YEDİTEPE UNIVERSITY
INSTITUTE OF HEALTH SCIENCES
DEPARTMENT OF RESTORATIVE DENTISTRY

AN IN VITRO EVALUATION OF THE EFFECT OF DIFFERENT CERAMIC TYPE, CERAMIC THICKNESS AND AGING ON COLOR AND TRANSLUCENCY CHANGES OF LITHIUM DISILICATE, ZIRCONIA REINFORCED LITHIUM SILICATE, LEUCITE REINFORCED AND FELDSPATHIC CERAMIC VENEERS

DOCTOR OF PHILOSOPHY THESIS

Şeyma Tuna ÜNAL, DDS

ISTANBUL - 2022

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APPROVAL

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DECLARATION

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree except where due acknowledgement has been made in the text.

10.06.2022

Şeyma Tuna ÜNAL

DEDICATION

This thesis work is dedicated to my beloved family, my father Adnan Kemali Ünal, my mother Hatice Songül Ünal, my sister Nisan Asena Ünal, and my little girl Bal Ünal who have been a constant source of unconditional love, support, and encouragement during all my life and the challenges of my academic life. I am truly thankful for having you in my life. This work is also dedicated to my grandmother Şükran Çakıcı and in loving memory of my great grandmother Münevver Gönül.

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LIST OF SYMBOLS AND ABBREVIATIONS

%	Percentage
°C	Celsius degrees
a* value	Redness / greenness of an object
ADA	American Dental Association
Al_2O_3	Aluminium oxide
b* value	Yellowness / blueness of an object
BiS-GMA	Bisphenol A-glycidyl methacrylate
CAD/CAM	Computer-aided design and computer-aided manufacturing
CIE	Commision Internationale de l'Eclairage
CR	Contrast ratio
ΔE	Color difference (Delta E)
K_2O	Potassium oxide
La_2O_3	Lanthanum oxide
L* value	Lightness of an object
mm	milimeter
MPa	Megapascal
μm	Micrometer
$Si0_2$	Silica
TEG-DMA	Triethylene glycol dimethacrylate
TP	Tanslucency Parameter
UDMA	Urethane Dimethacrylate
UV	Ultraviolet
Y	Spectral reflectance
ZrO_2	Zirconium dioxide

ABSTRACT

UNAL, T. (2022). An In Vitro Evaluation of the Effect of Different Ceramic Type, Ceramic Thickness and Aging on Color and Translucency Changes of Lithium Disilicate, Zirconia Reinforced Lithium Silicate, Leucite Reinforced and Feldspathic Ceramic Veneers. Yeditepe University, Institute of Health Science, Department of Restorative Dentistry, Doctor of Philosophy Thesis. Istanbul.

The aim of the present study was to evaluate the color stability (CS) and translucency change of different glass-ceramic CAD/CAM blocks in two different thicknesses (0.5mm and 1.00mm) after hydrothermal aging. Four types of CAD/CAM blocks; lithium disilicate (IPS e.max CAD, Ivoclar Vivadent; E.Max), leucite-reinforced (Initial LRF, GC; LRF), zirconia-reinforced lithium silicate (Celtra Duo, Dentsply; CD), and feldspathic (Cerec, Dentsply; CER) glass-ceramics were cut in 0.5mm and 1.00mm slabs (n=12 for each thickness) using a low-speed diamond saw (Isomet). To represent dental hard tissues, a total of 96 micro-hybrid resin composite discs (G-eanial, GC; A2) were prepared in 2mm thickness. CAD/CAM slabs and resin composite substrates were luted with a light-cured resin cement (G-CEM; GC) and polymerized (VALO Cordless, Ultradent) according to the manufacturer's instructions. Immediate after cementation initial color measurements (E_0) were evaluated using a spectrophotometer (CM-2600d, Minolta). Following storage in distilled water for 24 hours at 37 ^{O}C, second color measurements (E_1) were evaluated using a spectrophotometer (CM-2600d, Konica Minolta) and this readings set as baseline measurement. Then all the specimens were exposed to hydrothermal aging between 5-55°C for 30000 cycles (SALUBRİS). Color and TP measurements were repeated after every 10000 cycles (E_1, E_2, E_3). Color differences (ΔE) and TP measurements were evaluated by CIEDE2000. Data were analyzed with three-way ANOVA and post hoc Tukey's tests ($p<0.05$). ΔE_{00} was significantly influenced by ceramic type ($p<0.001$), ceramic thickness ($p<0.001$), and aging ($p<0.001$). Regarding to ceramic thickness, only CER 0.5mm and 1.0mm showed statistically significant differences at 10000, 20000, 30000 cycles aging ($p=0.006$, $p<0.001$, $p<0.001$, respectively). With respect to ceramic type, in 0.5mm thickness at 10000 cycles LRF showed statistically higher CS than CER ($p=0.001$), after 20000 and 30000 cycles CER showed statistically lower CS than LRF ($p<0.001$) and E.Max ($p=0.008$, $p<0.001$). TP was significantly influenced by the type of material ($p<0.001$) by

the thickness of the material (*p<0.001*) and by aging (*p<0.001*). A significant interaction between material, thickness and aging was found (*p<0.001*). Meanwhile, the association between material and thickness was significant (*p=0.44*), whereas between thickness and aging (*p=0.124*) and between material and aging were not significant (*p=0.125*). All materials in all aging periods showed statistically significant differences in different thicknesses (postcementation, Cerec 0.5mm-1.0mm *p<0.001*, CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*. 24 hours (baseline), Cerec 0.5mm-1.0mm *p<0.001*, CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*. 10000 thermocycling, Cerec 0.5-1.0 *p=0.001*, CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*. 20000 thermocycling, Cerec 0.5mm-1.0mm *p<0.001*, CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*, 30000 thermocycling CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*). CS of glass ceramics were affected by ceramic type, ceramic thickness, and aging. LRF and E.MAX glass ceramics presented more CS then the CD and CER glass ceramic CAD/CAM blocks after aging. CS of the CER CAD/CAM block was highly thickness-dependent. In 0.5mm thickness, feldspathic ceramic showed the lowest translucency, while in 1.0 mm zirconia-reinforced glass ceramic exhibited the lowest translucency after 3-years of aging. Luted CAD /CAM ceramic materials showed acceptable changes in translucency after 3-years of aging, regardless of thickness.

Keywords: CAD/CAM, ceramic, veneers, color stability, translucency, TP, hydrothermal, aging.

ÖZET

UNAL, T. (2022). Farklı Seramik Tipi, Seramik Kalınlığı ve Yaşlandırmanın Lityum Disilikat, Zirkonya ile Güçlendirilmiş Lityum Silikat, Lösit ile Güçlendirilmiş Cam Seramik ve Feldspatik Seramiklerin Renk Stabilitesi ve Translüsensi Üzerine Etkisinin In Vitro Olarak İncelenmesi. Yeditepe Üniversitesi, Sağlık Bilimleri Enstitüsü, Restoratif Diş Tedavisi Anabilim Dalı, Doktora Tezi. İstanbul.

Bu *in vitro* çalışmada, iki farklı kalınlıktaki (0,5mm ve 1,0mm) dört farklı CAD/CAM bloğunun hidrotermal yaşlandırma sonrası renk stabilitesi ve translüsens değişimi araştırılarak seramik yapısı, seramik kalınlığı ve yaşlandırmanın etkisi incelenmiştir.Dört farklı CAD/CAM bloğu; lityum disilikat (IPS e.max CAD, Ivoclar Vivadent; E.Max), lösit ile güçlendirilmiş (Initial LRF, GC; LRF), zirkonya ile güçlendirilmiş lityum silikat (Celtra Duo, Dentsply; CD), ve feldspatik (Cerec, Dentsply; CER) cam seramikler 0,5 ve 1,0mm kalınlığında düşük devirli elmas bıçakla (ISOMET) hazırlanmıştır (n=12, her bir kalınlık için). Diş sert dokularını temsil etmesi amacıyla (substrat olarak) 2mm kalınlığında 96 adet mikrohibrit resin kompozit disk (G-eanial, GC; A2) hazırlanmıştır. CAD/CAM blok kesitleri ve resin kompozit substratlar ışık ile polimerize olan rezin siman (G-CEM; GC) ile LED ışık cihazı (VALO Cordless; Ultradent) kullanılarak üretici talimatlarına uygun olarak simante edilmiştir. Simantasyonun hemen ardından ilk renk ölçümleri (E_0) spektrofotometre (CM-2600d, Konica Minolta) ile gerçekleştirilmiştir. 37 ^{O}C'de distile suda bekletilen monoblok örneklerin (substrat /rezin siman /cam seramik) 24 saat sonra 2. renk ölçümleri (E_2) gerçekleştirilmiştir (CM-2600d, Konica Minolta) ve bu ölçümler referans (baseline) olarak alınmıştır. Referans ölçümlerini takiben tüm örnekler 5-55°C arası 30000 siklus hidrotermal yaşlandırmaya maruz bırakılmıştır. Her 10000 siklus arasında (10000, 20000, 30000 siklus sonrası) renk ölçümleri önceki ölçümlerle aynı şekilde gerçekleştirilmiş ve kayıt altına alınmıştır (E_1, E_2, E_3) (CM-2600d, Konica Minolta). Renk değişimi (ΔE_{00}) ve translüsens parametresi (TP_{00}) tüm ölçümlerde CIEDE2000 formülü kullanılarak hesaplanmıştır. Veriler üç yönlü ANOVA ve post hoc Tukey's testleri kullanılarak analiz edilmiştir ($p<0,05$). ΔE_{00} seramik yapısı ($p<0.001$), seramik kalınlığı ($p<0.001$) ve yaşlandırmadan ($p<0.001$) istatistiksel olarak anlamlı ölçüde etkilenmiştir. Seramik kalınlığı açısından, yalnızca Cerec 0,5mm ve 1,0mm arasında istatistiksel olarak anlamlı fark 10000, 20000 ve 30000 siklus

sonrası saptanmıştır (*p=0.006*, *p<0.001*, *p<0.001,* sırasıyla). Seramik yapısı açısından, 0,5mm kalınlıktaki farklı cam seramikler birbirleriyle kıyaslandığında, 10000siklus sonrası LRF, Cerec'ten istatistiksel olarak anlamlı derecede yüksek renk stabilitesi göstermiştir (*p=0.001*). 20000 ve 30000 siklus sonrası Cerec LRF (*p=0.001*) ve E.Max'ten (*p=0.008*, *p<0.001*) istatistiksel olarak daha az renk stabilitesi göstermiştir (istatistiksel olarak daha fazla renk değişimi).TP seramik yapısı (*p<0.001*), seramik kalınlığı (*p<0.001*) ve yaşlandırmadan (*p<0.001*) istatistiksel olarak anlamlı ölçüde etkilenmiştir. Materyal yapısı, kalınlığı ve yaşlandırma parametreleri arasında anlamlı etkileşim saptanmıştır (*p<0.001*). Test edilen tüm materyaller kendi içlerinde farklı kalınlıklarında (0,5mm-1,0mm), tüm yaşlandırma periyotlarında istatistiksel olarak anlamlı fark göstermiştir (simantasyondan hemen sonra, Cerec 0.5mm-1.0mm *p<0.001*, CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*. 24 hours (referans ölçüm), Cerec 0.5mm-1.0mm *p<0.001*, CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*. 10000 tsiklus sonrası, Cerec 0.5-1.0 *p=0.001*, CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*. 20000 siklus sonrası, Cerec 0.5mm-1.0mm *p<0.001*, CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*, 30000 siklus sonrası CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*). Cam seramiklerin renk stabilitesi seramik yapısı, seramik kalınlığı ve yaşlandırmadan etkilenmektedir. LRF ve E.Max cam seramiklerin CD ve Cerec materyallerine göre yaşlandırma sonrası renk stabiliteleri daha yüksektir. Cerec bloğunun renk stabilitesi materyalin kalınlığına oldukça yüksek ölçüde bağlıdır. 30000siklus sonrası (3yıl yaşlandırma) 0,5mm kalınlıkta feldspatik seramik en düşük translüsensi gösterirken, 1,0mm kalınlıkta zirkonya ile güçlendirilmiş cam seramik en düşük translüsens değerine ulaşmıştır. Kalınlıklarından bağımsız olarak, simante edilmiş CAD/CAM seramik materyaller 3 yılın sonunda en düşük translüsens değerlerine ulaşmışlardır.

Anahtar kelimeler: CAD/CAM, seramik, veneer, renk stabilitesi, translüsens, TP, hidrotermal yaşlandırma.

1. INTRODUCTION and PURPOSE

With the development of dental ceramic materials, resin cem ents and anterior restoration treatment options, demands of patients for esthtetic in dental practices have been increased (7).

Ceramic veneers not only meet the esthetic expectations but also show long-term clinical performance (8) (9). In terms of ideal esthetic and color harmony, ceramic veneers' and neighboring natural teeth's color match and this matching color's long-term stability plays a key role. Ceramic material's fabrication technique, material structure and quality, thickness, resin-based luting agent's type, color and polymerization methods are the parameters which affect the color harmony and long-term color stability. Due to these reasons material's color stability throughout its functional life is as important as it's mechanical properties (10) (11) (12).

In ceramic veneers, thickness of ceramic, the color of underlying tooth structure and the color of luting agent have direct action on the final color of restoration. In these restorations, matching the chosen color for the restoration and the final restoration color is very hard to achieve. Translucency of the ceramic is another important factor that affect color harmony. As translucency increases, the emitted and scattered light through the material also increase, thus the underlying resin cement's and tooth's color become even more important. High translucency brings more lifelike appearance to restoration, on the other hand decreases masking ability of restoration (13) (8).

Barizon *et al.* stated that ceramic veneers which are made from different ceramic systems have different translucencies and conventional feldspathic ceramic have the highest translucency. In the same study, it is presented that material thickness and color have an impact on transucency, but thickness of material has the major influence on translucency.

Currently restorations can be produced with CAD/CAM (computer aided design/ computer aided manufacturing) technology. Blocks which are produced for this purpose, are made in the laboratory with heat and pressure, thus they are more homogeneous and contains less defect. However, just as the other materials used intraorally, restorations made with CAD/CAM blocks can show color changes in time.

According to International Color Commission (the Commission Internationale de l'Eclairage (CIE)) material's color parameters (L*, a*, b*) can be measured with reflection or transmittance spectrum by using a standart illuminant, observer and with the use of recommended geometries. However it is confirmed that CIEDE2000 formula is more compatible with visual perception (14-16) and a better fit for perceptibility and acceptability thresholds for ceramic materials, and enhance the discrepancy of CIELab, espeacially for slight differences in color (17, 18).

Aging systems are the systems can be used for evaluation of color stabilities of materials including ceramics and resin cements. These systems mimic the clinical conditions with applying ultraviolet light, heat, continious humidity, temperature change or thermal change to material.

Hydrothermal aging is an aging technique which simulates clinical conditions by exposing the material to 5°C -55°C temperature distilled water with a certain cycle. It is stated that 10000 cycles with 30 seconds dwelling time hydrothermal aging, equals to 1-year clinical condition exposure of material (19, 20).

Purpose of this in vitro study is to evaluate the color change of four different types of glass ceramic materials (Leucite reinforced glass ceramic; LRF, GC Corp., Japan. Zirconia Reinforced Lithium Silicate glass ceramic; Celtra Duo, Dentsply Sirona,USA. Feldspathic ceramic; Cerec Blocks, Dentsply Sirona, USA. Lithium Disilicate glass ceramic; IPS e.max CAD, Ivoclar Vivadent, Liechtenstein) in two different thicknesses (0.5mm-1mm) luted with the same light-cure resin cement G-Cem Veneer (GC Corp., JAPAN) after hydrothermal aging.

Various in vivo and in vitro studies have compared the clinical performance of ceramics. However, the color compatibility and stability of ceramic systems in the fabrication of ceramic veneers with different parameters such as the presence of substrate, different fabrication techniques, and microstructures is still worth investigating.

Furthermore, few studies have focused on the optical properties of luted ceramic veneers after artificial aging, which is important for the long-term success of a restoration (21).

In the light of the study's results, color stability and translucency change of ceramic veneers manufactured from different glass ceramic CAD/CAM materials in different thicknesses will be discussed.

Null hypotheses (H_0) of the present study were:

H_0: There would be no differences between different glass ceramics in terms of color stability.

H_0: There would be no differences between different thicknesses of the same glass ceramic in terms of color stability.

H_0: Hydrothermal aging would not have a significant effect on color stability of glass ceramic materials.

H_0: There would be no differences between different glass ceramics in terms of translucency change (ΔTP).

H_0: There would be no differences between different thicknesses of the same glass ceramic in terms of translucency change (ΔTP).

H_0: Hydrothermal aging would not have a significant effect on translucency change (ΔTP) of glass ceramic materials.

1.1 Color In Dentistry:

1.1.1 Light:

Light is not a physical but a psychosensorial phenomenon of electromagnetic waves, at the interface of three elements: a light source, an object and an observer (the eye and visual cortex in the brain)(22). Due to its energy, object pigments become visible to the human eye. There is no color without light. Isaac Newton established a principle still accepted today: light is color (3).

1.1.2 Color:

Although color is generally perceived as an art form, there is a true science behind color theory. Isaac Newton was the first to break down the physics of color. Color have been described by Newton as a spectrum. In this specific spectrum, the interval of 400-700nm wavelengths which is in between infrared and ultraviolet lights, describes as 'visible light spectrum'. Eyes can only perceive these particular wavelengths of light. . These wavelengths were named as red, orange, yellow, blue, indigo, violet. Human eye can perceive these colors as variations of green, red, and blue due to the presence of three types of color receptors. Each hue is precisely defined by its wavelength (3, 23-25)

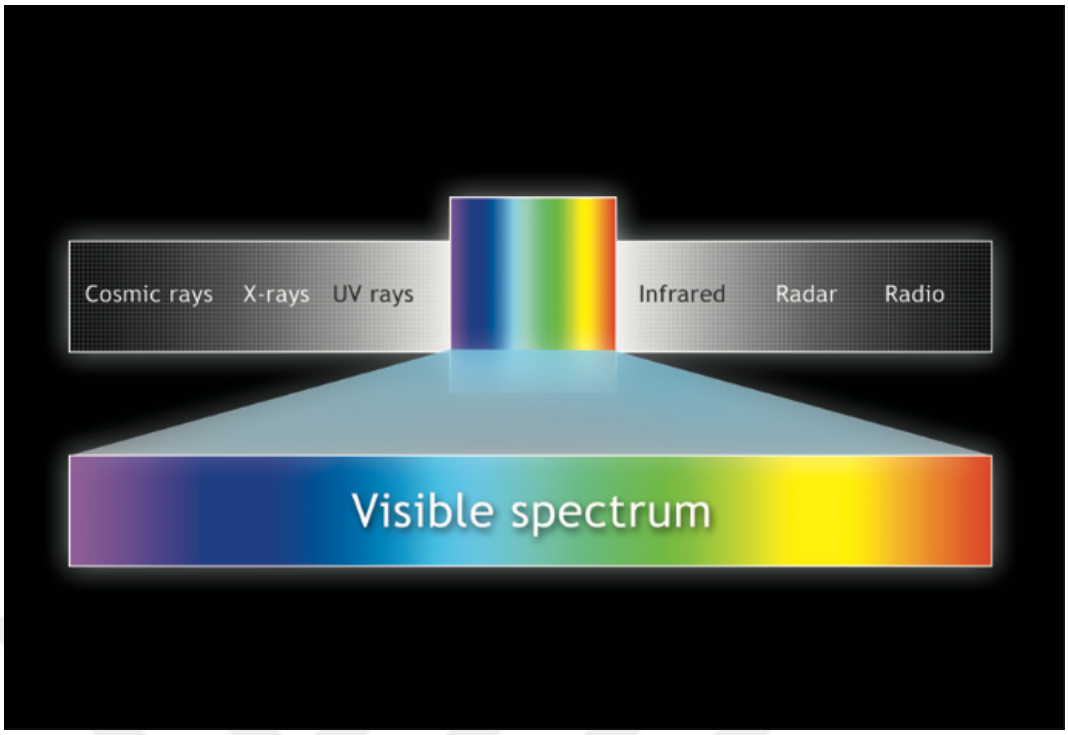


Figure 1: The visible light spectrum compared to the total electromagnetic (3).

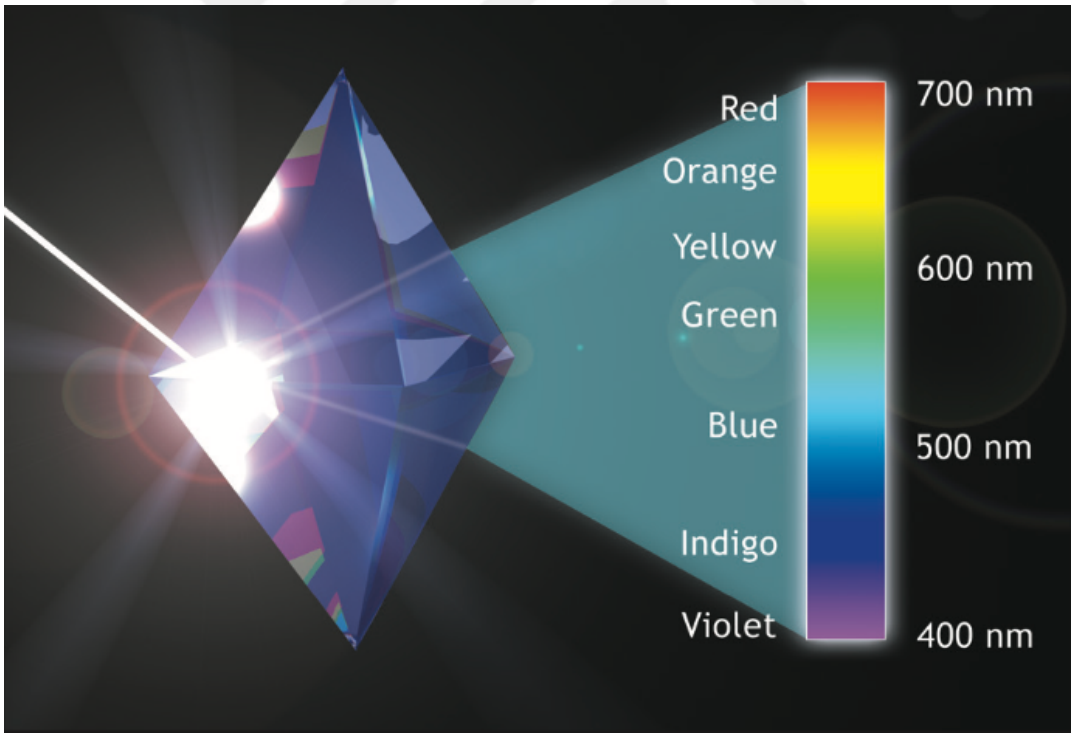


Figure 2 :The wavelengths of visible light from 400nm (violet) to 700nm (red)(3).

Table 1: Wavelengths of colors(3)

Color	Wavelength (nm)*
Red	650–800
Orange	590–649
Yellow	550–589
Green	490–539
Blue	460–489
Indigo	440–459
Violet	390–439

*1 nm = 0.000001 mm.

