	a*	b*
Sample 1	84.06	-1.47	15.2
	83.99	-1.43	15.03
	83.98	-1.43	15.11
Mean	84.01	-1.44333	15.11333
Sample 2	84.06	-1.34	15.06
	84.01	-1.36	15.07
	84.08	-1.46	15.18
Mean	84.05	-1.38667	15.10333
Sample 3	83.86	-1.36	15.08
	83.77	-1.46	15.2
	83.85	-1.49	14.95
Mean	83.82667	-1.43667	15.07667
Sample 4	84.21	-1.42	14.83
	84.14	-1.21	14.93
	84.17	-1.58	14.92
Mean	84.17333	-1.40333	14.89333
Sample 5	83.78	-1.64	15.1
	83.88	-1.72	14.88
	83.81	-1.53	15.05
Mean	83.82333	-1.63	15.01
Sample 6	84.03	-1.54	15.26
	84.11	-1.51	15.2
	84.03	-1.52	15.2
Mean	84.05667	-1.52333	15.22
Sample 7	83.9	-1.71	15.11
	83.98	-1.65	14.98
	83.88	-1.6	15.09
Mean	83.92	-1.65333	15.06
Sample 8	83.81	-1.36	14.91
	83.89	-1.39	14.84
	83.83	-1.44	14.91
Mean	83.84333	-1.39667	14.88667

APPENDIX B (Continued)

L* a* b* Values for 2.0mm E.max Over White Zirconia Abutment

	L*	a*	b*
Sample 1	82.32	-1.01	16.31
	82.25	-0.99	16.35
	82.34	-0.98	16.31
Mean	82.30333	-0.99333	16.32333
Sample 2	82.34	-1.06	16.26
	82.24	-1.06	16.29
	82.43	-1.06	16.31
Mean	82.33667	-1.06	16.28667
Sample 3	82.31	-1.19	16.23
	82.29	-1.01	16.1
	82.22	-1.04	16.19
Mean	82.27333	-1.08	16.17333
Sample 4	82.34	-1.17	16.39
	82.4	-1.19	16.35
	82.37	-1.05	16.26
Mean	82.37	-1.13667	16.33333
Sample 5	82.52	-1.01	16.44
	82.45	-1.01	16.2
	82.37	-0.96	16.17
Mean	82.44667	-0.99333	16.27
Sample 6	82.34	-1.19	16.14
	82.52	-1.02	16.13
	82.37	-1.16	16.11
Mean	82.41	-1.12333	16.12667
Sample 7	82.28	-0.98	16.57
	82.04	-0.85	16.36
	82.26	-0.99	16.36
Mean	82.19333	-0.94	16.43
Sample 8	81.88	-1.15	15.95
	81.73	-1.29	15.84
	81.64	-1.12	15.83
Mean	81.75	-1.18667	15.87333

APPENDIX C

L* a* b* Values for 0.5mm E.max Over Lightly Shaded Zirconia Abutment

	L*	a*	b*
Sample 1	82.94	-1.96	16.62
	82.88	-1.95	16.63
	83.01	-1.88	16.5
Mean	82.94333	-1.93	16.58333
Sample 2	82.91	-2.21	16.69
	82.72	-2.08	16.75
	82.79	-1.82	16.52
Mean	82.80667	-2.03667	16.65333
Sample 3	82.6	-1.55	16.45
	82.49	-1.82	16.44
	82.67	-2.21	16.47
Mean	82.58667	-1.86	16.45333
Sample 4	82.75	-2.11	16.61
	82.99	-1.74	16.48
	83.28	-1.94	16.53
Mean	83.00667	-1.93	16.54
Sample 5	83.15	-2.17	15.91
	82.65	-2.33	16.11
	82.88	-2.09	16.11
Mean	82.89333	-2.19667	16.04333
Sample 6	82.59	-1.87	16.19
	82.61	-1.87	16.09
	82.51	-1.86	16.3
Mean	82.57	-1.86667	16.19333
Sample 7	83.09	-2.13	16.57
	82.83	-1.89	16.72
	82.79	-1.92	16.57
Mean	82.90333	-1.98	16.62
Sample 8	82.82	-1.93	16.77
	83.02	-1.9	16.76
	82.93	-1.79	16.51
Mean	82.92333	-1.87333	16.68