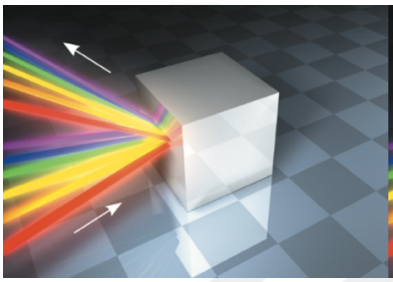


Figure 3: A white object reflects all wavelengths of light (3).

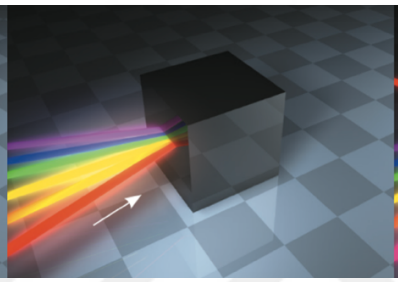


Figure 4: A black object absorbs all wavelengths of light (3).

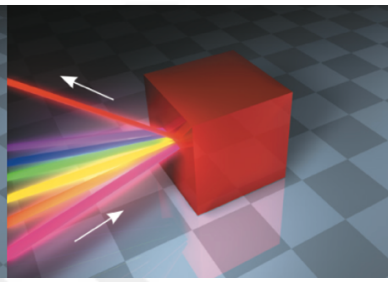


Figure 5: A red object reflects red light and absorbs all other wavelengths of light (3).

With the Newton's epochal study regarding color science draw attention to the light. Newton stated that white light comprises all colors. If an object appears in a specific color, this means that particular wavelength of the light has been reflected and the rest has been absorbed by the object. Perception of the human eye develops with the interaction of the object and the light. The object absorbs the other colors and reflects the specific color that has been perceived by human eye. Therefore, without the presence of light, there would be no color. The perceived color is related to individual color perception, age, sex, retinal fatigue, light conditions, background effect, differences between two eyes, and certain psychologic factors (15, 26, 27).

After the process of color perception is well-defined, it can be applied to dentistry, specifically in terms of shade-matching techniques.

The process by which images are captured to produce a media (e.g., the images by a digital camera) is simulant to the procedure of the color perception of human eye. According to Chu *et. al.* (3) it is substantial to consider that a digital camera has subjective valuations as human eye and cannot evaluate a patient's tooth color precisely. However more recently there are various studies that contradict with this statements (28) (29), therefore this context is controversial.

The additive principle of complementary colors can be used to change the value (brightness) of a restoration. If the value of the restoration needs to be lowered, the complementary color can be added to this restoration to make the restoration grayer and thus lesser value. Such as shade A3 contains an orange hue; therefore, adding blue color material will create a lower value.

1.1.3 Dimensions of color:

Since color is completely multidimensional, the expression of the color is as complicated as the perception of color. To clarify this complexity and to define color in a standard, quantitative, and objective way, Professor Albert H. Munsell used a 'color wheel' to establish that each color has a logical connection to all other (3, 30, 31). The 'color wheel' contains the dimensions of chroma, value and hue. In addition to these dimensions, it is essential to add translucency, which is absent in Munsell's color analyzes but is probably the most important factor in the esthetic outcome of a restoration.

The four dimensions are defined as follows:

1.1.3.1 Hue: Identical to the term color, the degree of mixture of the three primary colors (red, yellow, blue). In other words, the name of the color (3, 4, 24, 26).

1.1.3.2 Value: Describes the degree of brightness, in other words the lightness or darkness of the hue. The higher the proportion of reflected light, the higher the value. The value scale ranges from 0 (completely black) to 10 (completely white) (3, 4, 24, 26).



Figure 6: Scale of Value

Drawn by Seyma Tuna Ünal, DDS.

1.1.3.3 Chroma: The purity and intensity (saturation) of color (hue). As the reflectance of the wavelength of a particular color increase (compared to all other wavelengths), that particular color becomes more chromatic (3, 4, 24, 26).

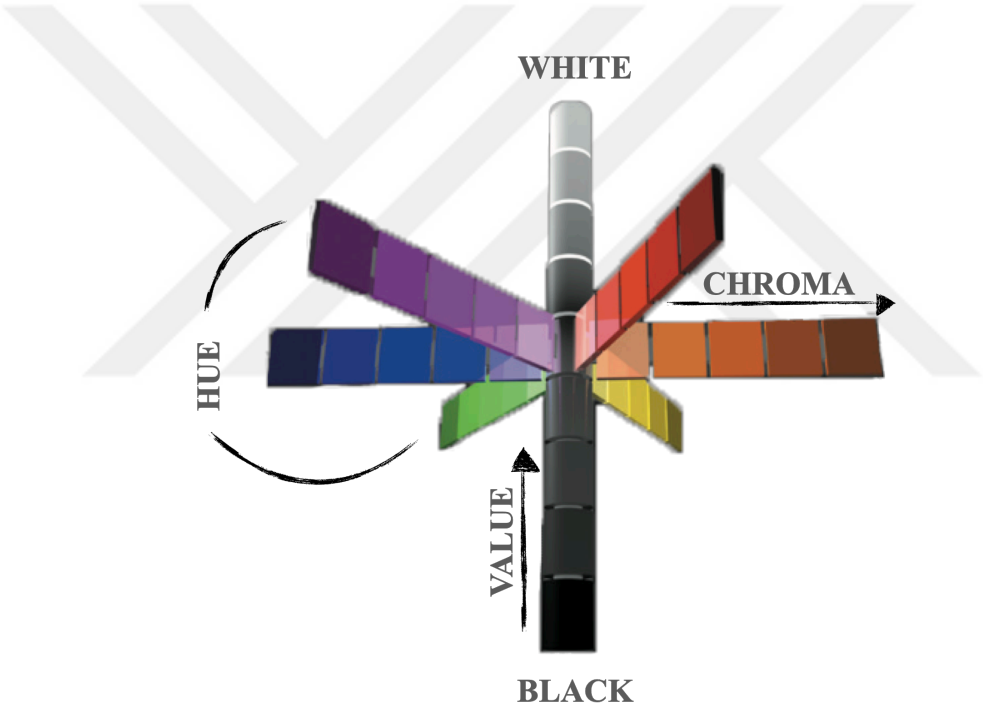


Figure 7: Munsell Color System

Drawn by Seyma Tuna Ünal, DDS.

1.1.3.4 Translucency: The degree of light transmitted as opposed to reflected or absorbed. Absolute translucency is transparency, while the absence of translucency means opacity (32). In terms of optical properties, translucency is an important characteristic of natural tooth enamel. One of the complex procedures in dentistry is to determine the degree of translucency of the natural enamel and match it with the corresponding restoration. Although the quantification of translucency is still controversial (33), in the clinical setting ceramists can use a densitometer to measure the degree of translucency of a restoration. In in vitro studies, translucency can be measured using either translucency parameters (TP) or contrast ratios (CR) (34, 35). TP is the difference in color of the same material on a black and white background at uniform thickness and is directly related to translucency, while CR is the ratio of light reflected from a given surface on a black and white background, and since as light reflectance increases, so does opacity, this formula is related to opacity (33-36).

$$CR = Y_{black} / Y_{white}$$, where Y represents the light reflentance

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

$$TP_{00} = \left[\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)\right]^{1/2}$$

In general, trained eyes can designate hue and value when exhibited separately. However, challenges arise when chroma and value are displayed together, leading to inconsistencies in determining the value of restorations (37).

1.1.4 Optical Properties:

1.1.4.1 Fluorescence: It can be defined as the absorption of UV light by an object and the uncaused emission of the light. In dentistry, the dentin layer and its proteins that form the attachment with the enamel are the most fluorescent compounds in the entire body. In restorative treatments, fluorescence is a significant optical property. Especially for ceramic restorations, as ceramics contain active ingredients that cause the restoration to become fluorescence. In addition to these, fluorescence makes the restorations more natural and minimizes the metameric effect (24, 26).

1.1.4.2 Opalescence: The appearance of a translucent material as blue in reflected light and red in transmitted light. The opalescent effect depends on the translucency of the natural teeth. Under direct illumination, the shorter wavelengths (e.g. blue wavelengths) are reflected by the fine particles of the enamel and restorative material, resulting in a bluish appearance, when the longer wavelengths (e.g. red-orange wavelengths) are absorbed (38).

Fluorescence and opalescence develop the intrinsic brightness of natural teeth that clinicians and ceramists aim to simulate in restorations(3). It is important to decide how much translucency and opacity is required for lifelike and harmonious restorations. Since extreme opacity can result in a dull appearance, just as extreme translucency can result in a low value that appears too gray and dark with the reflection of the oral cavity.

Color-corrected lighting is produced to match the relative amount and wavelengths of visible light from the sun (6500K). However, a patient's smile can be viewed under various lighting conditions, resulting the restorations to appear entirely different in terms of value, chroma, and hue. As the restorations can appear different under several lighting conditions, leading to challenges in color matching.

1.1.4.3 Metamerism: The phenomenon that two objects match in color under one condition but have obvious differences under another condition is called **metamerism**, and the two objects become a **metameric pair** (3, 4, 26).

In Restorative Dentistry, metamerism occurs when optical properties of a restoration match the natural dentition under day light but does not appear to match the natural teeth under color-corrected or fluorescent light. Metamerism might occur frequently, and the errors are often apparent, resulting in a revisit of the patient and renewal of the restoration.

Although manufacturers have showed effort to overcome metamerism by improving materials that present chameleon effect by blending with surroundings, metamerism is still a problematic issue in the Restorative Dentistry. Since a few degrees of metamerism is usually inevitable, clinicians can explain to their patients that it is unexceptional for the optical properties of restorations to diverge merely under different lighting conditions and that this is a corollary of light, not a failure.

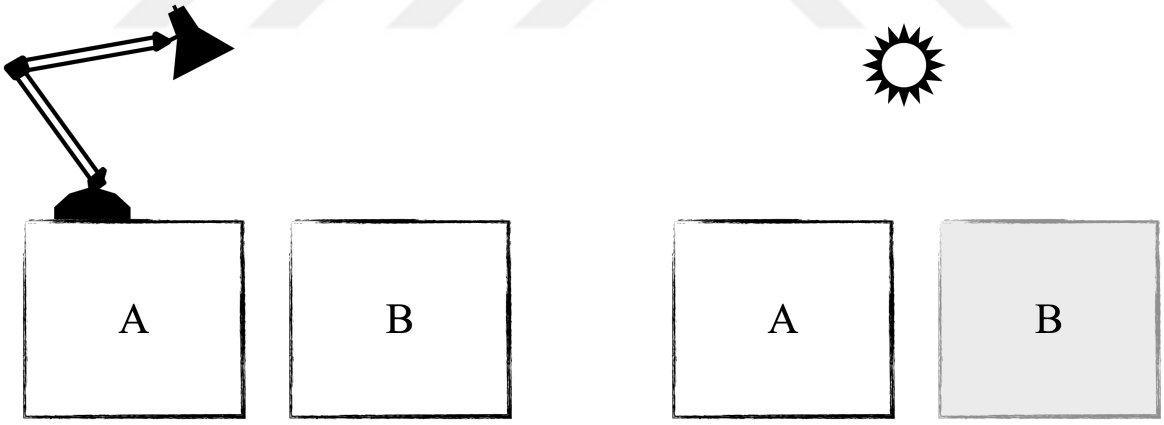


Figure 8: A and B objects are metameric pairs of each other.

Drawn by Seyma Tuna Ünal, DDS.



Figure 9: Two different aspects of the same place under different lighting conditions(4).

1.1.5 Light Phenomena in Dental Hard Tissues:

Direct Transmission: The light passes without any obstacle.

Diffuse Transmission:

Following the contact with the object light diffuses in different directions.

Selective Transmission: Certain wavelengths can pass.

Reflection: Rejection of the light.

Refraction: Change in direction of the propagation of the light (5).

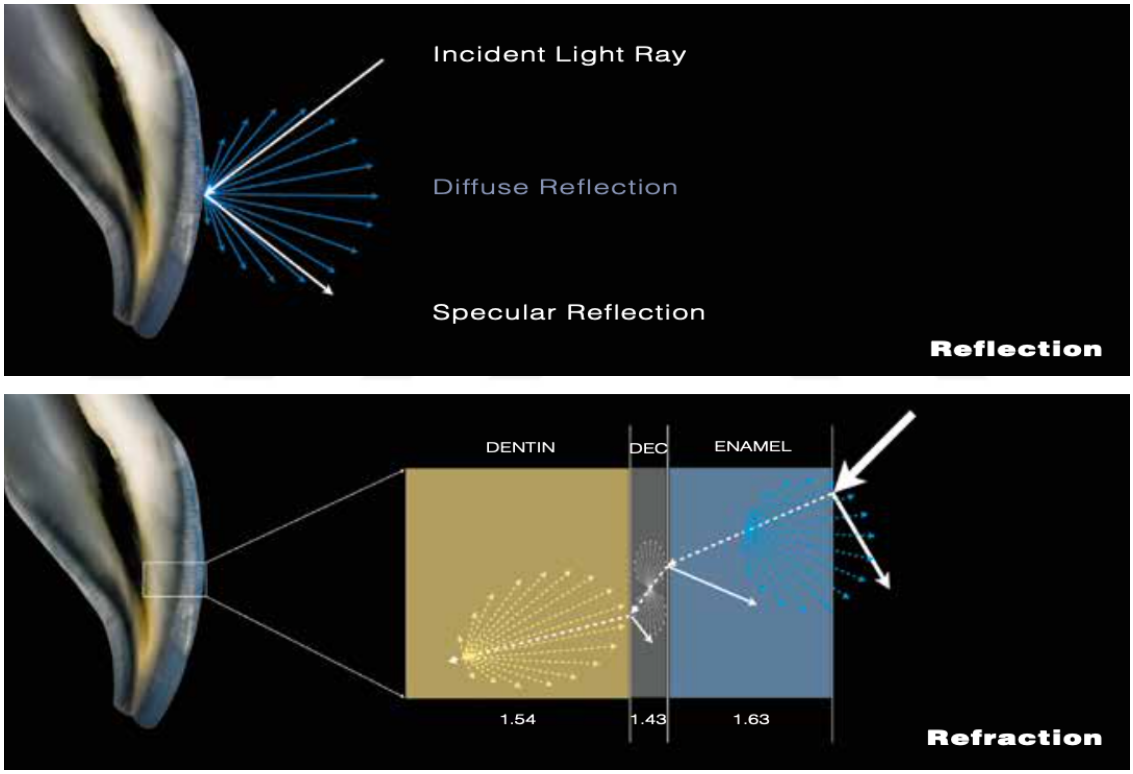


Figure 10: Reflection and refraction of the light through the surface of tooth (5).

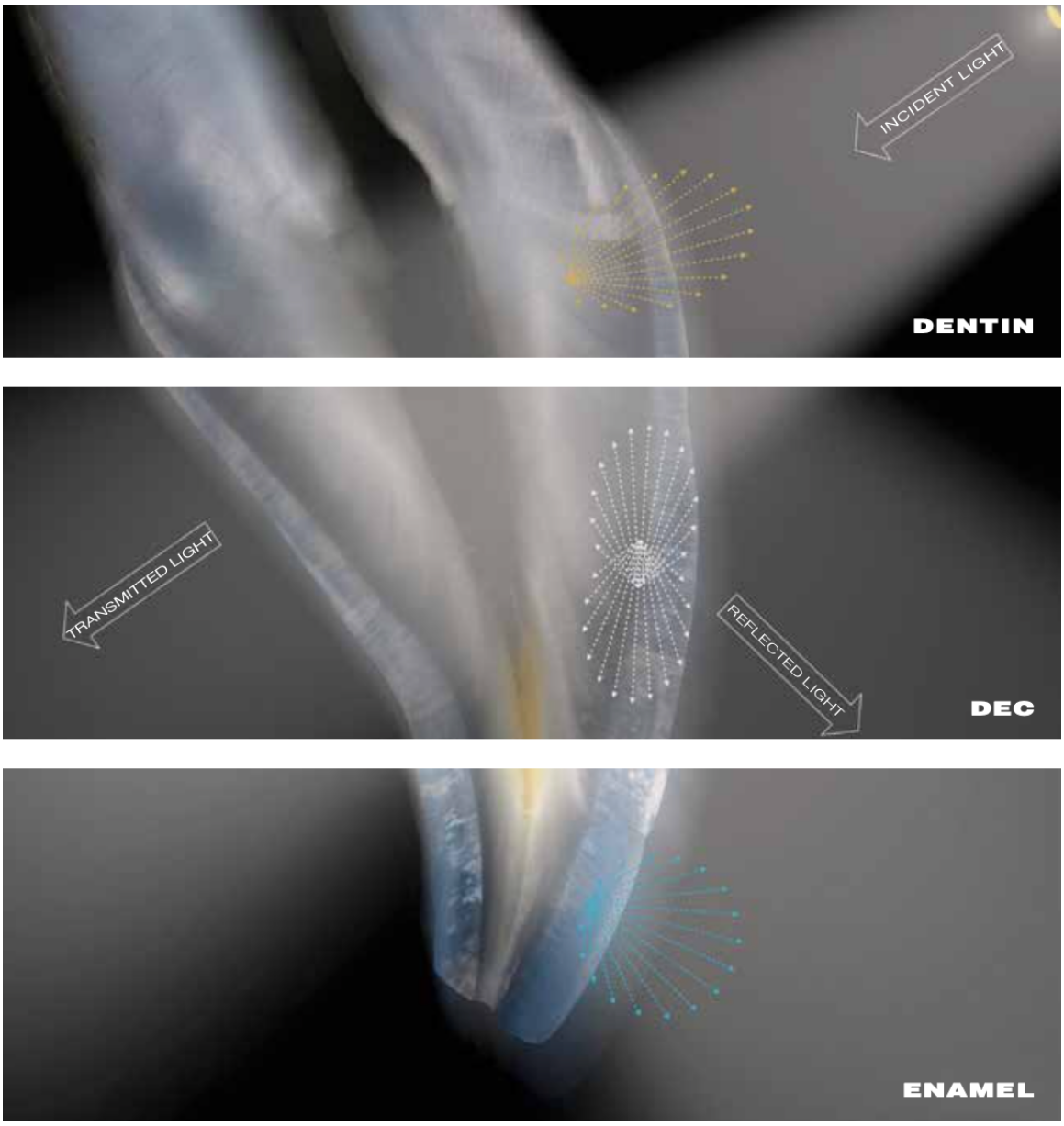


Figure11: Pattern of the light through dental hard tissues (5).

1.1.6 Color Systems:

1.1.6.1 CIE Lab (*Commission Internationale de l'Eclairage*):

CIE Lab color space is a regular structure that quantifies color, while ΔE_{ab} measures color difference of two specimens in color studies (14, 39-41).

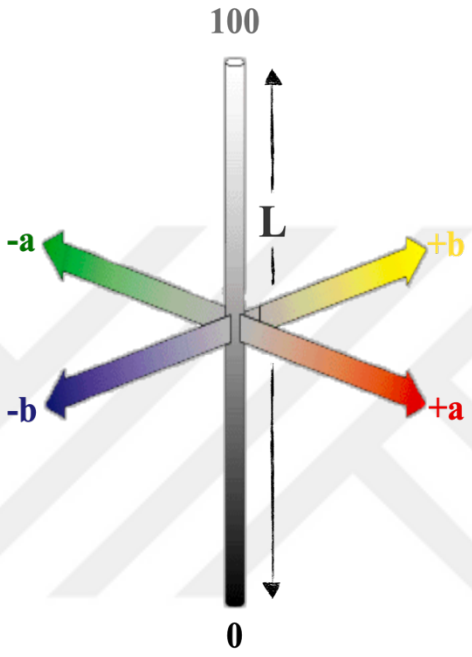


Figure12: L*, a*, b* coordinates of CIELab Color System.
Drawn by Şeyma Tuna Ünal, DDS.

The ΔE can be obtained with the following formula:

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

Where L value represents lightness of the color. a and b values are represent chromatic characteristics; a refers to the red-green axis and b blue-yellow axis (39, 42). The resulting ΔE_{ab} is the shortest distance between point a and b (3). In digital color analyses, the aim is to achieve the most precise ΔE value possible for the cervical, coronal, and incisal areas of the tooth. It is important to indicate that ΔE values are non-linear, they do not compare whether

one shade is darker or lighter than another. The ΔL (change in value) is the most significant parameter because the human eye can detect even minor changes in value more easily than hue or chroma (13, 43-45). It is reported that less than 2.0 units of ΔL value is clinically acceptable (46).

1.1.6.2 CIEDE 2000 :

In order to increase the alinement between instrumental and percieved color difference of CIE Lab formula, several formulas have been developed. More recently, CIEDE2000 formula recommended by CIE among all previous formulas (1, 17, 40, 47, 48).

The CIEDE2000 formula includes weighting functions of value (S_L), hue (S_H), chroma (S_C), therefore, emphasizes the importance of Munsell Color System. In addition, with an interactive term between hue and chroma (rotation term R_T) differences, the performance of blue colors evolved, while with the modification (scaling factor) of the a* coordinate the performance of gray colors (low chroma) and parametric factors (K_L, K_H, K_C) improved with the following formula (1, 2, 40):

$$\Delta E_{00} = \left[\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{K_C S_C}\right)\left(\frac{\Delta H'}{K_H S_H}\right)\right]^{1/2} \qquad (1, 2)$$

In the literature, various studies compared CIELab and CIEDE2000 formulas (14, 49, 50) and showed significant correlation between ΔE_{ab} and ΔE_{00}, after polymerization and thermocycling. However, this correlation refers only that the resulting values of formulas were proportional, not interchangeable. Moreover, it is confirmed that CIEDE2000 formula is more compatible with visual perception (14-16) and a better fit for perceptibility and acceptability thresholds for ceramic materials, and enhance the discrepancy of CIELab, espeacially for slight differences in color (17, 18).

There are two thresholds for evaluating color differences, perceptibility threshold (PT) and acceptability threshold (AT) (1), these thresholds can function as guide for restorative material selection, evaluate color stability of materials, interpret the instrumental and visual differences, compare the results of different researches, and standardization (47).

The 50:50% perceptibility threshold defines a situation where 50% of the observers can detect the color difference, while the remaining 50% cannot detect color difference between two objects. Similarly, where 50% of the observer consider the color change as acceptable, while the other unacceptable, this situation corresponds to 50:50% acceptability threshold (51-53). There are several studies that evaluated visual thresholds of teeth and restorative materials (17, 40, 53-55), however a well-accepted thresholds defined by Paravina *et. al.*: CIELab ΔE_{ab}=1.2 units refer to perceptibility threshold, while ΔE_{ab}=2.7 units refer to acceptability threshold. For CIEDE2000, associated AT and PT values are ΔE_{00}=1.8 and ΔE_{00}=0.8, respectively (47).

1.1.7 Measurement of Color:

In terms of color measurement, the most preferred methods are visual and instrumental measurements (56). Although in clinical situation traditional visual assessment commonly used, this method is subjective and indefinite since various parameters can affect the visual assessment such as age, eye fatigue, sex, lightning condition etc. (27, 57). Color measurement instruments provide more precise and accurate results than visual evaluation (27). Accuracy and precision are two different necessities of color measurement. Accuracy demonstrates the ability of ensure correct color match of the method, while precision indicates the repeatability of the method in time or the repeatability of the entire measuring process (58).

1.1.7.1 Spectrophotometers are highly accurate and precise color measurement instruments. The device measures the extent of reflected light wavelengths from an object in approximately every 10 nm through the visual spectrum, and these measurements creates spectral color data. Spectrophotometer contains a means of dispersing light, a source of optical radiation, a detector, an optical system for measuring, and a means of converting light obtained to a signal that can be analyzed. A spectrophotometer measures and records the amount of visible radiant energy for each chroma, hue, and value present in the entire visible spectrum. These measurements result in a complex data set of reflectance values, which are visually interpreted in the form of a spectral curve. Spectrophotometers measure the reflectance or transmittance factors of an object one wavelength at a time, and they have been used to measure the spectral curves of porcelains and extracted teeth. Because of their high

cost and complexity, widespread use of this devices has been hindered. Their use increases accuracy by 33% compared with visual observation and produces 93.3% success in color determination (3, 27, 39).

1.1.7.2 Colorimeters estimate the spectral function of the standard observer's eye and are engineered to measure color as human eye sensation. A colorimeter limitedly filters light in three or four regions of the visible spectrum to define the color of an object. These devices are difficult to design, and if made incorrectly, the outcome will be less accurate in comparison with a spectrophotometer. On the other hand, due to their limited filtering hence specified color mapping, colorimeters can decrease the data load time by comparison spectrophotometers (3, 27, 39).

1.1.7.3 Digital photography technique has been embraced by clinicians. Digital photography provides information not only on color, but also on morphology, surface texture, characteristics of the tooth under intraoral conditions (28). In addition, this technique enables communication with technicians and other colleagues in interdisciplinary treatments. However, various parameters should be standardized such as resolution, light source, exposure, film speed, and white balance (59-63). To improve the standardization different tools have been used, cross-polarizing filters are one of them. These filters eliminate specular reflections through tooth surface and ensures correct color selection without diffuse white opacities of flashes (5, 64). White balance eliminates unrealistic color casts such as reflection of red tones from gingiva. Automatic white balance selection can standardize this parameter by adding cyan to image to neutralize the red tones of gingiva (62). Sampaio *et. al.* compared different digital photography techniques including Iphone7 camera, and concluded that a white balanced image with digital camera, cross-polarizing filter, close-up flashes, and gray reference card will result optimal (29).

1.2 Selection of Restorative Material:

Due to the complex optical properties of tooth, achieving desired final color and color match with restorations is challenging for clinicians. In order to meet the increased esthetic expectations of the patients, it is essential to have knowledge of the optical properties and characteristics of restorative materials. The problem of matching the natural tooth and restoration color have been evaluated and concluded that even in slight difference of shade and thickness of opaque and translucent ceramic layers can affect the final color of a restoration (8, 65). Especially, color matching with bleached teeth can be highly problematic, due to their achromatic color with white hue, low chroma and high value. In this case, value is the only solid parameter that is assessable; however, it is directly related to translucency and opacity. Certain materials have high translucency (e.g., glass ceramics), while others have high opacity (e.g., zirconia). Therefore, a comprehensive knowledge on the material type and microstructure, thus its optical properties, is vital for the final color and color match of a restoration (66, 67). It is also important to emphasize that despite the selection of the correct restorative material and shade, the possibility of error may still exist due to the dynamic nature of intraoral conditions.

In these clinical conditions, clinical and in vitro studies as well as systematic reviews have confirmed that ceramic veneers are a durable and minimally invasive treatment alternative to full crowns and a more durable option compared with composite veneers, providing long-term high-quality esthetics and superior mechanical properties (13, 68-73). However, ceramic materials have structural differences that are reflected in their optical and mechanical properties. These materials comprised of nonmetallic and metallic elements in order to create crystalline and non-crystalline ceramics. Non-crystalline ceramics have crystalline minerals as feldspar, alumina and silica in a glass matrix which is in amorphous and non-crystalline form. Feldspathic ceramic, for example, is a non-crystalline ceramic and is fragile due to its low flexural strength. A high glass matrix content imparts high translucency and esthetic properties to ceramic restorations, which is essential for creating enamel-like optical properties. However, a high glass content is also responsible for low flexural strength and lower resistance to crack propagation. To maintain mechanical properties, the glass matrix of the ceramic is reinforced with fillers such as leucite, alumina

or zirconia. Depending on the type and quantity of the reinforced filler, the mechanical and optical properties and thus the indications of the restorative material differ. The higher the proportion of filler, the higher the mechanical properties and the lower the esthetic properties (74-76).

1.3 Composition of Ceramic Materials :

1.3.1 Feldspar: Is a naturally occurring material and the main building block of porcelain (75-85%). Due to their low melting temperature, this grayish material melts in the first instance and builds the glass matrix. There are two chemically different aspects of feldspar, soda aluminum silicate (soda feldspar) and potassium aluminum silicate (potash feldspar). Melting temperature of potash feldspar is 1200-1500 °C, after melting glass matrix is built with the fusion of quartz and kaolin. Most of the current ceramic materials have translucence characteristics due to their potash feldspar substance. On the other hand, soda feldspar produces lesser fusion temperature and affects pyroplastic flow during sintering process, results in reduced fluidity to form porcelain (24, 26, 77, 78).

1.3.2 Quartz: During the heating process quartz remains unchanged due to its high fusion temperature (1700°C) and provides stability to the framework. It is responsible for the strength and creating framework to other contents (24, 26, 77, 78).

1.3.3 Kaolin: Is the bonding agent of ceramic particles. Depending on kaolin amount, the level of opaqueness changes, thus it is limited in restorative materials (24, 26, 77, 78).

1.3.4 Glass Modifiers: Such as sodium, potassium and calcium are used to produce higher coefficient of thermal expansion. Color pigments are affecting the esthetic outcome of the restoration (24, 26, 77, 78).

1.4 Classification of Ceramic Materials:

There are various classifications for ceramics according to different parameters.

1. According to their fusing temperature (24, 79) :

-High fusing (>1300°C)

-Medium fusing (1101-1300°C)

-Low fusing (850-1100°C)

-Ultra low fusing (<850°C)

2. According to processing methods (24, 79) :

-Slip Casting

-Sintering

-Hot-isostatic pressing

-CAD/CAM milling

3. According to microstructure (76, 80, 81):

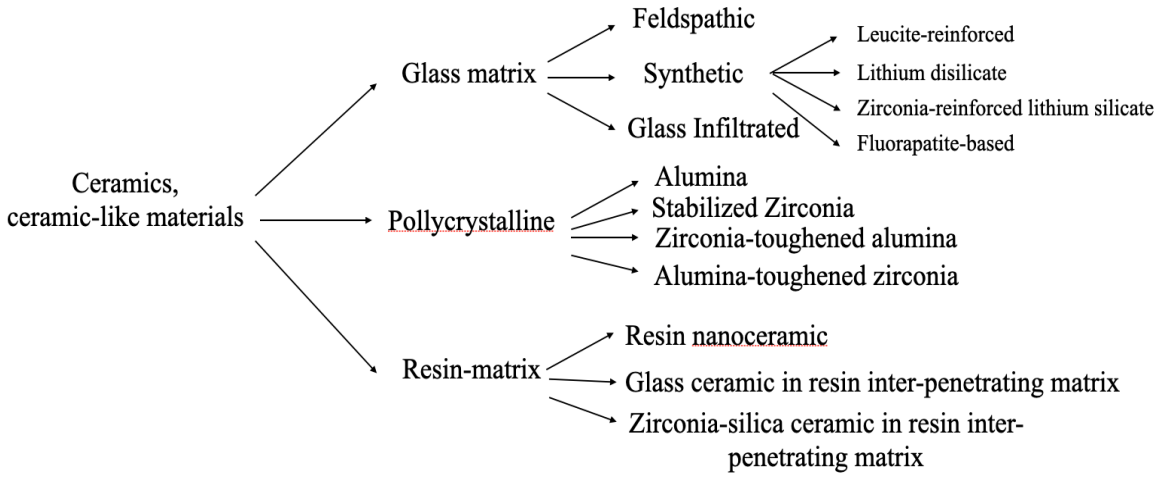
-Mainly glass-based

-Glass-based with fillers (leucite, lithium disilicate)

-Polycrystalline solids (zirconia, alumina)

Although this classification system provides correct material selection and protocol, it is also unspecified and does not enable development regarding new materials as resin-matrix materials. American Dental Association classified resin-matrix materials as ceramics. Gracis et. al. classified ceramic materials as in three groups, glass matrix ceramics, polycrystalline ceramics, resin matrix ceramics (6).

Table 2: The Classification of Dental Ceramics and Ceramic-like Materials (6).



1.4.1 Glass Ceramics (Glass-Matrix Ceramics):

Glass ceramics consists of feldspar, kaolin, and silica (quartz), and are defined as traditional ceramic materials. They comprise of leucite crystals (15-25%) embedded in glass phase. Leucite crystal procures strength, fluorescence, translucency, and opalescence. Glass ceramics are highly esthetic materials due to high glass content that provides resembling optical properties to natural tooth. However, they also exhibit low mechanical properties such as 20-60 MPa tensile strength and 350-550 MPa compressive strength(82-84).

1.4.1.1 Feldspathic Ceramics:

Feldspathic ceramics are the best biomimetic materials that consist of feldspar, kaolin, and silica. Silica builds the matrix and ensures translucency, however since it is a fragile element, matrix is reinforced with alumina (20-25%). Kaolin is the bonding agent for the particles, yet its use is limited due to the high opacity (82, 84-86). This material has low mechanical properties (120 MPa (85, 87, 88)) with relatively large particle size of about 2-4 μm. In the market there are different feldspathic ceramics with different optical properties, monochromatic or polychromatic. VITA MarkII (VITA Zahnfabrik, Germany), Cerec Blocks (Dentsply Sirona, Germany) are examples for feldspathic ceramics. Different thicknesses in monochromatic version are highly important for masking underlying structure. Feldspathic veneers thinner than 0.7mm cannot mask the underlying substrate,

however they also considered as the most esthetic material with their enamel-like translucency. Feldspathic ceramics are indicated for veneers and non-load-bearing areas (85).

1.4.1.2 Synthetic Ceramics:

In order to improve the mechanical properties of feldspathic ceramic and avoid thermal expansion mismatch between metals and crack propogation, manufacturers started to add apatite crystals into the glass matrix, such as leucite and lithium disilicate (6, 84, 86).

a. Leucite-Reinforced Glass Ceramic:

Leucite is the first filler which is embedded up to 45% in the glass matrix of feldspathic ceramics and has a relatively fine particle size of 1-5 μm. The leucite glass matrix has a refractive index similar to that of the feldspathic glass matrix, so there is less compromise in translucency while preventing crack propagation and moderately increasing flexural strength (160-300MPa by (89), 185MPA by (85)) and fracture resistance. In addition, leucite crystals have faster etching rate than glass base, this etching pattern produce micro recessions such as resin tags in enamel surface, resulting in stronger micromechanical bond (80). IPS Empress CAD (Ivoclar Vivadent, Liechtenstein), Initial LRF (GC Corp., Japan) are examples for leucite-reinforced glass ceramics, and are available in high translucency (HT), low translucency (LT) options regarding light transmission properties. Their indications are veneers, crowns and inlay/onlays since they are relatively improved in terms of mechanical properties compared to feldspathic ceramics. In a clinical study, veneer restorations made with leucite-reinforced glass ceramics exhibited %96.4 survival rate in 5 years follow-up (70).

b. Lithium Disilicate Glass Ceramic:

The crystalline phase of lithium disilicate ceramics is 70% and are higher than feldspathic ceramic, thus present higher mechanical properties. The first lithium disilicate ceramic IPS Empress II (Ivoclar Vivadent, Liechtenstein) can fabricated both by heat-pressed and CAD/CAM milling, however their flexural strength is low for multi-unit restorations

(350-450 MPa). For this reason, the same manufacturer improved the material and revealed IPS e.max for both pressed (IPS e.max Press) and milling (IPS e.max CAD) fabrication.

In the early phase of the material, primarily, ceramic is cast into transparent glass ingots that are containing lithium orthosilicate. Following partial crystallization, the formation of 40% of platelet-shaped lithium metasilicate crystals (with the size of 0.2-1.0 μm) are formed in a glass matrix. This phase is called intermediate crystalline (pre-crystalline) phase in other words 'blue phase' (purple block). In 'blue phase' the material has 130 ± 30 MPa flexural strength which makes the milling process rather easy, thus in this phase preparation of the restoration is performed. After the milling, final sinterization executed at 850°C, and lithium disilicate crystals are formed in 1.5 μm size needle-like pattern. The material's final flexural strength becomes 530MPa (85, 90-92). This microstructure and high flexural strength make this type of ceramic the material of choice for many restoration types by achieving good clinical outcomes at a specified thicknesses in load-bearing areas while preserving advanced optical properties. Hence lithium disilicate glass ceramics can be used in a variety of restorative treatments such as veneers, inlays, overlays and single crowns (91, 93).

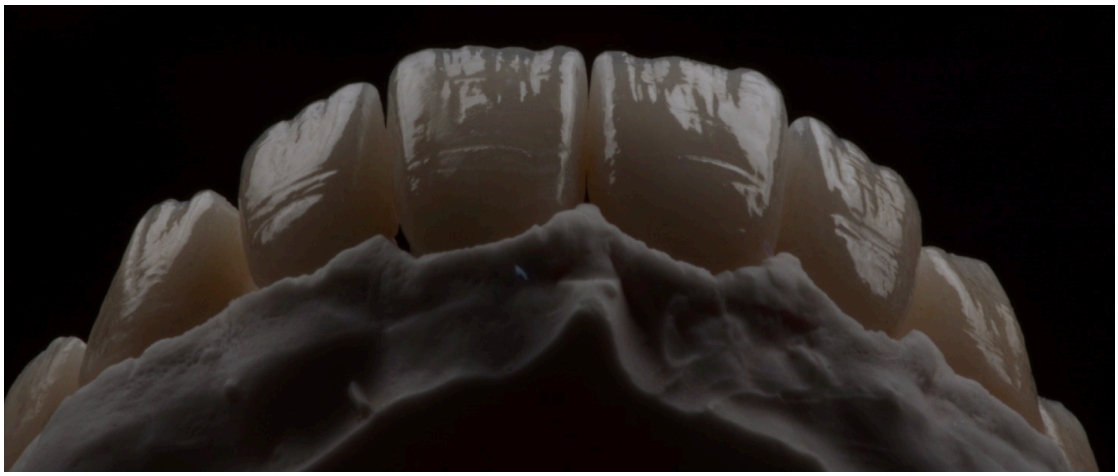


Figure 13: Ceramic veneers made with IPS e.max Press (Ivoclar Vivadent,Liechtenstein.).
Photography by Şeyma Tuna Ünal, DDS.

c. Zirconia-Reinforced Lithium Silicate Glass Ceramic:

Zirconia-reinforced lithium silicate was introduced in 2013, VITA Suprinity by VITA Zahnfabrik (Germany), the aim was to combine the esthetic properties of lithium disilicate with the mechanical properties of zirconia. The other example of this type of glass ceramic is Celtra Duo by Dentsply Sirona (Germany). Celtra Duo has zirconia content approximately 10% by weight. Although both Celtra Duo and VITA Suprinity contains similar crystal phases embedded in a glass matrix, Celtra Duo has approximately 0.5 μm larger in length lithium silicate crystals (94). Crystalline phase of Celtra Duo contains lithium silicate crystals with a size of 0.5-0.7 μm. Due to small crystal size and high glass content (64-70%) the material has superior translucency. On the other hand, despite its high glass content, Celtra Duo has improved flexural strength because of the zirconia content (~10%) (90, 94-96) .This material is indicated for single unit restorations such as crowns, overlays, inlays, and veneers (95). Celtra Duo is a fully sintered block and the manufacturer claims that it can be immediately seated and luted after fabrication (95, 96). However, with additional sintering flexural strength increases from 210 MPa to 370 MPa (95).

1.5 CAD/CAM Technology (Computer Aided Design/ Computer Aided Manufacture):

The first CAD/CAM prototype launched by Dr.Duret who is a French dentist, in 1971. In 1983, Duret produced the first chairside restoration by taking an impression with an optic scan. After 2 years, CEREC device was produced by Mörmann and Brandestini. The main goal of this technology is to produce esthetic, accurate restorations with a precise workflow in a single appointment (86, 97).

3D model produced by taking the impression of the prepared tooth and periodontal tissues, the restoration designed by software and the restoration was milled by milling machine from prefabricated blocks (84, 97, 98).

This technology brought various advantages over analogues technique, processing techniques such as wax-up, firing, casts are not required. With the existence of milling machine, the restoration will be prepared in single visit without any provisional restorations

which are not comfortable and bad for the periodontal tissues with their retentive surfaces, in addition to these due to the absence of laboratory and provisional treatment cost will be reduced. Digital scanning is faster and easier especially with the up-to-date scanning devices (Ithero, ABD and Trios, 3Shape, Copenhagen, Denmark). However, it should also be considered that these high-tech devices are rather expensive (97).

The blocks produced for this technology are homogenous with less defects and pore populations, resulting in reliable outcomes with their dense structure. CAD/CAM blocks should be suitable fast milling and have resistance to milling damages, also the burrs should not be worn out so that the blocks can milled fast without damaged (98).

CAD/CAM systems are indicated for inlays/onlays, veneers, crowns, implant abutments and full-mouth restorations, in other words for all type of restorations (97).

1.5 Resin Cements:

Resin cements have been used for luting of the ceramic laminate veneers and full crown restorations since porcelain is etchable providing an effective bonding of the restorative material to the dental hard tissues. Resin cements are basically low-viscosity resin composites with high tensile and compressive strength and fracture toughness compared to conventional cements. They exhibit low solubility under intraoral conditions and can combine (bond) tooth structure and restorative material with the ability to adhere different surfaces. Their bonding strength and biocompatibility improves when used in combination with adhesive systems. Resin cements are available in different shades and translucency levels (99). However, there are several disadvantages of resin cements, as with all adhesion protocols, the use of resin cements also requires technical sensitivity, difficulty in removing excess material, the possibility of pulp sensitivity or microleakage, the possibility of local immunological reactions in periodontal tissues when excess material is present, and, in some cases, the inability to perform complete polymerization (100-103).

1.6.1 Composition of Resin Cements:

Resin cements comprise of inorganic fillers and organic resin matrix (101, 104). The organic matrix consists of Bis-GMA (bisphenol A glycidyl methacrylate), but recently most

manufacturers have preferred to use UDMA (urethane dimethacrylate) as the monomer instead of Bis-GMA because of better adhesion and color stability. Later, the monomer TEGDMA (triethylene glycol dimethacrylate) was included in the organic matrix to reduce viscosity. However, this monomer is also responsible for increased water sorption due to its hydrophilic ether bonds. Therefore, replacing TEGDMA with UDMA may ensure less water sorption and thus less color change (105).

On the other hand, the inorganic matrix is responsible for the physical and mechanical properties. The inorganic matrix consists of filler particles diffused into the organic matrix with different size and shape (106). These inorganic fillers improve durability, increase viscosity and thus facilitate the application of the material, provide radioopacity and inhibit polymerization shrinkage (e.g. barium, strontium, zinc for radioopacity, silica particles for translucency). The organic matrix and the inorganic fillers are bonded together by silane coupling agents. Silane coupling agents are bipolar molecules that simultaneously bind polymer structures in the organic matrix and free hydroxyl groups on the surface of the inorganic fillers. These agents improve the physical and mechanical properties of the material. Inorganic fillers prevent water transmission throughout silanization interface and thus reduce water sorption and solubility of the material (107).

1.6.2 Classification of Resin Cements According to Their Polymerization Mechanism:

Resin cements can be chemically cure, light-cure, or dual-cure (combination of light- and chemical-cured) (108, 109) In chemically-cured resin cements, due to the absence of control over working time, clinicians prefer whether light-cured or dual-cured resin cements (110, 111).

1.6.2.1 Chemically cure (self-cure) Resin Cements:

Self-cured resin cements were presented as two-component materials. One component (paste) contains an aromatic tertiary amine activator, the other a benzoyl peroxide initiator (amine/peroxide components). Curing occurs through the reaction of the activator and the initiator, this reaction forms free radicals. These radicals are necessary for polymerization to begin. Self-cured resin cements are suitable for restorations where light

transmission is low, such as thick and metal-supported restorations. The known disadvantage of this material is the chemical change of the tertiary amine accelerator and the associated color change of the material over time (23, 24, 26).

1.6.2.2 Light-cure Resin Cements:

Light-cure resin cements are single component materials in a lightproof syringe. Photoinitiator and amine initiator produce free radicals, and without proper light exposure the components do not react. The photoinitiator camphorquinone is activated within 400-500nm wavelengths(24). Light-cure resin cements are beneficial with their extended working time, improved color stability, and the polymerization started on demand. In order to increase polymerization, it is essential to adjust the curing time, otherwise the mechanical properties of the material may be affected. They are indicated in thin restorations where light transmission is adequate such as thin ceramic veneers (112, 113).

1.6.2.3 Chemically and Light Activated (dual-cure) Resin Cements:

Dual-cure resin cements can be two-component materials. These materials contain amine/peroxide components which are also found in self-cure resin cements and photoinitiator camphorquinone which is found in light-cure resin cement. Therefore, the material ensures the advantages of both light- and self-cure resin cements with extended working time and sufficient degree of polymerization(114, 115). With the light-curing, polymerization begins and with self-curing, the material achieves adequate degree of polymerization. These materials are suitable for all-ceramic restorations, composite restorations, and thick restorations. As the restoration thickness increases, the light transmission decreases (116). Lee and Greener (117) stated that the decreased light transmission is caused by the absorption and scattering of the light, inside the ceramic layer. Therefore, dual-cure resin cement can be suggested for the thick restorations (118).

2. MATERIALS AND METHODS

Our study was executed mainly in Hard Tissue Laboratory of Yeditepe University Faculty of Dentistry, hydrothermal aging was conducted in Bezm-i Alem University Faculty of Dentistry. In this study, four different types of CAD/CAM glass ceramic blocks were used; lithium disilicate (IPS e.max CAD, Ivoclar Vivadent, Liechtenstein), zirconia reinforced lithium silicate (Celtra Duo, Dentsply Sirona, Germany) leucite reinforced glass ceramic (Initial LRF, GC Corp., Japan), feldspathic ceramic (CEREC Blocks, Dentsply Sirona, USA). Blocks were selected in A1 shades, and with high translucency (HT).



Figure 14: Tested CAD/CAM blocks.

2.1 Sample Preparation

2.1.1 Sample Preparation of LRF and Cerec CAD/CAM Blocks:

Ceramic blocks were fixed horizontally and cut with low-velocity milling machine (Isomet 1000, Buehler Ltd., Lake Bluff, IL, USA) in 400 cycles per minute under water cooling. Specimen thicknesses were 0,7mm and 1, 2mm. Every specimen's single surface was wet-finished with 800, 1000, 1200 grit silica carbide papers by turn and the final thicknesses of the samples were standardized to 0.5mm and 1.0mm (Phonex Beta Twin Whell, Buehler Ltd., Lake Bluff, USA). After polishing thicknesses of samples were measured with digital caliper.

Specimens were divided into two groups (n=12/group) in accordance with the ceramic thicknesses (0.5mm and 1.0mm).



Figure 15: Milling machine, Isomet 1000, Buehler Ltd., Lake Bluff,IL,USA



Figure 16: Initial LRF block in milling machine.