APPENDIX C (Continued)

L* a* b* Values for 1.0mm E.max Over Lightly Shaded Zirconia Abutment

	L*	a*	b*
Sample 1	82.18	-1.9	16.93
	82.19	-1.79	16.89
	82.09	-1.92	16.79
Mean	82.15333	-1.87	16.87
Sample 2	81.61	-1.85	16.82
	81.61	-1.9	16.8
	81.66	-2.08	16.76
Mean	81.62667	-1.94333	16.79333
Sample 3	82.21	-1.94	17.11
	81.92	-1.79	16.71
	82.04	-1.89	17.05
Mean	82.05667	-1.87333	16.95667
Sample 4	81.97	-1.5	16.35
	82.41	-1.85	16.46
	82.66	-1.83	16.61
Mean	82.34667	-1.72667	16.47333
Sample 5	82.29	-2	16.67
	82.14	-1.73	16.58
	82.12	-1.69	16.67
Mean	82.18333	-1.80667	16.64
Sample 6	82.07	-1.85	17.12
	82.01	-1.84	16.98
	82.12	-1.95	16.71
Mean	82.06667	-1.88	16.93667
Sample 7	82.37	-1.95	16.93
	82.37	-1.82	16.89
	82.25	-1.78	17.01
Mean	82.33	-1.85	16.94333
Sample 8	82.16	-1.95	16.85
	82.24	-1.98	16.86
	82.26	-2.04	16.83
Mean	82.22	-1.99	16.84667

APPENDIX C (Continued)

L* a* b* Values for 1.5m E.max Over Lightly Shaded Zirconia Abutment

	L*	a*	b*
Sample 1	80.84	-1.19	17.63
	80.89	-1.22	17.5
	80.76	-1.21	17.65
Mean	80.83	-1.20667	17.59333
Sample 2	80.96	-1.08	17.54
	80.89	-1.09	17.63
	80.71	-1.03	17.64
Mean	80.85333	-1.06667	17.60333
Sample 3	80.98	-1.19	17.66
	80.81	-1.14	17.7
	80.75	-1.11	17.75
Mean	80.84667	-1.14667	17.70333
Sample 4	80.79	-1.39	17.15
	81.22	-1.12	17.22
	81.34	-1.18	17.42
Mean	81.11667	-1.23	17.26333
Sample 5	80.8	-1.11	17.37
	80.87	-1.28	17.51
	80.65	-1.23	17.66
Mean	80.77333	-1.20667	17.51333
Sample 6	80.93	-1.26	17.66
	80.86	-1.12	17.64
	80.86	-1.1	17.58
Mean	80.88333	-1.16	17.62667
Sample 7	81.03	-1.17	17.63
	81.09	-1.06	17.6
	81	-1.26	17.61
Mean	81.04	-1.16333	17.61333
Sample 8	80.99	-1.08	17.58
	81.03	-1.19	17.54
	81.06	-1.05	17.5
Mean	81.02667	-1.10667	17.54

APPENDIX C (Continued)

L* a* b* Values for 2.0mm E.max Over Lightly Shaded Zirconia Abutment

	L*	a*	b*
Sample 1	79.83	-0.81	17.37
	79.78	-0.72	17.39
	79.95	-0.7	17.4
Mean	79.85333	-0.74333	17.38667
Sample 2	79.92	-0.75	17.51
	79.79	-0.75	17.46
	79.95	-0.69	17.36
Mean	79.88667	-0.73	17.44333
Sample 3	79.92	-0.64	17.24
	79.75	-0.59	17.22
	79.68	-0.7	17.17
Mean	79.78333	-0.64333	17.21
Sample 4	79.79	-0.74	17.36
	79.8	-0.77	17.46
	79.85	-0.69	17.29
Mean	79.81333	-0.73333	17.37
Sample 5	80.03	-0.69	17.37
	80.02	-0.99	17.46
	79.83	-0.78	17.3
Mean	79.96	-0.82	17.37667
Sample 6	79.74	-0.76	17.11
	79.74	-0.91	17.39
	79.78	-0.6	17.2
Mean	79.75333	-0.75667	17.23333
Sample 7	79.91	-0.87	17.26
	79.93	-0.85	17.47
	79.95	-0.73	17.39
Mean	79.93	-0.81667	17.37333
Sample 8	80.14	-0.81	17.25
	79.99	-0.75	17.4
	80.1	-0.81	17.29
Mean	80.07667	-0.79	17.31333