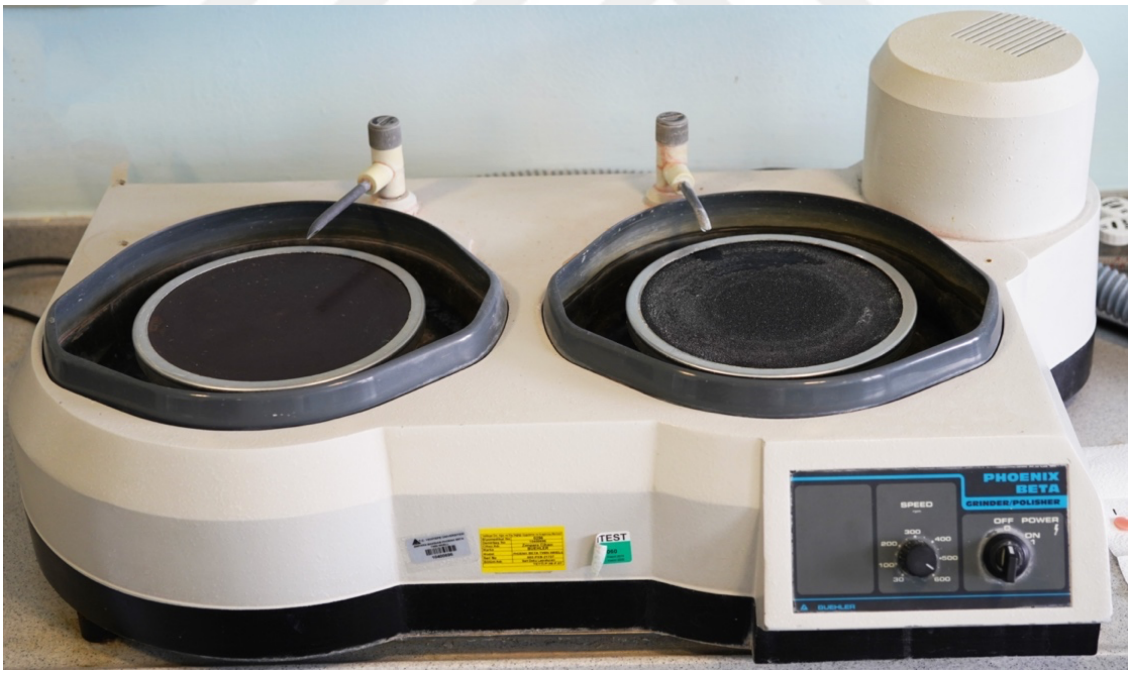


Figure 17: Phonex Beta Twin Whell, Buehler Ltd., Lake Bluff, USA

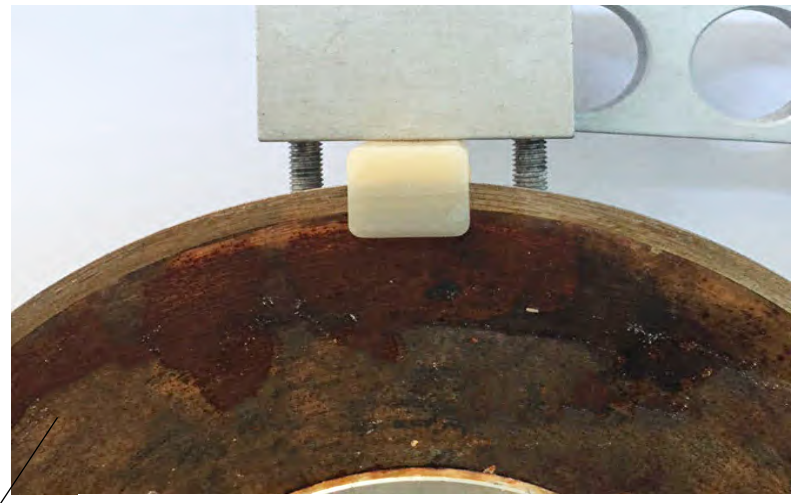


Figure 18: Preparation of CEREC Block sample.

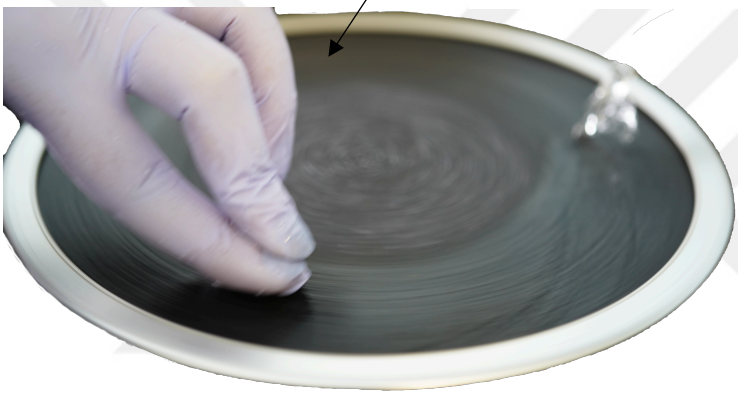


Figure 19: Finishing of CEREC Block Sample.



Figure 20: Measurement of thickness.

2.1.2 Sample Preparation of IPS e.max CAD and Celtra Duo CAD/CAM Blocks:

Ceramic blocks were fixed horizontally and cut with low-velocity milling machine (Isomet 1000, Buehler Ltd., Lake Bluff, IL, USA) in 400 cycles per minute under water cooling. Specimen thicknesses were 0,7mm and 1,2mm. Every specimen's surfaces were wet-finished with 600, 800, 1000, 1200 grit silica carbide papers by turn and the final thicknesses of the samples were standardized to 0.5mm and 1.0mm (Phonex Beta Twin Whell, Buehler Ltd., Lake Bluff, USA). After polishing, samples were glazed then fired in accordance with manufacturer's instructions (DEKEMA, Austromat 624, Germany). With the completion of firing, thicknesses of samples were measured with digital caliper. Specimens were divided into two groups (n=12/group) in accordance with the ceramic thicknesses (0.5mm and 1.0mm).

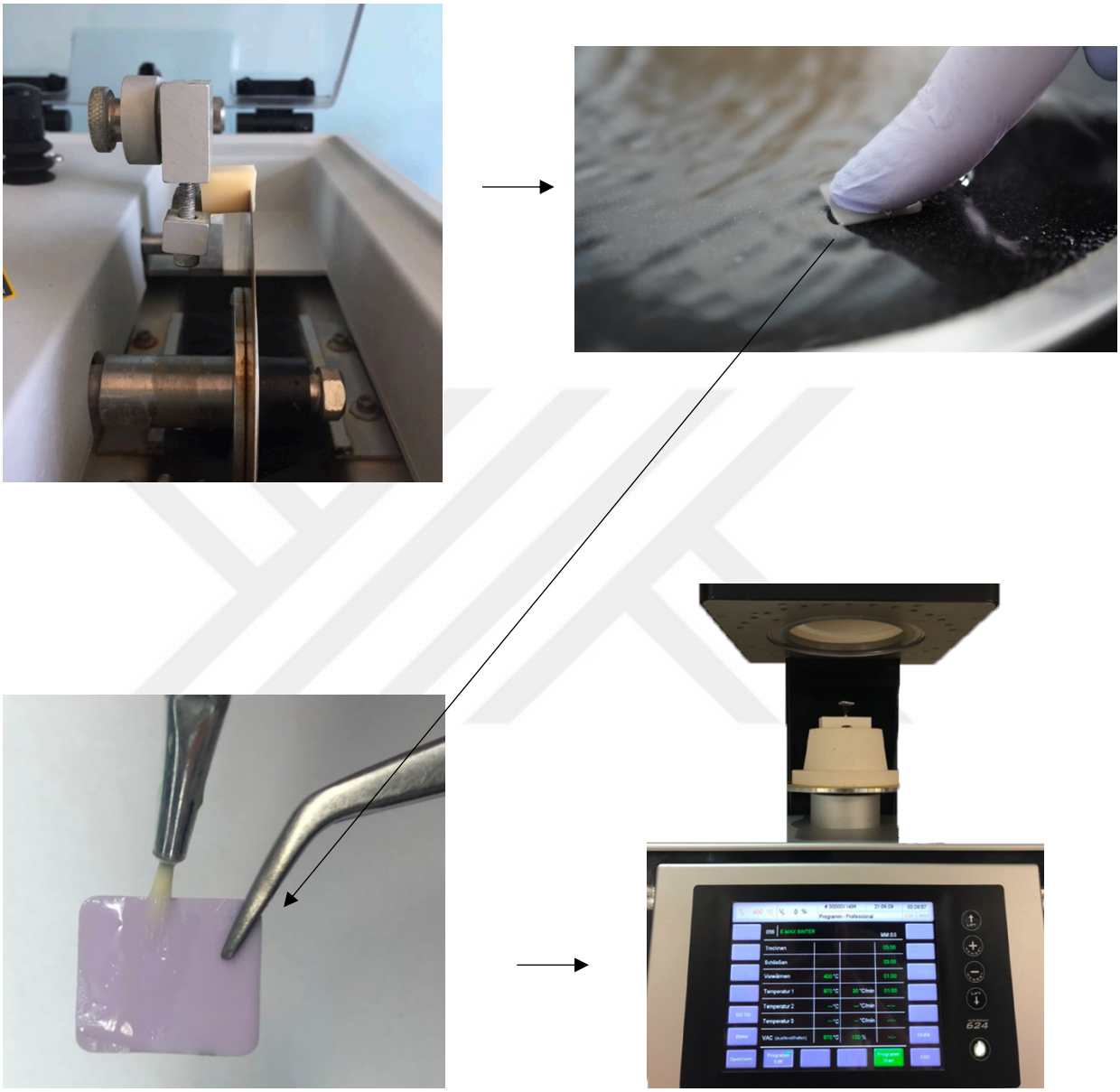


Figure 21: Preparation flow of IPS e.max CAD samples.



Figure 22: IPS e.max CAD samples at a thickness of 0.5mm.

2.1.3 Preparation of Resin Composite Substrates:

In this study, as a dental hard tissue simulating substrate, a micro-hybrid composite material, G-aenial (GC Corp., JAPAN) A2 shade was used in 2mm thickness.

For composite substrate a silicon molding was prepared in accordance with the size of ceramic samples, in 11mm x 14 mm x 2mm dimensions. Silicon molding was placed onto clean and dry glass, then composite applied into silicon molding with incremental technique. Samples were polymerised from both bottom and top surfaces with LED device (Valo Cordless, Ultradent Products Inc., USA). Polymerization was perfomed with the device's restorative mode (1400mW/cm^2 light intensity) at vertical angle to the surface for 20sec each surfaces. After polymerization samples were wet-polished with 800, 1000, 1200 grit silica carbide papers by turn (Phonex Beta Twin Whell, Buehler Ltd., Lake Bluff, USA). Then sample thicknesses were measured with digital caliper.



Figure 23: Micro-hybrid resin composite.



Figure 24: Resin composite sample.

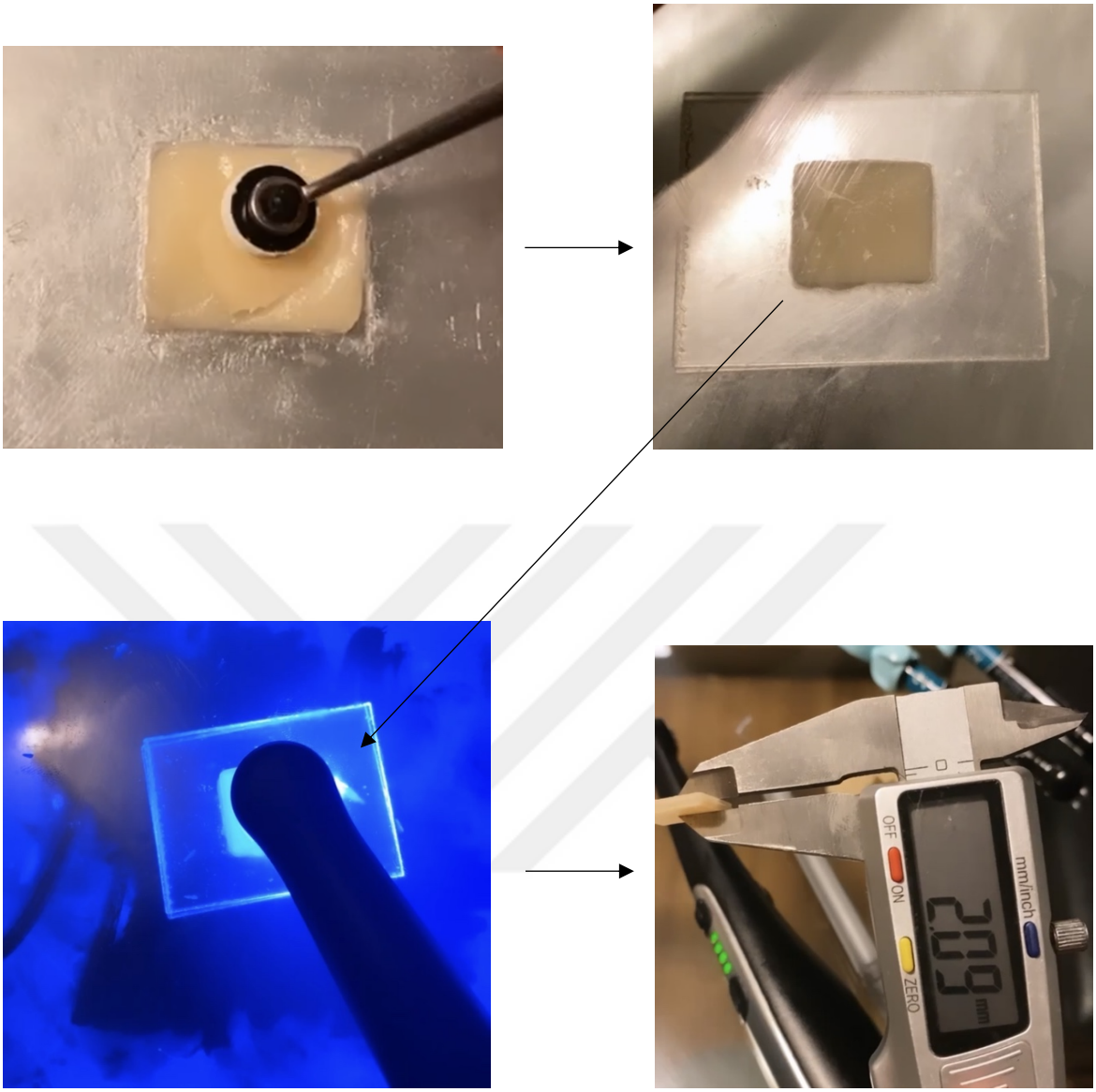


Figure 25: Preparation of resin composite substrates.

2.1.4 Preparation of ceramic/resin cement/substrate monoblock samples:

Before cementation, ceramic surfaces were treated with 5% hydrofluoric acid (HF) (Ultradent Products Inc., USA) (LiSi and LRF for 20 seconds, FC for 60 seconds, Celtra Duo 30 seconds) washed and air dried. Substrate surfaces were etched with 35% phosphoric acid for 30 seconds, washed and air dried. In order to increase wettability of surfaces G-Multi Primer (GC Corp., Japan) was applied to both substrate and ceramic surfaces for 60 seconds settle time, in a light-proof box. Bonding was performed with 8th generation adhesive G-Premio Bond (GC Corp., JAPAN) to etched surfaces of ceramic blocks and substrates for 10 seconds with agitation and then 5 seconds strong air drying (to achieve 3microns film thickness). Then both ceramic and substrate surface's adhesive layers were polymerized with an LED device (Valo Cordless, Ultradent Products Inc., USA) for 20 sec with 1400mW/cm2 light intensity. Following the surface treatments, a light-cure resin cement G-Cem Veneer (GC Corp., Japan) translucent shade, was applied to substrate surface and unglazed surfaces of ceramic samples. Cementation was standardized with constant 1kg sitting pressure for 1 min per sample to achieve 0.1mm cement thickness(21, 119, 120). The excess cement was removed with microbrush before the polymerization. In order to simulate clinical conditions samples were polymerized through the ceramic surface by using LED device (Valo Cordless, Ultradent Products Inc., USA) for 40 sec with 1400mW/cm2 light intensity(21). After cementation, the excessive cement on the sides of the samples was removed with 600 grit silicon carbide paper then thicknesses were measured again with a digital caliper (21).

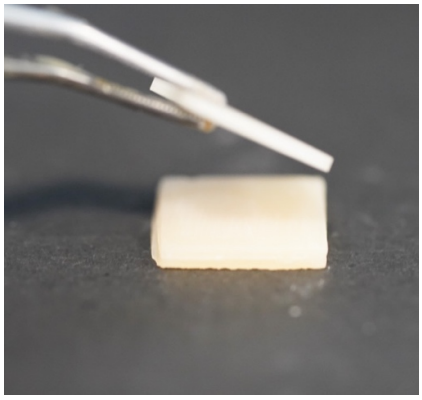


Figure 26: Resin composite & ceramic layers.



Figure 27: Light-cure resin cement.

Figure 28: Hydrofluoric acid for ceramic surface.

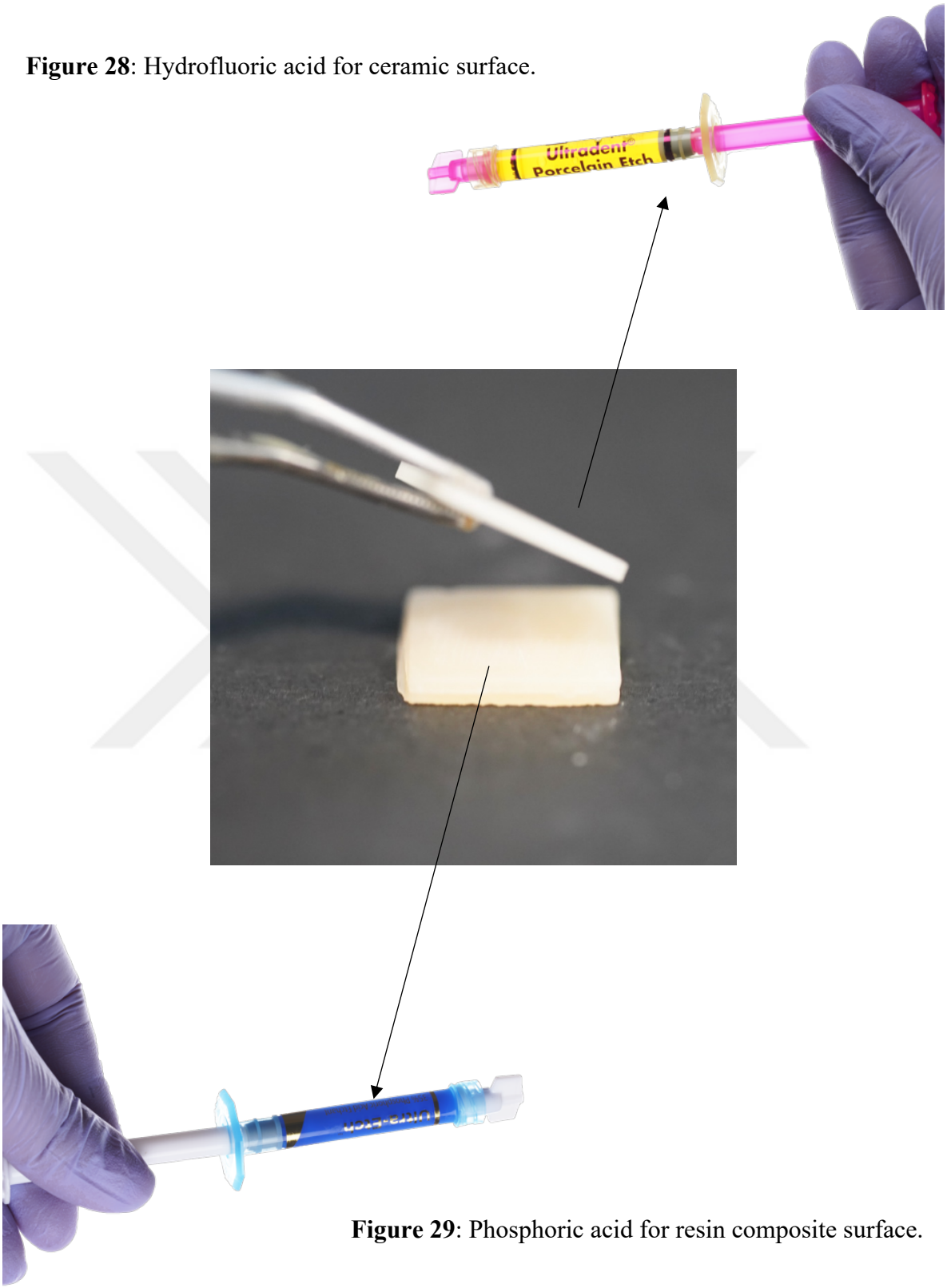


Figure 29: Phosphoric acid for resin composite surface.

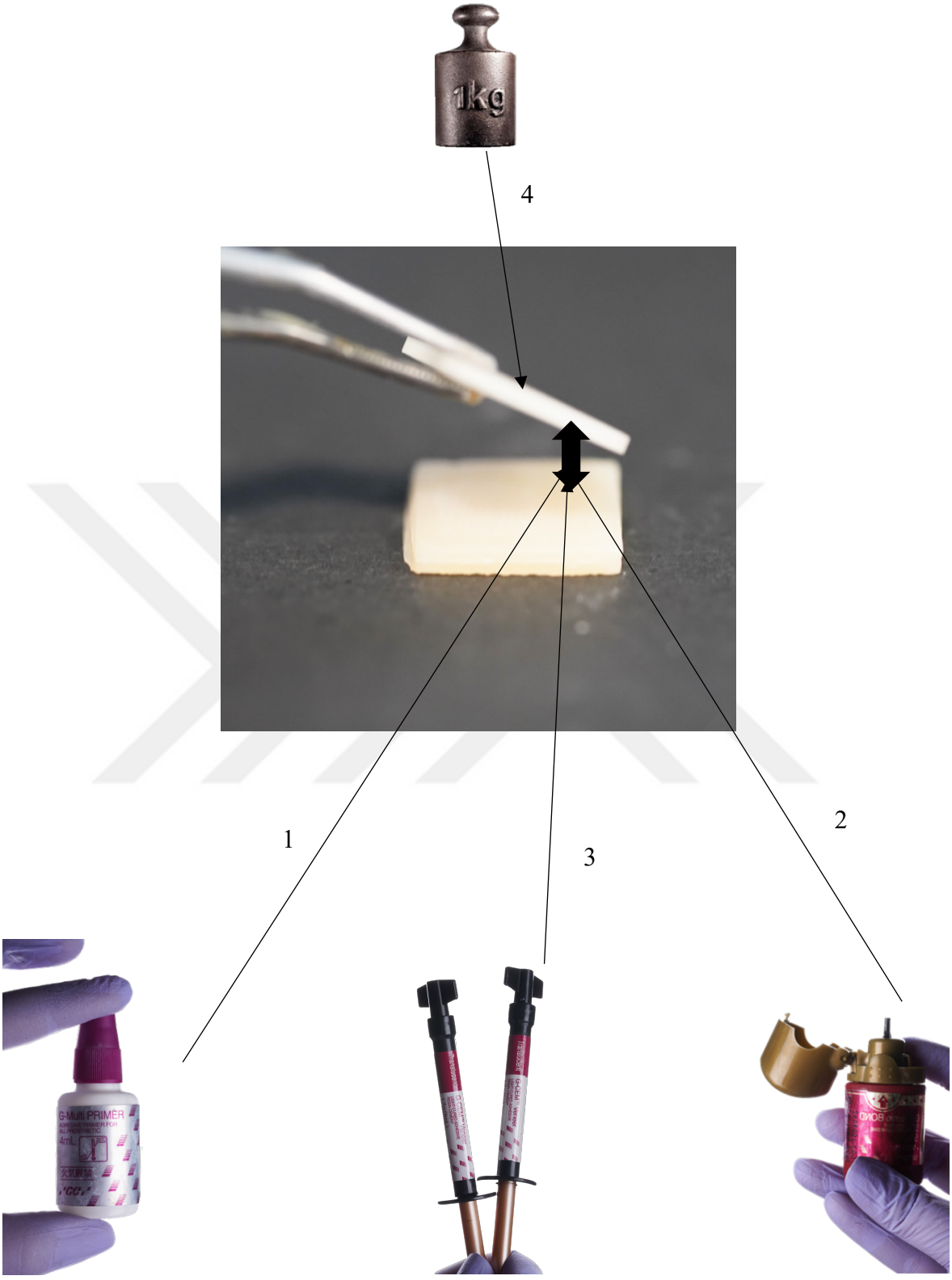


Figure 30: Cementation. 1. Primer, 2. Adhesive, 3. Resin cement, 4. 1kg weight.