APPENDIX D

L* a* b* Values for 0.5mm E.max Over Medium-Dark Zirconia Abutment

	L*	a*	b*
Sample 1	78.75	-0.81	19.45
	78.78	-0.9	19.48
	78.71	-0.87	19.55
Mean	78.74667	-0.86	19.49333
Sample 2	78.68	-0.76	19.15
	78.56	-0.78	19.48
	78.58	-0.96	19.37
Mean	78.60667	-0.83333	19.33333
Sample 3	78.75	-0.83	19.49
	78.62	-0.79	19.43
	78.67	-0.91	19.4
Mean	78.68	-0.84333	19.44
Sample 4	78.89	-0.75	19.5
	78.86	-0.76	19.43
	78.68	-0.77	19.44
Mean	78.81	-0.76	19.45667
Sample 5	79.12	-0.95	19.22
	79.01	-0.98	19.08
	78.9	-1	19.05
Mean	79.01	-0.97667	19.11667
Sample 6	78.89	-1.03	19.29
	78.78	-0.87	19.53
	78.84	-0.86	19.46
Mean	78.83667	-0.92	19.42667
Sample 7	78.98	-0.27	19.5
	78.88	-0.76	19.7
	78.78	-0.84	19.69
Mean	78.88	-0.62333	19.63
Sample 8	78.75	-0.76	19.02
	78.79	-0.62	19.27
	78.78	-0.69	19.09
Mean	78.77333	-0.69	19.12667

APPENDIX D (Continued)

L* a* b* Values for 1.0mm E.max Over Medium-Dark Zirconia Abutment

	L*	a*	b*
Sample 1	79.68	-0.95	18.19
	79.69	-0.97	18.07
	79.63	-1.05	18.21
Mean	79.66667	-0.99	18.15667
Sample 2	79.52	-1.12	18.24
	79.59	-1.06	18.15
	79.58	-0.89	17.96
Mean	79.56333	-1.02333	18.11667
Sample 3	79.64	-0.97	18.14
	79.73	-0.79	18.07
	79.63	-1.03	18.11
Mean	79.66667	-0.93	18.10667
Sample 4	79.77	-0.75	18.15
	79.85	-0.78	18.07
	79.81	-0.86	18.03
Mean	79.81	-0.79667	18.08333
Sample 5	79.81	-0.78	18.14
	79.58	-1.08	18.22
	79.84	-0.74	17.69
Mean	79.74333	-0.86667	18.01667
Sample 6	79.7	-1.15	18.05
	79.88	-0.91	18.11
	79.84	-0.91	18.3
Mean	79.80667	-0.99	18.15333
Sample 7	79.6	-0.87	18.22
	79.6	-0.99	18.23
	79.6	-0.93	18.26
Mean	79.6	-0.93	18.23667
Sample 8	79.64	-0.9	18.11
	79.64	-0.91	18.1
	79.56	-0.96	18.25
Mean	79.61333	-0.92333	18.15333

APPENDIX D (Continued)