Table 3: Materials included in the methodology and their compositions.

Materials	Type	Shade	Translucency	Manufacturer	Composition
CEREC Blocks	Feldspathic Ceramic	A1	HT	Dentsply Sirona, USA	56-64% SiO_2 20-23% Al_2O_3 6-9% Na_2O 6-8%K_2O 0.3-0.6% CaO 0.0-0.1% TiO_2
Celtra Duo	Zirconia-reinforced Lithium Silicate	A1	HT	Dentsply Sirona, USA	58% SiO2 5% P4O10 1.9% Al2O3 18.5% Li2O 10.1% Zr2O 1.0%Tr4O7 2%CeO2
IPS e.max CAD	Lithium Disilicate	A1	HT	Ivoclar Vivadent AG, Liechtenstein	58-80% SiO2 11-19% LiO2 0-11% P2O5 0-13% K2O 0-8 ZrO2 0-5% AL2O3 0-5% Mg 0-8% coloring oxides
LRF	Leucite-reinforced	A1	HT	GC Corp., Japan	no info. Available
G-ænial Resin Composite	Resin Composite	A2		GC Corp., Japan	81% fillers (SiO2, Sr, lantoid glass), UDMA, DMA, monomers, pigment, catalyst

2.2 Color Measurements of Samples:

Color measurements of this study was carried out in Yeditepe University Faculty of Dentistry, Dental Hard Tissue Laboratory with spectrophotometer device (CM-2600d, Konica Minolta Sensing, INC. Japan) and "Spectra-Magic 3.1" computer programme (Minolta, Tokyo, Japan). Spectrophotometer was calibrated and adjusted with the programme before the measurements. Measurements were performed five different times from three different points for each sample on a white and black backgrounds. In the present study, to ensure the standardization of the measurements, all the evaluations were performed by the same researcher and all the specimens were placed into a clear (translucent) vinyl polysiloxane ring (Exaclear, GC Corp., Japan) in the spectrophotometer, hence every specimen measured in the same position without interfering the color of the specimen due to the ring's translucency. First measurements (E_0) were immediate after cementation of ceramic and composite samples (measurements of monoblock ceramic/resin cement/resin composite substrate samples). Second measurement (E_1) was 24hours after cementation, and this measurement considered as 'baseline'. Meanwhile (first 24 hours) the specimens were immersed in distilled water at 37 °C. After the second measurements, specimens were exposed to hydrothermal aging with thermocycling. Third measurement (E_2) was after 10000 cycles which is equal to 1 year aging in clinical conditions (20). Following, fourth measurement (E_3) was after 20000 cycles. Fifth and the last measurement (E_4) was after 30000 cycles. In total, samples were exposed to 30000 cycles to simulate 3-years of aging, color measurements repeated after every 10000cycles. With this workflow color and translucency changes in 24-hours, 1-year, 2-years, and 3-years after hydrothermal aging were observed in this study.

CIEDE2000 color variation between two different color measurements was obtained by using the following equation:

$$\Delta E_{00} = \left[\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{K_C S_C}\right)\left(\frac{\Delta H'}{K_H S_H}\right)\right]^{1/2}$$

Where ΔH', ΔC', ΔL' are differences in hue, chroma, and lightness between two color measurements and R_T is the rotation function that calculates the interaction between chroma and hue differences in the blue region. S_L S_C, and S_H are weighting functions used to determine the total color difference for variation in perceived magnitude with variation in the location of the color coordinate difference between measurements. K_L, K_C, and K_H are correction terms for the conditions of experiment (1, 2, 14).

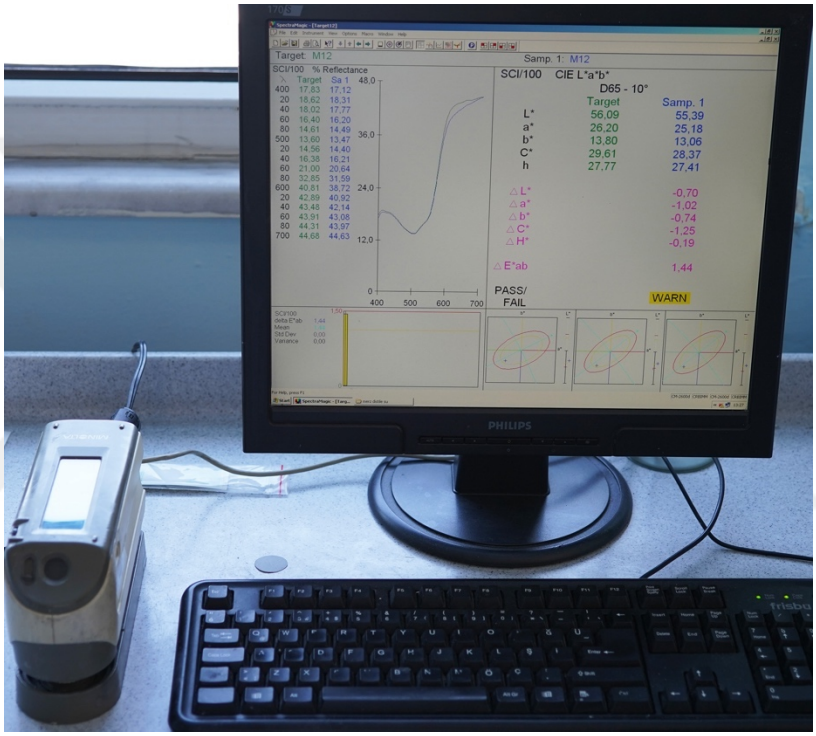


Figure 31: "Spectra-Magic 3.1" computer programme (Minolta, Tokyo, Japan) and spectrophotometer device (CM-2600d, Konica Minolta Sensing, INC. Japan)





CIEDE2000*
PT= ΔE_{00} < 0.8 units
AT= 0.8 < ΔE_{00} < 1.8



Figure 32: Color measurement of sample with Exaclear Ring (GC Corp., Japan)

2.3 Hydrothermal Aging:

The aging test was completed with hydrothermal aging by using thermocycling device (THE-1100, SD Mechatronik, Feldkirchen- Westerham, Germany) in Bezm-i Alem University Faculty of Dentistry, Dental Hard Tissue Laboratory. Monoblock samples were sewed into permeable socks one by one, then clustered by their groups. Following the arrangements, all samples were exposed to 5°C -55°C temperature distilled water with 10000 cycles and 30 seconds dwelling time. Gale and Darvell (20) stated that these artificial aging conditions simulates 1-year clinical condition . This process was repeated 3 three times for each 10000cycles. In between every 10000 cycles, color and translucency measurements have been done. In between cycle periods, all samples were immersed in distilled water in order to prevent opacity due to dehydration.



Figure 33: Thermocycling device (THE-1100, SD Mechatronik, Feldkirchen- Westerham, Germany)



Figure 34: Sample group sewed into permeable sock.

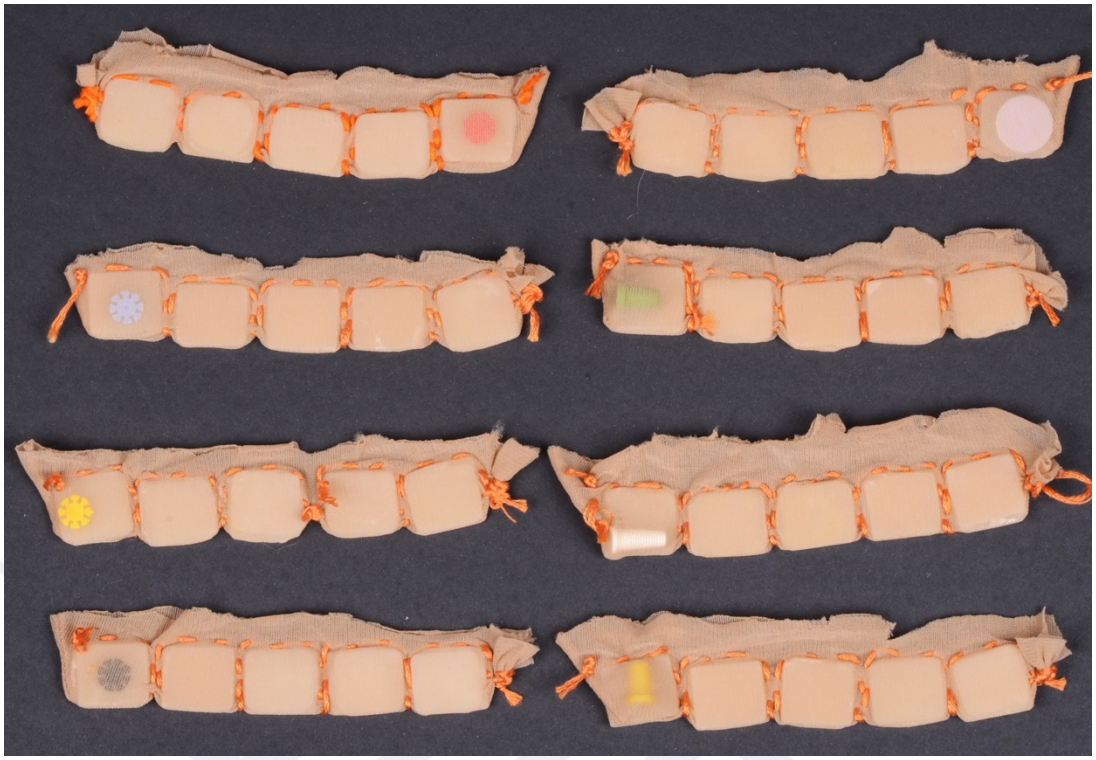


Figure 35: Sewed sample groups. Red flower: Celtra Duo 0.5mm, Blue flower: Cerec 0.5mm, Yellow flower: Celtra Duo 1.0mm, Black flower: Cerec 1.0mm, Purple button: LRF 0.5mm, Green cap: LRF 1.0mm, White cap: E.max 0.5mm, Yellow cap: e.max1.0mm (first group of samples).

2.4 Statistical Analyses:

Analyses were performed by using SPSS software version 25. Descriptive analyses were presented with means and standard deviations. Data were analyzed with three-way ANOVA and post hoc Tukey's tests in order to evaluate the interactions between parameters. A 5% type-1 error level was selected to interpret the significance ($p<0.05$).

3. RESULTS

3.1 Results of ΔE_{00} value:

Mean and standard deviation of ΔE_{00} of the feldspathic, zirconia reinforced lithium silicate, leucite reinforced feldspathic and lithium disilicate glass ceramic materials in two thicknesses after aging by thermocycling are presented in Table 5.

ΔE_{00} was significantly influenced by the type of material ($p<0.001$) by the thickness of the material ($p<0.001$) and by aging ($p<0.001$). A significant interaction between thickness, material, and aging was found ($p<0.001$). Significant interactions between material and thickness ($p<0.001$) as well as between thickness and aging were found ($p=0.003$) while the interaction between material and aging was not significant ($p=0.064$).

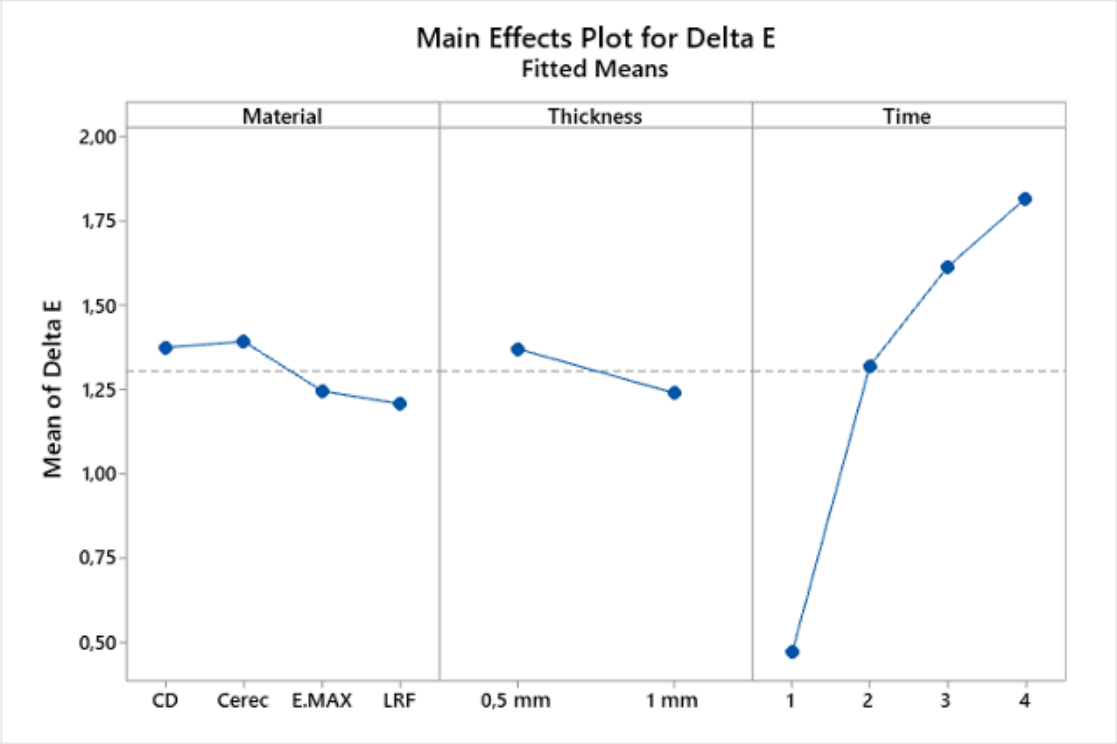


Table 4: Mean ΔE_{00} values according to material, thickness, and aging parameters.

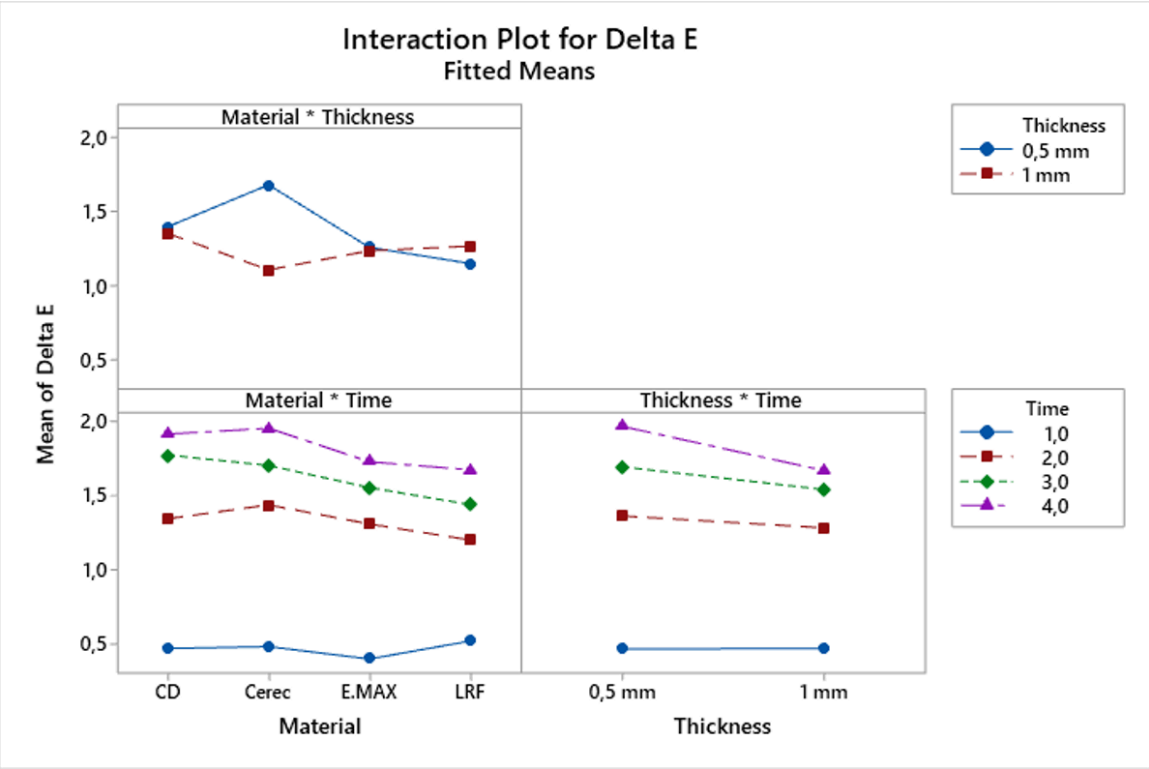


Table 5: Interaction Plot for ΔE_{00}

Ceramic Material	Thickness	ΔE00			
		24 hours	10000 cycles	20000 cycles	30000 cycles
Cerec	0.5mm	0,478 ± 0,207 a, A[a]	1,693 ± 0,367 c, B[c]	2,054 ± 0,360 e, BC[g]	2,494 ± 0,367 h, C[k]
	1.0mm	0,487 ± 0,184 a, D[b]	1,176 ± 0,169 b, E[f]	1,345 ± 0,167 d, E[j]	1,412 ± 0,138 f, E[p]
CD	0.5mm	0,494 ± 0,183 a, F[a]	1,262 ± 0,296 bc, G[cd]	1,758 ± 0,168 de, H[gh]	2,073 ± 0,446 gh, H[km]
	1.0mm	0,446 ± 0,175 a, K[b]	1,421 ± 0,260 bc, L[f]	1,781 ± 0,329 de, L[j]	1,756 ± 0,316 fg, L[p]
E.Max	0.5mm	0,398 ± 0,185 a, M[a]	1,363 ± 0,195 bc, N[cd]	1,545 ± 0,292 d, N[h]	1,723 ± 0,386 fg, N[mn]
	1.0mm	0,401 ± 0,139 a, I[b]	1,250 ± 0,258 bc, O[f]	1,557 ± 0,262 d, OP[j]	1,731 ± 0,534 fg, P[p]
LRF	0.5mm	0,492 ± 0,096 a, R[a]	1,122 ± 0,319 b, S[d]	1,404 ± 0,298 d, ST[h]	1,574 ± 0,351 f, T[n]
	1.0mm	0,548 ± 0,274 a, U[b]	1,275 ± 0,184 bc, V[f]	1,468 ± 0,210 d, VY[j]	1,771 ± 0,552 fg, Y[p]

Table 6: Mean and standard deviation of tested materials' ΔE_{00} in two thicknesses, after hydrothermal aging.

Different upper-case letters in the same raw indicate significant differences between the time periods of the same material in the same thickness, while different lower case letters in the same column indicate significant difference between thicknesses of the same material in the same time period, whereas superscript letters in the same column significant difference between materials in the same thickness and time period.

The CIEDE2000 coordinates were used to calculate the color difference (ΔE_{00}) between the "before" and "after" periods of 24 h, 24 h, 10000 cycles, 20000 cycles and 30000 cycle.

3.1.1 With respect to the effect of material type on ΔE_{00}; there were no significant differences among different materials in 0.5mm and 1.0 thicknesses between cementation and 24 hours storage period (for all comparisons both in 0.5mm and 1.0mm *p=1.000*). After 10000 thermocycling only Cerec 0.5mm and LRF 0.5mm showed statistically significant color change between each other (*p=0.001*), while the other materials were statistically similar (Cerec 0.5mm-CD 0.5mm *p=0.087*, Cerec 0.5mm-E.max 0.5mm *p=0.604*, CD-E.max *p=1.000*, CD-LRF p=1.000, E.max-LRF *p=0.983*). Following 20000 thermocycling, Cerec 0.5mm showed higher color change than the other ceramic materials, however statistically significant differences were only detected between E.max 0.5mm (p=*0.008*) and LRF 0.5mm (*p<0.001*), while there was no significant difference between CD 0.5mm and Cerec 0.5mm (*p=0.825*). After 30000 thermocycling, Cerec 0.5 mm and CD 0.5 mm showed statistically higher color change than LRF (Cerec 0.5mm-LRF 0.5mm *p<0.001*, CD 0.5mm-LRF 0.5mm *p=0.011*), which were not different from each other (Cerec 0.5 mm- CD 0.5 mm *p=0.111*). Cerec 0.5 mm presented statistically higher color change than E.max (*p<0.001*) while, CD 0.5mm showed statistically similar color change with E.max 0.5 mm (*p=0.470*). E.max 0.5 mm and LRF 0.5mm were statistically similar (*p=1.000*).

In 1.0mm, the difference between all materials' color change was statistically similar (after 10000 thermocycling Cerec 1.0 mm- CD 1.0 mm *p=0.978*, E.max 1.0 mm- CD 1.0 mm *p=1.000*, LRF 1.0mm- CD 1.0 mm *p=1.000*, E.max 1.0 mm- Cerec 1.0 mm *p=1.000*, LRF 1.0 mm- Cerec 1.0 mm *p=1.000*, LRF 1.0 mm- E.max 1.0 mm *p=1.000*).

3.1.2 When the ΔE_{00} data from the same ceramic material in the same thickness with respect to the aging was compared:

Compared to baseline, Cerec 0.5mm showed significant color change after 10000 ($p<0.001$), 20000 ($p<0.001$) and 30000 ($p<0.001$) thermocycling. The difference in color change between 30000 and 10000 thermocycling was significant ($p<0.001$), while the difference between 10000 and 20000 ($p=0.396$), 20000 and 30000 ($p=0.067$) were not significant. Cerec 1.0mm showed significant color change by aging with 10000 ($p<0.001$) thermocycling, the difference between 10000 - 20000 ($p=1.000$), 20000 – 30000 ($p=1.000$) and 10000 – 30000 thermocycling ($p=0.987$) were not significant. Celtra Duo 0.5mm showed significant color change after 10000 ($p<0.001$), 20000 ($p<0.001$), 30000 ($p<0.001$) compared to baseline thermocycling, only the difference between 20000 – 30000 thermocycling was not significant ($p=0.714$). On the other hand Celtra Duo 1.0mm showed significant color change by aging with 10000 ($p<0.001$), 20000 ($p<0.001$) and 30000 ($p<0.001$) thermoycle aging, the difference between 10000 - 20000 thermocycle aging ($p=0.400$), 20000 – 30000 thermocycle aging ($p=1.000$) and 10000 – 30000 thermocycle aging ($p=0.566$) were not significant. Similarly E.max 0.5mm showed significant difference in ΔE_{00} after 10000 ($p<0.001$), 20000 ($p<0.001$) and 30000 ($p<0.001$) cycles compared to baseline while the difference between 10000 - 20000 ($p=1.000$), 30000 – 20000 ($p=1.000$) and 30000 – 10000 ($p=0.397$) were not significant. E.max 1.0mm showed significant color change after 10000 ($p<0.001$), 20000 ($p<0.001$) and 30000 ($p<0.001$) thermocycling, there were no significant color change between 10000 - 20000 ($p=0.758$), 10000 - 30000 ($p=0.020$) and 20000 - 30000 aging periods ($p=1.000$). With respect to LRF 0.5 significant differences in ΔE_{00} after 10000 ($p<0.001$), 20000 ($p<0.001$) and 30000 ($p<0.001$) thermocycling compared to baseline were detected. The difference was also significant between 10000 and 30000 thermocycling ($p=0.049$), while the differences between 10000 and 20000 ($p=0.885$), 20000 and 30000 ($p=1.000$) were statistically not significant. In a similar manner, LRF 1.0 showed significant color change only after 10000 ($p<0.001$), 20000 ($p<0.001$) and 30000 ($p<0.001$) thermocycling compared to baseline. The difference between 10000 and 30000 thermocycling was statistically significant ($p=0.012$) however, 20000 thermocycling resulted in significantly similar color change with 10000 and 30000 thermocycling ($p=1.000$, $p=0.784$ respectively).

3.1.3 When the ΔE_{00} from the different thickness of the same materials in the same aging period were statistically compared:

There were no significant differences between Cerec 0.5mm and 1.0mm (*p=1.000*) , CD 0.5mm and 1.0mm (*p=1.000*), E.max 0.5mm and 1.0mm (*p=1.000*), LRF 0.5mm and 1.0mm (*p=1.000*) at baseline. On the other hand, there were significant differences between Cerec 0.5mm and 1.0mm at 10000, 20000 and 30000 thermocycling (*p=0.006*, *p<0.001*, *p<0.001*, respectively). All ceramic materials in the study (except Cerec) presented similar color change in different thicknesses (0.5mm- 1.0mm) among all thermocycling periods (after 10000 thermocycling CD 0.5mm-1.0mm *p=1.000*, E.max 0.5mm-1.0mm p=1.000, LRF 0.5mm-1.0mm *p=1.000*, 20000 thermocycling CD 0.5mm-1.0mm *p=1.000*, E.max 0.5mm-1.0mm *p=1.000*, LRF 1.0mm-0.5mm *p=1.000*, 30000 thermocycling CD 0.5mm-1.0mm *p=0.701*, E.max 0.5mm-1.0mm *p=1.000*, LRF 0.5mm-1.0 mm *p=0.999*).

3.2 Results of TP value:

Mean and standart deviations of TP values of the feldspathic, zirconia reinforced lithium silicate, leucite reinforced feldspathic and lithium disilicate glass ceramic materials in two thickness after aging by thermocycling are presented in Table 9.

TP was significantly influenced by the type of material (*p<0.001*) by the thickness of the material (*p<0.001*) and by aging (*p<0.001*). A significant interaction between material, thickness and aging was found (*p<0.001*). Meanwhile, the association between material and thickness was significant (*p=0.044*), whereas between thickness and aging (*p=0.124*) and between material and aging were not significant (*p=0.125*).

Table 7: Mean TP values according to material, thickness, and aging parameters.

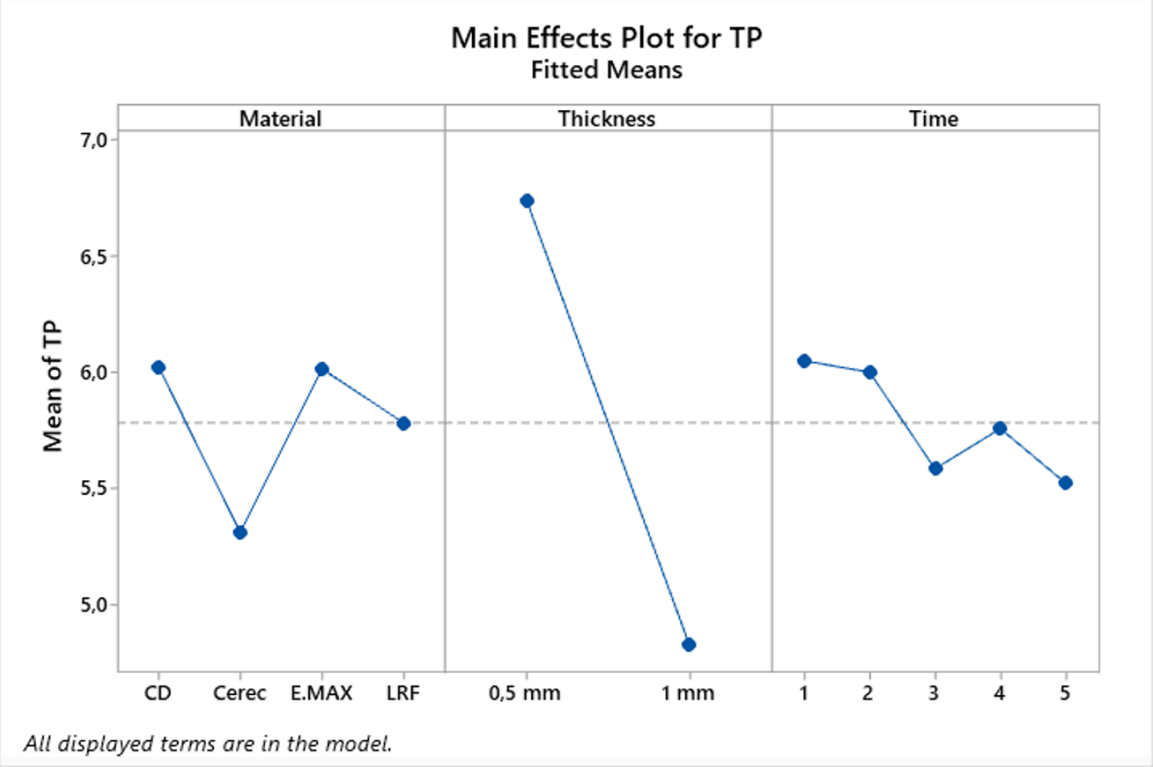


Table 8: Interaction Plot for TP values.

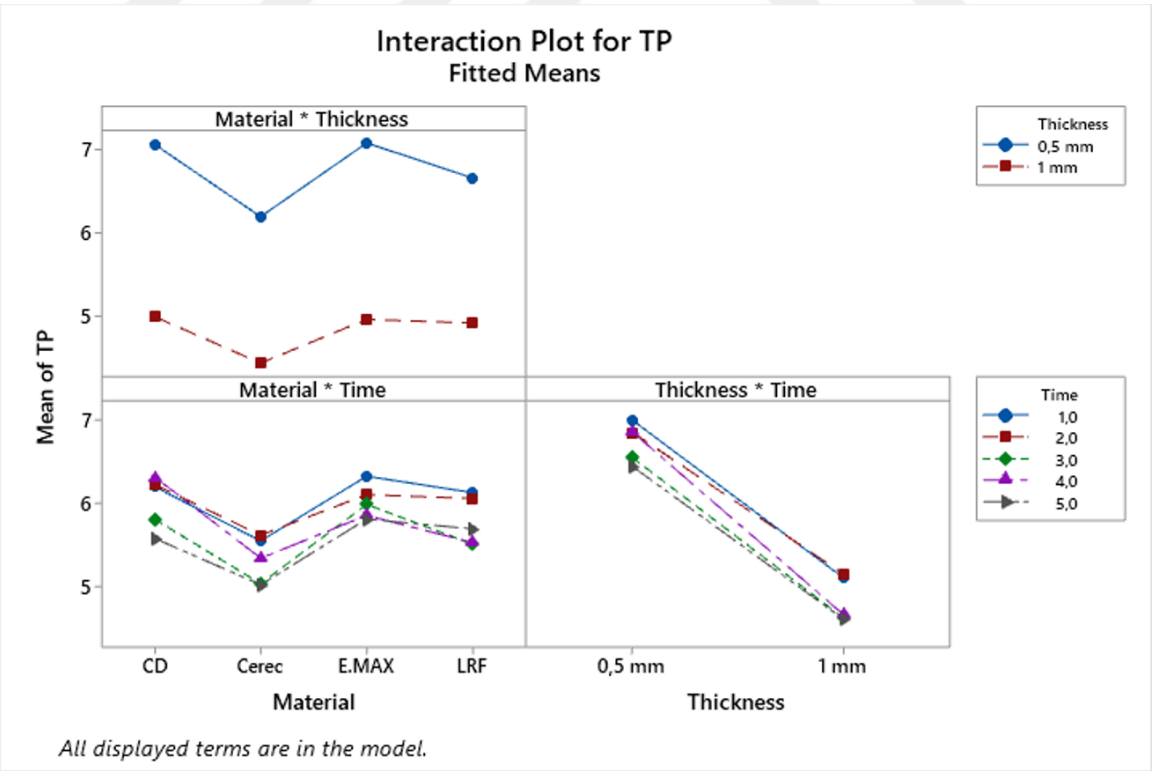


Table 9: Mean and standard deviation of tested materials' TP values in two thicknesses, after hydrothermal aging.

Ceramic Material	Thickness	TP				
		Immediate after cementation	24 hours (baseline)	10000 cycles	20000 cycles	30000 cycles
Cerec	0.5mm	6,460 ± 0,673 a, ABC^{a}	6,529 ± 0,586 a, AB^{c}	5,688 ± 0,948 a,BC^{e}	6,792 ± 1,226 a, A^{h}	5,471 ± 0,780 a, C^{m}
	1.0mm	4,637 ± 0,587 b, D^{b}	4,708 ± 0,521 b, D^{d}	4,386 ± 0,737 b, D^{g}	3,884 ± 0,662 b, D^{j}	4,566 ± 0,566 a, D^{o}
CD	0.5mm	7,162 ± 0,634 a, E^{a}	7,051 ± 0,796 c, E^{c}	6,890 ± 0,702 c, E^{f}	7,317 ± 1,118 c, E^{h}	6,848 ± 1,026 c, E^{n}
	1.0mm	5,233 ± 0,437 b, FG^{b}	5,395 ± 0,496 d, F^{d}	4,730 ± 0,532 d, FG^{g}	5,306 ± 0,703 d, FG^{k}	4,301 ± 0,417 d, G^{o}
E.Max	0.5mm	7,408 ± 0,555 a, H^{a}	7,069 ± 0,395 e, H^{c}	7,138 ± 0,557 e, H^{f}	6,869 ± 0,637 e, H^{h}	6,865 ± 0,718 e, H^{n}
	1.0mm	5,237 ± 0,422 b, J^{b}	5,136 ± 0,361 f, J^{d}	4,832 ± 0,712 f, J^{g}	4,839 ± 0,571 f, J^{jk}	4,753 ± 0,453 f, J^{o}
LRF	0.5mm	6,959 ± 0,785 a, K^{a}	6,760 ± 0,445 g, K^{c}	6,483 ± 0,589 g, K^{ef}	6,456 ± 0,549 g, K^{h}	6,590 ± 0,610 g, K^{n}
	1.0mm	5,294 ± 0,232 b, L^{b}	5,351 ± 0,362 h, L^{d}	4,538 ± 0,657 h, L^{g}	4,600 ± 0,821 h, L^{jk}	4,794 ± 0,622 h, L^{o}

Different upper-case letters in the same row indicate significant differences between the time periods of the same material in the same thickness, while different lower case letters in the same column indicate significant difference between two thicknesses (0.5mm-1.0mm) of the same material in the same time period, whereas superscript letters in the same column significant difference between materials in the same thickness and aging period.

The CIEDE2000 coordinates were used to calculate the color difference between black and white backgrounds to calculate TP_{00}.

3.2.1 With respect to the type of ceramic material on TP value;

Immediate after cementation, all materials in the 0.5mm thickness (Cerec-CD p=*0.836*, Cerec-E.max *p=0.166*, Cerec-LRF *p=0.999*, CD-E.max *p=1.000*, CD-LRF *p=1.000*, E.max-LRF *p=1.000*) and in 1.0 mm thickness (Cerec-CD *p=0.978*, Cerec-E.max *p=0.975*, Cerec-LRF *p=0.918*, CD-E.max *p=1.000*, CD-LRF *p=1.000*, E.max-LRF *p=1.000*) showed statistically similar TP values. Similarly, after 24hour from cementation,

both in 0.5mm (Cerec-CD *p=0.988*, Cerec-E.max *p=0.996*, Cerec-LRF *p=1.000,* CD-E.max *p=1.000*, CD-LRF *p=1.000*, E.max-LRF *p=1.000*) and 1.0mm thicknesses (Cerec-CD *p=0.867*, Cerec-E.max *p=1.000*, Cerec-LRF *p=0.937*, CD-E.max *p=1.000*, CD-LRF *p=1.000*, E.max-LRF *p=1.000*) all materials presented statistically similar TP value. After 10000 thermocycling, Cerec 0.5mm showed statistically significant difference in TP values to E.max (*p<0.001*) and CD (*p=0.005*) which was statistically similar to LRF (*p=0.937*). On the other hand the difference in TP values between E.max 0.5mm, CD 0.5mm and LRF 0.5mm was not significant (CD-E.max *p=1.000*, CD-LRF *p=1.000*, E.max-LRF *p=1.000*). At 20000 thermocycling, all materials in 0.5mm demonstrated statistically similar TP values (Cerec-CD *p=0.997*, Cerec-E.max *p=1.000*, Cerec-LRF *p=1.000*, CD-E.max *p=1.000*, CD-LRF *p=0.361*, E.max-LRF *p=1.000*). At 30000 thermocycling, Cerec 0.5mm showed statistically the lowest TP value among all the tested ceramic materials (Cerec-CD *p<0.001*, Cerec-E.max *p<0.001*, Cerec-LRF *p=0.019*) while, the difference between CD E.max LRF was not significant (CD-E.max *p=1.000*, CD-LRF *p=1.000*, E.max-LRF *p=1.000*).

Regarding 1.0mm thickness, except Cerec at 20000 thermocycling all the ceramic materials showed statistically similar TP values at 10000 (*p=1.000*), 20000 (*p=1.000*), 30000 (*p=1.000*) thermocycling. At 20000 thermocycling Cerec showed significantly lower TP values than CD (*p<0.001*) which was not significantly different than LRF (*p=0.801*) and E.max (*p=0.153*). Similarly, the difference between CD, LRF and E.max was not significant (CD-E.max *p=1.000*, CD-LRF *p=0.826*, E.max-LRF *p=1.000*).

3.2.2 Regarding to aging effect on TP value;

All ceramic materials both in 0.5mm and 1.0mm thicknesses showed statistically similar TP values in all aging periods (Cerec 1.0mm, postcementation-baseline *p=1.000*, 10000-baseline *p=1.000*, 20000-baseline *p=0.475*, 30000-baseline *p=1.000*. CD 0.5mm, postcementation-baseline *p=1.000*, 10000-baseline *p=1.000*, 20000-baseline *p=0.475*, 30000-baseline *p=1.000*. CD 1.0mm, postcementation-baseline *p=1.000*, 10000-baseline *p=0.906*, 20000-baseline *p=1.000*. E.max 0.5mm, postcementation-baseline *p=1.000*, 10000-baseline *p=1.000*, 20000-baseline *p=1.000*, 30000-baseline *p=1.000*. E.max 1.0mm, postcementation-baseline *p=1.000*, 10000-baseline *p=1.000*, 20000-baseline *p=1000*,

30000-baseline *p=1.000*. LRF 0.5mm, postcementation-baseline *p=1.000*, 10000-baseline *p=1.000*, 20000-baseline *p=1.000*, 30000-baseline *p=1.000*. LRF 1.0 mm, postcementation-baseline *p=1.000*, 10000-baseline *p=0.510*, 20000-baseline *p=0.704*, 30000-baseline *p=0.993*) , except Cerec 0.5mm and CD 1.0mm. Cerec 0.5mm showed statistically significant between baseline and 30000 (*p=0.045*), 10000 cycles and 20000cycles (*p=0.024*) and between 20000 cycles and 30000 cycles (*p=0.001*). While the rest of the thermocycling periods showed statistically similar TP values to baseline values (10000-baseline *p=0.424*, 20000-baseline *p=1.000*). CD 1.0mm presented statistically significant decrease on TP value after 30000 thermocycling (*p=0.028*), while the other thermocycling periods showed similar values with the baseline (10000-baseline *p=0.906*, 20000-baseline *p=1.000*).

3.2.3 When the TP from the different thickness of the same materials in the same aging period were statistically compared:

All materials in all aging periods showed statistically significant difference in different thicknesses (postcementation, Cerec 0.5mm-1.0mm *p<0.001*, CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*. 24 hours (baseline), Cerec 0.5mm-1.0mm *p<0.001*, CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*. 10000 thermocycling, Cerec 0.5-1.0 *p=0.001*, CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*. 20000 thermocycling, Cerec 0.5mm-1.0mm *p<0.001*, CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*, 30000 thermocycling CD 0.5mm-1.0mm *p<0.001*, E.max 0.5mm-1.0mm *p<0.001*, LRF 0.5mm-1.0mm *p<0.001*). 0.5mm thickness showed statistically higher TP value by comparison to 1.0mm thickness (*p<0.001*) apart from Cerec in 30000 thermocycle aging. Cerec presented similar TP values after 30000 thermocycle aging in 0.5mm and 1.0mm thicknesses (*p=0.250*).

4. DISCUSSION

The patients' demand for esthetic restorative treatments is constantly growing. As a result, various treatment options have been recommended to restore the esthetic appearance of the anterior teeth. Throughout the years, full crowns have provided a predictable and durable treatment option for the esthetic correction. However, this approach is highly invasive with substantial removal of the dental hard tissues and potential of adverse effect on periodontal tissues and pulp (68, 69, 121, 122). The significant development on bonding to dental hard tissues with the introduction of multi-step etch-rinse adhesive systems (123-125), along with small particle hybrid resin composites have led to less invasive restorative approaches such as composite veneers or ceramic veneers to deal with the esthetic appearance of anterior region (68). Resin composite veneers indicated in masking discolorations, anatomical form, and alignment corrections. However, these restorations are highly technique sensitive and practitioner dependent applications. Moreover, regular recalls are essential in order to maintain the surface characteristics and color stability due to the resin composite's dynamic nature, thus these restoration's durability is also dependent on patient's oral hygiene habits, and motivation. Consequently, the search for more esthetic and durable restorations led to the introduction of glass ceramic veneers (126, 127). In a clinical trial that compared ceramic veneers and composite indirect veneers after 10-years, concluded that in terms of survival rate and quality of the surviving restorations, ceramic veneers outperformed significantly indirect composite veneers (128). Several in vivo studies showed the durability of glass ceramic veneer restorations with substantial clinical results. A retrospective study evaluated the clinical performance of glass ceramic veneers for up to 20-years and concluded that the estimated survival rate was 94.4% after 5-years, %93.5 at 10-years, 82.93% at 20-years (129). Similarly, Peumans *et. al.* performed 87 ceramic laminate veneers in 25 patients, at 5-year recall they resulted with 4 fractures, 2 recurrent carries, 1 veneer with clinically unacceptable color change and concluded that overall 93% of the veneer restorations were fulfilling without intervention.(130) In a 6-years follow-up clinical study with 83 leucite-reinforced glass ceramic veneers, only 1 failure was detected with a success rate of 98.8% (131). Fradeani *et. al.* evaluated 182 ceramic veneers in 46 patients after 12-years. With respect to color stability 96.61% of the restorations were considered as 'perfect', while in

regard to surface properties 89.83%, marginal discoloration 86.44% and marginal integration 92.09% of the restorations were rated as ‘perfect’(132). Another retrospective clinical study conducted by Arif *et. al.,* assessed longevity of ceramic veneers after 7 to 14-years clinical service and high survival rate of 97.6% at 7-years and 88.2% survival rate at 14-years was reported (69). Nejatidanesh *et. al.* retrospectively evaluated 197 CAD/CAM ceramic veneer restorations placed in 71 patients and stated that after 5-years the mean survival rate of ceramic laminate veneers was 99.0% while the success rate was 96.4% (70). Another clinical study which evaluated 617 CAD/CAM ceramic veneers for 9-years, 98.8% of the patients considered their restorations as successful while 90.9% of the restorations were resulted in perfect color stability (133). Fractures of the ceramic (11%) and deteriorations in marginal adaptation (20%) were determined as the main failure reasons for glass ceramic veneers in a follow-up clinical after 10 years. Marginal defects led to severe marginal discoloration (19%) and caries (10%) especially at locations where the veneers restoration ended in an existing resin composite. However, only 4% of the ceramic laminates were needed to be replaced at 10-yearsm (134).

In the light of these in vivo studies, ceramic veneers were confirmed by systematic reviews and meta-analysis as durable and minimally invasive treatment alternative to full crowns and a more durable option compared to resin composite veneers due to their ability to provide high-quality esthetics and superior mechanical properties in long term (13, 68-73). However in addition to the ceramic restoration’s individual esthetics, color stability of the glass ceramic veneers and harmony between the restoration and the dentition are also essential parameters for long lasting esthetic outcome (135). Color stability is a multifactorial phenomenon that is influenced by the type of the ceramic material, its thickness, shade, and translucency, by the resin cement’s shade, substrate shade, and aging (time). Several in vitro studies investigated the effect of these different variables on color stability and concluded that the type, shade, or brand of the resin cement do not have a significant effect on the color stability of glass ceramic veneers (21, 105, 136-140). Pires *et. al* stated that the resin cement influence the restoration color stability less than the ceramic thickness and the substrate.(141) Similarly, Perroni *et. al.* indicated that color stability of porcelain veneers using translucent and dental shade resin cements were influenced by the type and thickness of the ceramic material rather than the shade of the resin cement itself (142). Kilinc *et. al.* indicated that

none of the various resin cements involved in their study caused a noticeable color change on ceramic and even though a significant color change of the resin cement occurs it may be unnoticeable when covered by the ceramic (138).

Translucency (TP) of the ceramic material is another important factor that determines the esthetic outcome of the restoration, as it provides the restoration a lifelike appearance. (143) (144) Translucency of dental ceramics is influenced by their crystalline structure, pigments, grain size, distribution, number, and size of defects and porosities which means overall by the ceramic type (11, 143-146) (147). Barizon *et. al.* stated both ceramic type and thickness are affecting translucency, nevertheless ceramic thickness has the most significant effect (13). On the other hand, Turgut *et. al.* indicated that ceramics exhibit different TP values with respect to their thickness and 1 mm thickness exhibited significantly lower TP value compared to 0.5 mm thickness (11). Similarly, several other in vitro studies mentioned a negative correlation between ceramic thickness and its translucency (9, 32, 100, 148)
Another important factor that affects material's optical properties and color stability is the microstructure of the ceramic itself. Glass ceramics, resin-matrix ceramics, and polycrystalline ceramics are the most frequently used materials in contemporary restorative dentistry. However within the ceramic materials glass ceramics are the most frequently used materials in restorative dentistry for veneers (96). The success of glass ceramic restorations is mainly attributed due to their biocompatibility, and distinguished mechanical and optical properties. With respect to the microstructure, glass ceramics have two phases, glass matrix phase and crystaline phase. The difference in glass matrix ratio, crystaline content, and the dispersion of these crystals in the glass matrix, differentiates the materials from each other and makes them unique, and at the same time defines the material's optical properties. In the present study, four different types of CAD/CAM ceramic blocks were used to perform a wide-spectrum evaluation and to detect the effect of ceramic type on color change and translucency. The selected CAD/CAM blocks are feldspathic ceramic (CEREC Blocks, Dentsply Sirona, USA), leucite reinforced (Initial LRF, GC Corp., JAPAN), lithium disilicate (IPS e.max CAD, Ivoclar Vivadent, Liechtenstein) and zirconia reinforced lithium silicate (Celtra Duo, Dentsply Sirona, USA) glass ceramics.