L* a* b* Values for 1.5m E.max Over Medium-Dark Zirconia Abutment

	L*	a*	b*
Sample 1	77.61	-0.15	17.92
	77.6	-0.16	18
	77.63	-0.18	17.88
Mean	77.61333	-0.16333	17.93333
Sample 2	77.66	-0.07	17.97
	77.59	-0.23	17.86
	77.65	-0.14	17.83
Mean	77.63333	-0.14667	17.88667
Sample 3	77.62	-0.15	18.02
	77.59	-0.24	17.91
	77.53	-0.2	17.97
Mean	77.58	-0.19667	17.96667
Sample 4	77.54	-0.19	17.83
	77.58	-0.26	17.91
	77.54	-0.2	17.81
Mean	77.55333	-0.21667	17.85
Sample 5	78.02	-0.08	17.51
	77.86	-0.3	17.79
	77.77	-0.22	17.97
Mean	77.88333	-0.2	17.75667
Sample 6	77.72	-0.24	17.92
	77.6	-0.35	17.92
	77.7	-0.3	17.95
Mean	77.67333	-0.29667	17.93
Sample 7	77.66	-0.28	18.02
	77.61	-0.31	17.63
	77.77	-0.13	17.49
Mean	77.68	-0.24	17.71333
Sample 8	77.94	-0.27	17.64
	77.88	-0.05	17.91
	77.86	-0.11	17.84
Mean	77.89333	-0.14333	17.79667

APPENDIX D (Continued)

L* a* b* Values for 2.0mm E.max Over Medium-Dark Zirconia Abutment

	L*	a*	b*
Sample 1	78.21	-0.21	17.26
	78.17	-0.18	17.19
	78.15	-0.24	17.24
Mean	78.17667	-0.21	17.23
Sample 2	78.19	-0.16	17.24
	78.12	-0.26	17.23
	78.16	-0.23	17.27
Mean	78.15667	-0.21667	17.24667
Sample 3	78.25	-0.19	17.25
	78.2	-0.2	17.27
	78.17	-0.27	17.16
Mean	78.20667	-0.22	17.22667
Sample 4	78.28	-0.24	17.28
	78.25	-0.17	17.19
	78.23	-0.18	17.38
Mean	78.25333	-0.19667	17.28333
Sample 5	78.16	-0.49	17.33
	78.41	-0.13	17
	78.64	-0.15	17.24
Mean	78.40333	-0.25667	17.19
Sample 6	78.49	-0.26	17.13
	78.17	-0.21	17.36
	78.13	-0.2	17.13
Mean	78.26333	-0.22333	17.20667
Sample 7	78.24	-0.18	17.17
	78.3	-0.32	17.16
	78.4	-0.28	17.3
Mean	78.31333	-0.26	17.21
Sample 8	78.13	-0.31	17.12
	78.21	-0.03	17.06
	78.4	-0.37	17.06
Mean	78.24667	-0.23667	17.08

APPENDIX E

L* a* b* Values for 0.5mm E.max Over Lightly Shaded Zirconia Abutment with Resin Cement

	L*	a*	b*
Sample 1	80.29	-0.02	21.44
	80.21	-0.03	21.51
	80.21	-0.03	21.34
Mean	80.23667	-0.02667	21.43
Sample 2	80	-0.22	21.01
	79.57	-0.28	20.92
	79.88	-0.64	21.14
Mean	79.81667	-0.38	21.02333
Sample 3	80.03	-0.27	21.4
	80.18	-0.33	21.35
	80.12	-0.24	21.42
Mean	80.11	-0.28	21.39
Sample 4	80.15	0.04	21.72
	80.02	-0.05	21.68
	79.96	-0.05	21.54
Mean	80.04333	-0.02	21.64667
Sample 5	80.43	-0.17	21.48
	80.03	-0.11	21.49
	80.32	-0.19	21.37
Mean	80.26	-0.15667	21.44667
Sample 6	80.37	0.02	21.32
	80.15	0.11	21.29
	80.45	-0.23	21.2
Mean	80.32333	-0.03333	21.27
Sample 7	80.32	-0.15	21.4
	80.17	0.06	21.25
	80.19	-0.09	21.33
Mean	80.22667	-0.06	21.32667
Sample 8	80.34	0.11	21.26
	80.26	0.19	21.46
	80.32	0.09	21.09
Mean	80.30667	0.13	21.27

APPENDIX E (Continued)
L* a* b* Values for 1.0mm E.max Over Lightly Shaded Zirconia Abutment with Resin Cement