Feldspathic ceramics are considered as the best biomimetic material in Restorative Dentistry. CAD/CAM feldspathic blocks are being used for single crowns, ceramic veneers, inlays, onlays, and endocrown restorations with a high survival rate for years. Feldspathic ceramics offer good esthetic outcome by achieving natural enamel appearance due to their translucency (85). However, it is also stated in several studies that ceramic thickness has a major effect on feldspathic ceramic veneers in terms of their masking ability of the underlying substrate's color, thus indicating less than 0.7 mm feldspathic ceramic thickness cannot mask the underlying substrate color. Cerec Blocks C (Dentsply Sirona, Germany) is a feldspathic ceramic which contains large grains with a size of 2-4 μm embedded in a glass matrix. This material has low flexural strength (120MPa) and is susceptible to wear, thus surface roughness can be increased by time and this tendency can affect the color stability of the material (88).

In order to enhance mechanical properties of feldspathic ceramics, leucite crystals were added to their matrix, thus leucite-reinforced feldspar ceramics were produced. However, their mechanical properties enhanced slightly compared to feldspathic ceramics (91). In the present study Initial LRF HT (GC Corp., JAPAN) was selected as a leucite-reinforced feldspar ceramic, and it's flexural strength is 250MPa (85) which is higher than Cerec Blocks. Nevertheless, there is a lack of information in the literature about Initial LRF's microstructure since it's a relatively new product in the market and there is only limited information available in the literature.

Another glass ceramic subgroup is the lithium disilicate, which consists of approximately 70% by volume of crystalline phase embedded in a glass matrix (90, 91). In the early phase of the material, primarily, ceramic is cast into transparent glass ingots that are containing lithium orthosilicate. Following partial crystallization, the formation of 40% of platelet-shaped lithium metasilicate crystals (with the size of 0.2-1.0 μm) are formed in a glass matrix. This phase is called intermediate crystalline (pre-crystalline) phase in other words 'blue phase' (purple block). In 'blue phase' the material has 130 ± 30 MPa flexural strength which makes the milling process rather easy, thus in this phase preparation of the restoration is performed. After the milling, final sinterization executed at 850°C, and lithium disilicate crystals are formed in 1.5 μm size needle-like pattern. The material's final flexural

strength becomes 530MPa (85, 90-92). This microstructure and high flexural strength make this type of ceramic the material of choice for many restoration types by achieving good clinical outcomes at a specified thicknesses in load-bearing areas while preserving advanced optical properties. Hence lithium disilicate glass ceramics can be used in a variety of restorative treatments such as veneers, inlays, overlays and single crowns (91, 93). In the present study IPS e.max CAD was selected as a lithium disilicate glass ceramic and it also serves as the control group which had been intensively investigated and had proven it's in vivo (148-152) and in vitro success (8, 13, 43, 88, 96, 143, 153-160).

The last ceramic material tested in this study is the zirconia-reinforced glass ceramic Celtra Duo (Dentsply Sirona, Germany). This material consists of approximately 10% by weight zirconia, thus have enhanced mechanical properties. Zirconia-reinforced glass ceramic have a glass matrix and crystalline phase as the other glass ceramics. Crystalline phase of the material contains lithium silicate crystals with a size of 0.5-0.7 μm. Due to small crystal size and high glass content (64-70%) the material has superior translucency. On the other hand, despite its high glass content, Celtra Duo has improved flexural strength because of the zirconia content (~10%) (90, 94-96). This material can be used for single unit restorations such as crowns, inlays, overlays, and veneers (95). Celtra Duo is a fully sintered block and the manufacturer claims that it can be immediately seated and luted after fabrication (95, 96). However, with additional sintering flexural strength increases from 210 MPa to 370MPa. Therefore, in the present study Celtra Duo was used after sintering to evaluate the best version of the material.

It has been very well documented in the literature that aging affects the color stability and translucency of different restorative materials (19, 21, 135, 147, 156, 158, 161, 162). Several methods such as water aging, artificial accelerated aging (AAA), hydrothermal aging, UV light aging are used in the literature to evaluate the long-term performance of glass ceramics. In artificial accelerated aging, specimens are exposed to ultraviolet light, heat and humidity for 300 hours in a test machine with a 150kJ/m^2 total exposure energy. These conditions are reported as equal to 1-year clinical conditions (21, 58, 163). Hydrothermal aging by using a thermocycling device is another artificial aging method that is being used for evaluating color stability of restorative materials. With this aging method, tested

specimens are exposed to distilled water at temperatures between 5°C -55°C with 30 seconds dwelling time and 10 seconds of transfer time as proposed in ISO 11405 recommendations. In this aging method, 10000 cycles has been shown to represents 1-year service at clinical conditions (19, 20). In another method that has been defined as UV light aging, the samples are subjected to UV light for 120 hours by using UV-B cycle exposure at 37°C, similar to ISO 7491 (2000) instructions (51). Water aging is yet another artificial aging method which is essentially the immersion of samples to 37°C distilled water throughout the intended aging period. Renewal of the water every 7 days is recommended to to avoid biological contamination (51).

These artificial aging methods have been used in various *in vitro* studies to evaluate the color stability and translucency change of ceramic materials. Bagis and Turgut stated that all-ceramics (IPS e.max CAD, IPS e.max Press, IPS Empress Esthetic, IPS ZirPress, IPS Inline and IPS e.max Ceram) become more opaque, darker and more yellowish due to accelerated aging. (8). Another in vitro study revealed that the optical properties of leucite-reinforced (IPS Empress CAD), lithium disilicate (IPS e.max CAD), zirconia-reinforced lithium silicate (Celtra Duo), and feldspathic (Vita MarkII) CAD/CAM ceramic materials were affected by accelerated aging process even after representing 1-year clinical service (158). Vasiliu *et. al.* applied hydrothermal aging to both pressed and milled CAD/CAM glass ceramic materials and concluded that hydrothermal aging had a significant effect on surface roughness and translucency of lithium disilicate (IPS e.max CAD and IPS e.max Press), feldspathic (Vita Mark II and Vita PM9), and zirconia-reinforced lithium silicate (Celtra Press and Vita Suprinity) glass ceramics at 10000 cycles (88). Similarly, Ashy *et. al.* evaluated the effect of hydrothermal aging on color stability of lithium disilicate (IPS e.max CAD) and zirconia ceramics (Katana Zirconia) and stated that aging caused a significant change in the color coordinates of all the tested materials after 3000 cycles (156). Another *in vitro* study evaluated the color stability of luted ceramic veneers (Super Porcelain EX-3) and concluded that hydrothermal aging may affect the color stability of ceramic veneers (164). Similarly, Stamenkovic *et. al.* compared the effect of accelerated aging with staining solutions such as coffee and wine on color change of lithium disilicate (IPS e.max CAD) and zirconia-reinforced lithium silicate (Vita Suprinity) glass ceramics and concluded that both staining solutions and accelerated aging had an impact on color stability however coffee

resulted in the utmost color change (153). Likewise, an in vitro study evaluated the effect of coffee thermocycling on zirconia-reinforced lithium silicate (Celtra Duo), lithium disilicate glass-ceramic (IPS e.max CAD), zirconia-reinforced lithium silicate (VITA Suprinity), and zirconia (VITA YZ HT). The researhers concluded that the optical properties of all the tested materials were affected by coffee thermocycling (62). Silami *et. al.* also stated that accelerated aging yielded significant color change of IPS e.max Ceram both in 0.5mm and 1.0mm thickness, however higher color change was observed in 0.5mm thickness (71).

The ideal thicknesses of a minimally invasive ceramic veneer restorations may vary between 0.5 and 0.7 mm (165) (71). Nevertheless, in a clinical situation, it is not always possible or indicated to arrange ceramic thickness in these exact measures. Malpositioned or discolored teeth may need thinner or thicker ceramic restorations for alignment or masking. Therefore, in the present study, the effect of two different ceramic thicknesses; 0.5mm and 1.0 mm and hydrothermal aging on color stability and translucency change of four different CAD/CAM materials that are commonly used for ceramic veneers; feldspathic (Cerec), lithium disilicate (IPS e.max CAD), zirconia-reinforced lithium silicate (Celtra Duo), and leucite-reinforced (Initial LRF) glass ceramics were evaluated.

4.1 Discussion of the Materials & Methods

All the glass ceramic materials were cut with a slow speed diamond saw in 0.5mm and 1mm thicknesses from their respective HT blocks and IPS e.max CAD and Celtra Duo specimens were fired after the preparation according to the manufacturer's instructions. Each specimen's one surface was wet-finished with up to 1200 grit SCI papers to standardize the glass ceramic surfaces.

It has been stated that with the increase of difference between ceramic shade and resin cement shade, the color stability of the restoration decreases. HT CAD/CAM glass ceramic specimens luted with translucent resin cements exhibited significantly lower color change than those to other shades (21, 135). In the present study, resin cement was not chosen as a variable, therefore, to eliminate the minor effect of the resin cement, all the CAD/CAM glass ceramic blocks were selected in A1 shades, with high translucency (HT) and a translucent shade resin cement was used.

Among the studies that evaluated color stability, several of them left the resin cement uncovered without a substrate on the ceramic (21, 105, 136, 137, 161). However, the exposure of resin-based materials ,such as resin cements, to water may cause more hydrolytic degradation of organic components and oxidation of the residual unreacted carbon – carbon double bonds over time. Then the elution of oxidized and unreacted components may compromise (jeopardize) the color stability of the restoration (21, 142, 166-169). The uncovered surface of the resin cement exposed to hydrothermal aging procedures may accelerate the degradation, thus may result in a higher color and TP change compared to clinical conditions where the resin cement is always covered by the ceramic material. Perroni *et. al.* suggested that the resin cement should be embedded (sandwiched) between the ceramic and the substrate before aging (142). In the present study, in order to simulate the clinical conditions, ceramic specimens were luted with 0.1mm of resin cement thickness to 2mm thick resin composite substrates. It might be more reliable to use human enamel as the substrate to represent the clinical conditions, however standardization of enamel substrate's color would be very difficult. Therefore, monochromatic resin composite substrates were fabricated from a micro-hybrid resin composite and were polished up to 1200 SIC papers before the luting procedure to eliminate the oxygen inhibition layer, to protect the substrate against degradation over time and standardization of the substrate surface. In addition to these, initial color measurements were performed after the luting procedure, so that the substrate would not interfere with the color parameters. A certain number of studies also used the same substrate methodology with the present study (9, 11, 135, 162).

It has been shown that different aging methodologies affected color stability of substrate materials in different amounts. AAA and UV light aging induced color change of resin composite materials more than water aging did (51). Within this context, in the present study hydrothermal aging was preferred as the artificial aging method, since the substrates were produced from resin composite. With this approach, it was aimed to keep the color change of resin substrate at a minimum level that does not interfere with the evaluation of the glass ceramic material's color and TP changes. Hydrothermal aging was conducted using a thermocycling device and all the glass ceramic specimens were immersed into 5°C -55°C distilled water with 30 seconds dwelling time and 10 seconds of transfer time as proposed in ISO 11405 recommendations. In the literature 10000 cycles has been shown to represent one-

year clinical service (19, 20)As with the increase of aging time, color parameters of glass ceramic materials are more affected (135, 153), an aging regimen up to 30000 cycles was conducted, and color stability and TP of the tested glass ceramics were evaluated after each 10000 cycles.

Among various color evaluation methods such as colorimeters, visual inspections, and spectroradiometers, spectrophotometer has been shown to be the most precise and accurate instrument for the color measurements (27, 170-173). Therefore, in this study, color and translucency measurements; immediately after luting, 24-hours after luting, at 10000 cycles (1-year), at 20000 cycles (2-years) and at 30000 cycles (3-years) were performed with a spectrophotometer. Chen *et. al.* stated that two primary aspects may affect the precision of color measurements, the first one is the ability of an observer or instrument to present a repeatable outcome and the second one is the consistency of each step of the procedure, including the environment and obtaining the same positioning point for the specimens (27). In this study, to ensure the standardization of the measurements, all the evaluations were performed by the same researcher and all the specimens were placed into a clear (translucent) vinyl polysiloxane ring (Exaclear, GC Corp.) in the spectrophotometer, hence every specimen measured in the same position without interfering the color of the specimen due to the ring's translucency.

It is well documented in the literature that resin-based materials can reach sufficient degree of conversion and micro-hardness at 24-hours after polymerization and before 24-hours, even in small changes in measurement time can have a large effect on material properties (174-176). Thus, in order to achieve standard calculation settings, this *in vitro* study designated 24-hours readings as the baseline data.

Several studies mentioned that CIEDE 2000 (ΔE_{00}) formula provide a better fit than the CIELAB formula for both in vitro and in vivo evaluation of color difference thresholds of dental ceramics (1, 17, 18, 40, 47, 48, 153, 177). It is also stated that since the CIEDE2000 formula was authenticated to be more matched to human observer responses with confirmed data sets, this formula can be considered to assess color differences of dental materials (14). CIELAB (ΔE_{ab}) and CIEDE2000 (ΔE_{00}) formulas can be used for the evaluation of resin

composite's color change, however for the evaluation of color parameters such as hue, chroma, and lightness the CIEDE2000 formula could be considered for the color evaluation of dental materials. Therefore, in this study color stability, translucency change and the difference in lightness was evaluated using CIEDE2000 formula. The data received from CIEDE2000 formula, evaluated according to the clinical thresholds that defined by Paravina *et. al.* (47), which were ΔE_{00} <0.8 units and 0.8<ΔE_{00}<1.8 units for perceptibility and acceptability thresholds, respectively.

The translucency of restorative materials is usually measured by the Contrast Ratio (CR) or the Translucency Parameter (TP). The CR is the ratio of the light reflection of a material on a black and white background ($CR = Y_{black} / Y_{white}$, where Y represents the light reflection) (34, 178). As the light reflectance increases, the opacity of the material increases. Therefore, the CR is directly related to the opacity of the material and as translucency increases, CR decreases (179). The CR of a pure transparent material is 0, while the CR of a pure opaque material is 1 (180). On the other hand, TP is the color difference of a material between black and white background, in the uniform thickness, and is related to its translucency (8, 163). If the TP value is 0, then the material is totally opaque (163). According to the definitions of these two different measurements, TP and CR have strong negative correlations in the evaluation of ceramic materials, including CAD /CAM glass ceramics. However, both the TP and CR formulas are suitable for the evaluation of the relative translucency of ceramic materials (34).

Vichi *et. al.* (35) defined translucency thresholds for CAD /CAM ceramic materials through CR value. According to these thresholds, the tested ceramic materials in the present study were in the "high translucency group" (CR < 0.50). However, Spink *et. al.* (33) revealed that when the translucency of materials drops below 50%, the CR values approached 1 (total opacity). In their study, Vita InCeram Zirconia (VITA Zahnfabrik, Germany) exhibited CR value of 1 (totally opaque), while the total light transmission of the material is 15.25%. Thus, it can be considered as CR is not sensitive when the translucency of a material is below 50%. This inconsistency could be seen not only when the individual translucency of the material is lower than 50%, but also when the translucency drops below 50% by certain parameters, such as the hydrothermal aging and the associated increase in surface roughness, increase in

thickness, and the presence of an underlying substrate. Since these parameters all present at the methodology, the researchers of the present study could not foresee whether the translucency level of the monoblock specimens (resin composite/resin cement/CAD/CAM glass ceramic) would remain above 50% after 3-years of hydrothermal aging. Therefore, in order to develop a solid methodology, the TP measurement was preferred.

4.2 Discussion of the Results

In the present study, all null hypotheses were rejected. Color stability was significantly affected by the type of glass-ceramic CAD / CAM material, ceramic thickness, and aging. The mean TP value was also effected by the type of glass-ceramic CAD / CAM material, ceramic thickness, and aging.

4.2.1 Discussion of the Color Change

Regarding glass ceramic type on ΔE_{00}, all the tested materials showed similar color change both in 0.5mm and 1.0mm thicknesses between cementation and 24-hours. The mean ΔE_{00} values of E.max was 0.399, CD was 0.47, Cerec was 0.483, and LRF was 0.52, and all these values were lower than the perceptibility threshold value ($\Delta E<0.8$). This result is in accordance with the results of a similar conducted in vitro study by Pissaia *et. al.* in which they evaluated the color change of feldspathic ceramic veneers luted with different resin cements, and reported the 24-hours color changes were statistically similar for all the groups presented in the study (162). Several studies stated that the light-cured resin-based materials presented an increase in b values (through yellow) during the first 24-hours after polymerization, since the unreacted molecules of camphorquinone or the existing polymerization system (photo-initiator) return to their initial state/color, which is yellow (164), 75). However, light-cured resin cements that are polymerized under a ceramic layer which was also performed in the present study, exhibited lower color change (higher color stability) compared to those that are tested as monolithic resin cement specimens (21, 105, 181, 182). This result has been attributed to the possible masking ability of the ceramic layer. Moreover, a thin layer of the resin cement has a low volume of polymeric material, also the exposed margins of the resin cement enable the elution of the unreacted and oxidized components of the polymerization system, thus less color change is expected (164). Our 24-

hours results are in agreement with these statements, since there are no significant differences between immediate after cementation and the 24-hour color measurements.

Regardless of ceramic thickness, after 10000 cycles (1 year aging), all material's color change was higher than 24-hours, however it was still at the level of acceptability ($0.8<\Delta E<1.8$). With respect to thickness, in 0.5mm Cerec showed the highest color change among all the tested glass ceramics while in 1.0mm all the materials' color change was statistically similar except Cerec that was resulted in the lowest color change.

Tunçdemir *et. al.* compared the color stability of IPS e.max CAD and IPS e.max Press produced ceramic veneers and reported no difference between the two material's color change after 1-year accelerated aging. (155). Consistent with Tunçdemir *et. al.,* Turgut *et. al.* also stated, even though IPS e.max CAD and IPS e.max Press have different construction techniques, the optical properties of materials were statistically similar before and after aging. Microstructural differences may designate the optical properties rather than the construction technique (8). Therefore, materials which have similar crystalline composition can be comparable to constitute a discussion. The results of this study that different glass ceramic materials presented similar color change after 1-year artificial aging with the exception of the feldspathic glass ceramic Cerec, is consistent with the study of Choi et al. In their study, the authors evaluated a fine-structure feldspathic ceramic (Vitablocs Mark II), 2 different glass ceramics (IPS Empress CAD and IPS e.max CAD), and a zirconia-reinforced lithium silicate glass ceramic (Celtra Duo), 1 mm and 2 mm thicknesses. The specimens were exposed to UV aging process with a total radiant energy of 150kJ/m^2 (158) which equals to 1-year intraoral service of a restoration (147, 183, 184). IPS e.max CAD and Celtra Duo are the two common materials with the present study, furthermore Vitablocks Mark II has the same composition with Cerec because of their mutual feldspathic content (185). Similarly, IPS Empress CAD has similar structure with Initial LRF as both materials are leucite-reinforced glass ceramics. With respect to LRF there is only limited data available in the literature and in line with the results of the present study, Choi et. al also stated that Celtra Duo, IPS e.max CAD, Vitablocks MarkII, and IPS Empress CAD presented acceptable color changes and Cerec exhibited the least color change at 1 mm thickness after 1-year aging. Compared to the present study, the authors reported lower mean ΔE values for the tested

glass ceramics except IPS e.max CAD which can be due to the different aging protocols as well as to the underlying 2mm resin composite substrate used in the present study. It has been previously reported that IPS e.max CAD had a higher masking ability compared to Celtra Duo and Vita Suprinity (157). This masking ability may be the reason for the similar mean ΔE values with the underlying resin composite substrate in the present study compared to the afore-mentioned study without the substrate.

Lee *et. al.* (135) assessed color stability of ceramic veneers luted with different resin cements in an *in vitro* study. The researchers luted 0.5 mm HT lithium disilicate IPS e.max Press to acetal polyoxymethylene material with various light- and dual-cure resin cements and then subjected the specimens to accelerated aging with a total radiant energy of 150kJ/m^2 (1-year). The color change of HT lithium disilicate glass ceramic luted with the light-cure low brightness resin cement in that study can be comparable with the HT lithium disilicate glass ceramic IPS e.max CAD luted with the light-cure translucent resin cement in this study. In accordance with the present study's result, the authors reported that corresponding glass ceramic exhibited perceptible color change after 1-year accelerated aging (ΔE=1.10).

In the present study after 1-year aging, in 1mm thickness both IPS e.max CAD and Celtra Duo presented perceptible but acceptable color changes (0.8<ΔE<1.8) and the difference between the two glass ceramic materials was not significant. Aljanobi *et. al.* also compared the color stability of two glass ceramics (Vita Suprinity, IPS e.max CAD) and two different multilayer zirconia materials in 1mm thickness (19). After 1-year aging (10000cycles) the authors concluded that color stability was influenced by the type of material and all the tested materials presented in the range of clinically acceptable level of ΔE values. IPS e.max CAD resulted in lower but statistically similar color change with Vita Suprinity, which is consistent with our 1-year aging results for IPS e.max CAD and Celtra Duo (similar structure with Vita Suprinity) in 1 mm thickness. On the contrary, Alsayed *et. al.* reported significantly better color stability for IPS e.max CAD than Vita Suprinity after 1-year AAA (154). Color change of IPS e.max CAD was non-perceptible while Vita Suprinity was in acceptable level. The authors discussed the higher color change of Vita Suprinity over IPS e.max CAD with the tested materials microstructural difference. The breakdown of metal oxide substance of the ceramic to peroxide compound was assumed to

be responsible for the color change. In the present study, the aging procedure is hydrothermal, thus the difference in aging methodology could be the reason for the zirconia reinforced lithium silicate materials' (Vita Suprinity and Celtra Duo) different color change pattern between the studies. In accordance with these studies, Stemankovic *et. al.* evaluated staining and aging effects on 1mm thick CAD/CAM materials, and the researchers reported that color change appears to be material dependent, also IPS e.max CAD and Vita Suprinity were found to be more color stable than resin nanoceramics (RNC) and polymer infiltrated ceramic network (PICN) materials (153). However, at 1-year aging IPS e.max CAD presented higher color change than Vita Suprinity in accelerated aging group, this result differs from the present study and Aljanobi *et. al.* results. Yet there is a lack of information regarding the color change difference between IPS e.max CAD and Vita Suprinity, researchers mainly focused on the differences between hybrid materials (resin nanoceramics, polymer infiltrated ceramic network materials) and ceramic materials (lithium disilicate, zirconia reinforced lithium silicate materials). Nevertheless, the disagreement may be occurred due to the differnet aging methods (accelerated aging and hydrothermal aging). Belli *et. al.*(94) stated that major difference between Vita Suprinity and Celtra Duo is the size of the lithium silicate crystals, which appears to be approximately 0.5 μm bigger in Celtra Duo than in Vita Suprinity. Hence, theoretically it may be expected that, even though both composed of the similar crystal phases embedded in glassy matrix, crystal size could affect the optical properties and aging pattern of materials. In addition to the aging methodology and material structures different results may also be due to the difference between study methodologies. The 2-mm thick resin composite substrate in A2 shade in the present study may have degraded with hydrothermal aging, thus caused a reflection through the high-translucent material such as Celtra Duo.