	L*	a*	b*
Sample 1	79.67	-0.07	20.41
	79.75	-0.13	20.42
	79.71	-0.27	20.39
Mean	79.71	-0.15667	20.40667
Sample 2	78.34	0.44	21.45
	78.04	0.36	21.25
	78.67	0.71	21.51
Mean	78.35	0.503333	21.40333
Sample 3	80.04	0.01	20.31
	79.79	0.1	20.28
	79.94	0.22	20.3
Mean	79.92333	0.11	20.29667
Sample 4	79.65	-0.21	20.63
	79.61	-0.15	20.56
	79.51	-0.2	20.66
Mean	79.59	-0.18667	20.61667
Sample 5	79.71	0.01	19.99
	79.87	-0.04	20.44
	79.71	-0.08	20.16
Mean	79.76333	-0.03667	20.19667
Sample 6	79.86	0.19	20.43
	79.56	0.21	20.46
	80.01	0.21	20.44
Mean	79.81	0.203333	20.44333
Sample 7	79.92	-0.01	20.59
	79.79	0.08	20.62
	79.66	0.08	20.69
Mean	79.79	0.05	20.63333
Sample 8	79.65	-0.03	20.67
	79.38	0.18	20.47
	79.36	0.23	20.31
Mean	79.46333	0.126667	20.48333

APPENDIX E (Continued)
L* a* b* Values for 1.5m E.max Over Lightly Shaded Zirconia Abutment with Resin Cement

	L*	a*	b*
Sample 1	78.11	1.46	19.91
	78.08	1.37	19.86
	78.2	1.45	19.77
Mean	78.13	1.426667	19.84667
Sample 2	78.15	1.32	20.01
	77.98	1.35	20
	77.99	1.49	20.14
Mean	78.04	1.386667	20.05
Sample 3	78.45	1.27	20.16
	78.24	1.24	20.2
	77.96	1.23	20.11
Mean	78.21667	1.246667	20.15667
Sample 4	78.14	1.65	19.62
	77.86	1.69	19.58
	78	1.64	19.39
Mean	78	1.66	19.53
Sample 5	78.53	1.36	19.93
	78.38	1.2	19.62
	78.52	1.22	19.63
Mean	78.47667	1.26	19.72667
Sample 6	77.94	1.42	19.86
	78.01	1.34	20
	77.96	1.43	19.85
Mean	77.97	1.396667	19.90333
Sample 7	78.96	0.54	19.09
	77.49	0.58	18.85
	78.9	0.49	19.04
Mean	78.45	0.536667	18.99333
Sample 8	78.08	0.83	19.64
	77.95	0.76	19.59
	78.17	0.83	19.6
Mean	78.06667	0.806667	19.61

APPENDIX E (Continued)
L* a* b* Values for 2.0mm E.max Over Lightly Shaded Zirconia Abutment with Resin Cement

	L*	a*	b*
Sample 1	77.18	1.76	18.99
	77.11	1.79	18.82
	77.23	1.58	19.02
Mean	77.17333	1.71	18.94333
Sample 2	77.74	1.43	18.59
	77.27	1.47	18.84
	77.04	1.65	18.57
Mean	77.35	1.516667	18.66667
Sample 3	77.5	1.14	17.82
	77.32	1.14	17.91
	77.53	1.17	17.58
Mean	77.45	1.15	17.77
Sample 4	77.35	1.09	18.47
	76.91	1.11	18.41
	77.06	1.13	18.44
Mean	77.10667	1.11	18.44
Sample 5	77.92	1.06	17.94
	77.81	1.05	17.89
	77.78	0.95	17.83
Mean	77.83667	1.02	17.88667
Sample 6	77.18	1.5	18.49
	77.06	1.48	18.43
	77.19	1.48	18.59
Mean	77.14333	1.486667	18.50333
Sample 7	77.75	1.08	17.75
	77.2	1	18.11
	77.29	0.96	18.11
Mean	77.41333	1.013333	17.99
Sample 8	77.6	0.43	17.9
	77.55	0.58	17.86
	77.25	0.6	17.93
Mean	77.46667	0.536667	17.89667

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