Turgut *et. al.* evaluated color stability of lithium disilicate ceramic veneers in 0.5mm thickness (21). Ceramic specimens without an underlying resin cement from each material served as control group while in study groups ceramic specimens were luted with resin cements in 0.1mm thickness without any substrate material under the resin cement. Then all the specimens subjected to accelerated aging (AAA). In accordance with the present study, the authors reported that after 1-year aging, the IPS e.max Press luted with translucent light-cured resin cement exhibited acceptable color change (ΔE= 2.5 with CIELab calculation).

They also stated that the control groups' color change ranged between 0.8 and 1.2 units (non-perceptible and acceptable color changes). This significant difference in color stability which occurred only with the existence of 0.1mm resin cement may be due to the absence of an underlying substrate thereby, over-exposition of resin cements to aging conditions. This methodology does not reflect the clinical conditions since resin cements are not totally exposed to intraoral environment. In addition to this, it is known that AAA effects resin-based materials' color stability more than hydrothermal aging (51), hence the aging methodology may also have contributed to the difference in color change between luted ceramic and ceramic specimen. Apart from these studies Gugelmin *et. al.* evaluated color change of ceramic laminates by luting ceramic specimens to bovine incisors. This methodology is reliable in terms of simulating clinical conditions, however, it can be challenging to standardize bovine teeth color, since substrate, resin cement, and ceramic material overall create final color of the restoration, it can be necessary to standardize the possible variables, other than the variables that are aimed to evaluate. The researchers reported 0.8mm thick Vita Suprinity (ZLS) luted with light-cured resin cement exhibited acceptable color change (ΔE_{00}=1.3), after 1-year water aging. This result is similar to color change of Celtra Duo both in 0.5mm and 1.0mm thickness, at 10000cycles (1-year aging) in the present (for 0.5mm ΔE_{00}=1.26, for 1.0 mm ΔE_{00}=1.42). Similarly, Pissaia et. al. cemented 0.5mm thick Vita MarkII feldspathic ceramics to resin composite substrates, subjected to water aging to assess the color stability (162). After 1-year aging, the authors concluded that feldspathic ceramics, luted with translucent light-cured resin cements exhibited above acceptability threshold color change (ΔE_{ab}=3.62 and ΔE_{ab}=3.92 for two different translucent resin cements). This result contradicts with the results of the present study for the color change of Cerec 0.5mm after 1-year aging. Methodologies of these two studies are similar, however, it appears that the feldspathic ceramic specimens in the present study are more color stable. There is a lack of information about the thickness of the resin cement in Pissaia *et. al.* study which may have caused higher color change of the 0.5 mm thick feldspathic glass ceramic after 1 year aging.

After 2-years aging, all materials' mean color change was higher than 1-year, however still at the level of acceptability ($0.8<\Delta E<1.8$). Regardless of thickness, Celtra Duo showed the highest, Initial LRF presented the lowest ΔE values, and the rank of the materials

was CD>Cerec>E.max>LRF. However, with respect to thickness, in 0.5mm Cerec exhibited the highest, LRF presented the lowest color change while in 1.0mm thickness CD showed the highest, and Cerec demonstrated the lowest color change. The up-front data of this aging period was Cerec in 0.5mm that showed color change beyond the acceptability threshold ($\Delta E>1.8$), apart from material's mean color change. In the 2-year's results Stamenkovic *et. al.*, showed that IPS e.max CAD exhibited acceptable color change while Vita Suprinity's color change was non-perceptible ($\Delta E<0.8$) (54). This result is partially in agreement with the present study, since IPS e.max CAD showed acceptable color change in both studies ($\Delta E_{00}=1.55$ in the present study, $\Delta E_{00}=1.5$ in Stamnkovic *et. al*.), yet Celtra Duo which has similar microstructure with Vita Suprinity, showed perceptible but acceptable color change in the present study ($\Delta E_{00}=1.77$ for Celtra Duo, $\Delta E_{00}=0.3$ units for Vita Suprinity). The potential reasons for this different outcome have been discussed previously in the 1-year discussion. In sum, crystal size difference between Celtra Duo and Vita Suprinity, the existence of underlying substrate in the present methodology, and different aging methods may have caused different aging patterns between two materials in these studies. Another previously mentioned *in vitro* study regarding color change of lithium disilicate ceramic veneers luted with resin cements (135), pursued the accelerated aging up to 2-years. At two years the authors reported good color stability for IPS e.max Press in 0.5mm luted with low brightness light-cured resin cement ($\Delta E_{ab}=1.37$) which is consistent with the results of IPS e.max CAD at 2-years aging in the present study ($\Delta E_{00}=1.54$). Pissaia *et. al.* evaluated color stability of 0.5mm thick feldspathic ceramic veneers (Vita MarkII) luted with light-cured resin cements to resin composite substrates and stated that after 2-years aging feldspathic ceramic veneers exhibited ΔE values higher than acceptability level and this result is consistent with Cerec in 0.5mm at 2-years aging in the present study. The feldspathic glass ceramic Cerec is the only glass ceramic material that presented higher color change than acceptability level ($\Delta E_{00}=2.054$) after 2 years aging

In addition to in vitro studies, several *in vivo* studies evaluated the color stability of ceramic veneers at 2-years. Marchionatti *et. al.* evaluated color stability of IPS e.max Press ceramic veneers in 0.3mm thickness, and concluded that at 2-years, 40% of restorations luted with light-cured resin cement, presented unacceptable color changes for both the ΔE_{00} and ΔE_{ab} thresholds (186). This result differs from the present study since IPS e.max CAD

showed acceptable color change at 2-years (mean ΔE_{00}=1.55). Marchionatti *et. al.* prepared ceramic veneers in 0.3mm thickness while in the present study ceramic thickness was 0.5mm. Thinner ceramic layer can reflect the underlying resin cement's color and physiological discoloration of the teeth during the evaluation period which may account for the difference between the results.

With respect to material type effect on color stability, at **3-years aging**, regardless of the thickness Cerec presented the highest and Initial LRF showed the lowest color change. The rank of mean ΔE values of the tested glass ceramic materials was: Cerec>CD>E.max>LRF. All materials' mean ΔE values were statistically similar and higher than 2-years aging. Furthermore Cerec's, and CD's color changes were higher than the acceptability level (ΔE>1.8). In the literature, there are only a few *in vitro* studies that pursued the aging period of ceramic veneers up to 3-years. Pissaia *et. al.* assessed in the afore mentioned study the color stability of 0.5mm feldspathic ceramic veneers up to 3-years water aging and showed that 0.5mm feldspathic ceramic veneers exhibited unacceptable color change (ΔE_{ab}>2.66), which is in line with the results of Cerec 0.5mm at 3-years aging in the present study (ΔE_{00}=2.494). Similarly, Aljanobi *et. al.* evaluated color stability of Vita Suprinity and IPS e.max CAD in 1mm thickness up to 3 years aging (30000cycles) and stated that the glass ceramic material's color change was in clinically acceptable levels (68). The results are partially in agreement with the present study, since in 1mm thickness IPS e.max CAD and Celtra Duo (similar structure with Vita Suprinity) presented acceptable color changes at 3-years aging. However, in the study of Aljanobi *et. al.* IPS e.max CAD showed higher color change than Vita Suprinity which differs from the present study's 3- years aging results for IPS e.max CAD and Celtra Duo. In this study, the tested two glass ceramics showed similar color changes in 1mm thickness and this variation may be caused by the minor microstructural difference between Vita Suprinity and Celtra Duo materials. Lithium silicate crystals are 0.5 μm bigger in Celtra Duo than in Vita Suprinity and this dense structure can supply Vita Suprinity a better color stability. Another possible reason of this difference in findings can be that Celtra Duo is a translucent material thus may reflect the underlying resin cement's and resin composite substrate's color change caused by hydrothermal degradation. These diversities in methodologies may have caused differences, still in both studies the color changes of both materials are clinically in acceptable level.

Regarding leucite-reinforced glass ceramic veneers, Gresnigt *et. al. (187)* conducted a 3-year follow-up clinical study with the leucite reinforced glass ceramic IPS Empress Esthetic and researchers scored 4 restorations as 1 ('good' color match) and 19 restorations as 0 ('very good' color match). These findings can relate to the leucite reinforced glass ceramic Initial LRF color change after 3-years aging in the present study, which presented the lowest color change among all the tested glass ceramic materials (ΔE_{00}=1.672).

Regarding the effect of ceramic thickness on ΔE, in the first **24-hours** period, all the tested glass ceramic materials exhibited similar color changes between 0.5mm and 1.0mm thicknesses and all the ΔE values were non-perceptible (ΔE<0.8). Similarly, at **1-year aging**, all the materials presented similar and acceptable color changes between the two thicknessess except Cerec. Cerec showed higher color change in 0.5 mm than in 1.0mm, yet both were in clinically acceptable levels (ΔE<1.8). This difference may be due to the enamel-like high translucent structure of the feldspathic ceramic material (85). In addition to the material's high translucency, it is also a well known fact that decrease in ceramic thickness cause increase in translucency (TP value) (13, 143, 157, 158, 188). With the increased translucency, the underlying resin composite substrate's and resin cement's color change due to aging can be easily reflected from the thin ceramic layer. In accordance with this result, Kökat *et. al.* also stated that different thicknesses of ceramic veneers fabricated from monolithic feldspathic blocks are significantly effective on masking underlying substrate, however feldspathic veneers with a less than 0.7mm thickness can not mask the underlying substrate (85). This dramatic masking ability change hence color change in Cerec material, presented itself as the highest ΔE value in 0.5mm while the lowest ΔE value in 1.0mm thickness in the present study. Accordingly, at **2-years aging** while all tested materials presented similar ΔE values between 0.5mm and 1.0mm thicknesses, Cerec 0.5mm showed greater color change than Cerec 1.0mm, also Cerec 0.5 exhibited unacceptable and the highest color change (ΔE_{00}=2.054) among all materials. On the contrary, Cerec 1.0mm presented the lowest color change (ΔE_{00}=1.345) similar to 1-year aging results. At **3-years aging**, all the tested glass ceramics presented similar color change in both thicknesses except feldspathic Cerec. Moreover Cerec 0.5mm resulted in significantly highest ΔE values for all the evaluation periods (ΔE_{00}=2.494). Unlike the other aging periods, after 3-years aging, not only Cerec 0.5mm but also Celtra Duo 0.5mm presented unacceptable color change (ΔE_{00}=2.073). This

result of Celtra Duo may be attributed to it's 10% zirconia content and high translucency. Similar with the previous aging periods, Cerec 1.0 mm showed the lowest ΔE value among all the materials, while Cerec 0.5 mm showed the highest ΔE value. This result clearly showed that the feldspathic glass ceramic Cerec's color stability is thickness dependent and it can be suggested that when Cerec is being used in a clinical case, restoration color will be more stable over time when the ceramic thickness is adjusted to 1.0mm. In prepless or minimal prep. ceramic veneer cases, for color stability it would be a better approach to perform a vital bleaching treatment prior to the veneer preparation, since the feldspathic glass ceramic material may reflect the underlying substrate's color in less than 0.7mm thickness (39).

In the present study aging exhibited a significant effect on color stability for all the tested glass ceramic materials. In fact it was the most effective variable on color stability (F=396.43). All the tested materials exhibited significant color changes at 1-,2-, and 3-years aging periods which is consisent with the results of all aforementioned in vitro and in vivo studies.

From a clinical point of view, since all different types of glass ceramic materials; such as lithium disilicate, leucite reinforced, zirconia reinforced lithium silicate and feldspathic ceramics began to significant color change after 1 year aging, periodic bleaching treatments from the palatal side of the glass ceramic veneered teeth can be suggested. Furthermore, according to the results of the present study, lithium disilicate glass-ceramics (IPS e.max CAD) may be preferred in the treatment of discolored teeth due to their high masking ability. If a crown restoration is already present in the treatment plan for veneers, since no color change occurs in crown restorations, leucite-reinforced glass-ceramic (Initial LRF) can be used for ceramic veneers, which exhibited the least color change after 3-year of aging, regardless of thickness.

4.2.2 Discussion of the Translucency Parameter

Translucency is another factor that affects the esthetic outcome of the restorations, and the more increase in translucency, the more the restorations become lifelike (143, 189-192). The translucency of dental materials has been determined by the translucency

parameter (TP). This value is defined as the color difference of the same material over a black and a white background, in the same thickness (13, 144, 183, 189). Although translucency improves the esthetic outcome of the ceramic restorations, it also adds another level to the complexity of the final color and color match of the restoration (190, 191). The important point is the requirement of different levels of translucency in different clinical situations. The need for higher translucency or higher masking ability will be defined by the color and by the amount of remaining dental hard tissues, or by the glass ceramic core material. Therefore, it is critical to know the optical properties of different glass ceramics before using them properly in different clinical situations (13). Various *in vitro* studies and systematic reviews indicated that different ceramic materials exhibit different translucency parameters (18, 19, 35, 88, 142-144, 157-159, 163, 178, 193-197). The difference in translucency between materials was attributed to their different chemical compositions, particle sizes, crystalline structures, pore population, additives, number of firings, background shades, surface textures, material shades and thicknesses (8, 13, 65, 142, 144, 194, 198). In general, increase of crystalline content in glass matrix comprimises the translucency of ceramic materials in the same thickness (13, 142, 199). Nonetheless, if the crystals are smaller than the wavelength of the visible light (400-700 nm), materials provide higher light transmittance, hence become more translucent (143, 200).

Materials such as Celtra Duo with lithium silicate crystals with a size of approximately 0.5 μm (500nm) correspond well to the wavelength range of visible light and thus mimic the translucency of human enamel. Together with the high glass content of the material, these small crystals are responsible for the translucency of Celtra Duo (90). The size of the crystals plays a more important role when glass ceramics are aged. Feldspatic ceramics consist of crystals in 2-4 μm size, which is susceptible to wear and creates a rough surface. On the other hand, zirconia-reinforced glass-ceramics have a crystal size of about 0.5 μm (88, 90, 94). It has been stated stated that materials with a crystal size of 0.7 μm or less are more wear resistant (201). Even after the crystals are removed, the surface of zirconia-reinforced glass ceramic would be smoother than the surface of other type of glass ceramic materials due to the smaller crystal size. Vasiliu *et. al.* confirmed that zirconia-reinforced glass ceramics presented less surface roughness than lithium disilicate and feldspathic ceramics, after 1-year aging (88). It is also a known fact that surface roughness

and texture are directly related to the optical properties of ceramic materials (88, 96, 143, 160, 200). Smooth surfaces reflect light at the same angle, which is called specular reflection. This reflection ensures the blending of restoration with the tooth. However, when the surface becomes rougher, as in aging, the light becomes more diffuse because the surface behaves as countless micro-surfaces that scatter the light. This phenomenon leads to a decrease in translucency and an increase in brightness (L value) (13, 143, 202). In the context of crystallinity effect, it is stated that with the same shade and translucency notation, and the same processing technique, different ceramic materials presented different translucencies, in the same thickness (142, 203).

Partially in accordance with the literature, in the present study the mean TP values of the tested glass ceramic materials differed in regard of **ceramic material type and by aging**. In the present study, the underlying substrates were made of A2 shade resin composite specimens. Then resin composite substrates and glass ceramic materials were luted with 0.1mm thick translucent light-cured resin cement. As identical substrates made from the same material in the exact same thickness and the same shade was used for each ceramic specimen, the researchers of this study established the methodology in a way of TP comparison of the ceramic materials rather than TP measurements of the ceramic material itself. In addition, since certain parameters can directly affect the translucency of ceramic materials (8, 13, 65, 142, 144, 194, 198), comparing translucency in absolute values is difficult and controversial (13, 33). Moreover, it is mentioned that the masking ability of a ceramic veneer can be indirectly estimated by measuring its translucency (142, 195), with the presence of the underlying substrate, the masking ability of ceramic materials can also be discussable in the present study.

Regardless of thickness and aging, IPS e.max CAD and Celtra Duo presented the highest mean TP values, while Cerec showed the lowest. With regard to the underlying substrate, this result can be related to the higher masking ability of IPS e.max CAD and Celtra Duo. In an in vitro study, the translucency of Celtra Duo, IPS e.max CAD, Vita MarkII (feldspathic ceramic) and IPS Empress CAD (leucite-reinforced glass-ceramic) was investigated and it was found that IPS e.max CAD showed significantly the lowest TP, while Celtra Duo had a statistically lower TP than IPS Empress CAD and Vita MarkII (IPS e.max

CAD< Celtra Duo< Vita MarkII & IPS Empress CAD) (143). These differences can be explained by different microstructures. As mentioned above, IPS e.max CAD has dense, 1.5 μm needle-shaped, randomly oriented crystals that account for approximately 70% of the glass-ceramic volume. In addition to this, the aluminosilicate glass in IPS e.max CAD may result in lower translucency, as aluminum compounds make the material more opaque (143). On the other hand, Celtra Duo has a unique microstructure that combines high translucency and masking ability. Rod-like silicate particles that are four times smaller than conventional lithium disilicate and a high glass content provide high translucency, while a 10% zirconia content ensures sufficient masking ability (95, 143), although not as high as in IPS e.max CAD. It has been stated in various *in-vitro* studies that in various thicknesses IPS e.max CAD exhibited higher masking ability then two different zirconia-reinforced glass ceramics (157).

All the tested materials presented statistically similar TP values at immediate after cementation and 24-hour (baseline) measurements, both in 0.5mm and 1.0mm thicknesses. Although different glass ceramic materials present different translucencies, this result can be attributed to the underlying resin composite substrate, since translucency is directly related to the light transmision through the material (43, 157). From this point of view, it can be considered as the enamel's optical property with or without underlying dentin substrate as in cervical or incisal area of the tooth. TP data of human dentin and enamel were previously was evaluated by Yu *et. al.*(189), and was stated as 16.4 and 18.7, respectively, at 1mm thickness. In several other studies, TP values of glass ceramics were evaluated quantitatively (8, 193, 194), and these data are closely related to the TP values of human enamel and dentin, at the same thickness (184, 189). TP values of human enamel and dentin suggested as the first criteria for translucency evaluation of restorative materials (43, 184, 204). In this regard, the range of dentin and enamel TP values can be used as a basis for TP values of glass ceramics, which is not in a wide range. TP values of immediate after cementation and baseline results of the present study corresponds to this range.

At **1- year** aging, with respect to **ceramic type**, in 0.5mm Celtra Duo, IPS e.max CAD, and Initial LRF had statistically similar TP values, while Cerec exhibited statistically lower TP than Celtra Duo and IPS e.max CAD, however statistically similar to Initial LRF. At a thickness of 1.0 mm, all the tested materials presented statistically similar TP values.

The reason why Cerec had the lowest TP value at 0.5 mm, while similar TP value with the other tested materials at 1.0 mm, can be attributed to the high translucency of the material and it's low masking ability at lower thicknesses (13, 85, 161, 178, 195, 205). It is claimed that the more translucent a ceramic material is, the more TP changes would occur at different thicknesses (193). As discussed in detail in the ΔE discussion above, Cerec is a highly translucent and thus highly thickness-dependent material, especially when there is a substrate underneath. In the present study, the Cerec material demonstrated its ability to reflect the color change of the substrate at lower thickness with aging in ΔE and TP data. In an *in vitro* study evaluating TP of Vita MarkII (feldspathic), IPS Empress CAD (leucite reinforced), IPS e.max CAD and Celtra Duo before and after 1-year of accelerated aging, it was concluded that Celtra Duo had the lowest TP (158). This statement differs from the results of Awad *et. al.* (143), in which they mentioned that TP of Celtra Duo was statistically higher than IPS e.max CAD. The authors (158) explained this discrepancy by the difference between aging and polishing methodology. Alp *et. al.* evaluated IPS e.max CAD and Vita Suprinity (zirconia-reinforced glass-ceramic) before and after aging with 5000 thermal cycles in coffee solution and concluded that IPS e.max CAD presented higher TP before and after aging. The higher firing temperature of IPS e.max CAD has been shown as the reason for the lithium disilicate reinforced glass ceramic's high translucency (18). It is a known fact that the processing technique of the ceramic material is directly related to it's translucency. Even Celtra Duo and Vita Suprinity, both zirconia-reinforced glass-ceramics, showed different TP values in an in *vitro study* by Arif *et. al.* ($TP_{CD} > TP_{VS}$) (159). Although both materials consist of similar crystal phases embedded in a glass matrix, Celtra Duo has approximately 0.5 μm larger in length lithium silicate crystals (94). The difference between the TP values could be due to the difference in particle size and firing temperatures. Similarly a systematic review also concluded that different processing techniques may result in different microstructures within the same ceramic composition, which may affect translucency due to pore distribution and population (142). Vasiliu *et. al*. (88) investigated Vita Suprinity, Vita Mark II and IPS e.max CAD with glazed and polished surfaces at a thickness of 1.5 mm and subjected the materials to 1-year hydrothermal aging. Before aging measurements, Vita Mark II, a milled feldspathic ceramic, had the highest TP with both glazed and polished surfaces, while Vita Suprinity, a zirconia-reinforced glass ceramic, had the lowest TP with

glazed and polished surfaces. After aging, Vita Suprinity exhibited the most significant TP change among all the materials with the glazed surface exhibiting the greatest change. The authors concluded that the glazed surface is affected by aging, by changing its structure and suffering from chipping, resulting in a rougher surface (88).

Regarding the effect of the **ceramic type** on the TP comparisons after **2-years** of aging, in 0.5 mm thickness all the tested materials showed similar TP, while in 1.0 mm thickness Celtra Duo showed significantly higher TP. This result could be due to the above-mentioned microstructure of Celta Duo, which provides high translucency together with sufficient masking ability. The material retains its optical properties despite the underlying substrate. To the authors' knowledge, there is no study in the literature that compared the TP of different glass ceramic materials after 2-years aging. In the present study, all materials had statistically similar TP after **3-years** aging at a thickness of 0.5 mm, with the exception of Cerec, which had statistically the lowest value. As explained in detail above, the high translucency of Cerec and the thickness-dependent masking ability could have led to this result. In 1.0mm thickness, all the tested materials had statistically similar TP, including Celtra Duo which had a statistically higher TP value after 2-years aging. In this respect extending the aging process up to 3-years provided more reliable results.

Similar to the results of the present study, Aljanobi *et. al.* revealed a lower TP for zirconia-reinforced glass ceramic (Vita Suprinity) than IPS e.max CAD, after 3-years of hydrothermal aging (19). The authors explained this difference by the 10% zirconia content of the material as in this study.

In the present study, **ceramic thickness** showed the most significant influence on TP (F= 1005.32, while the F value of the nearest material type was 30.47). This result is consistent with the statement of Barizon et. al. that ceramic shade and thickness influence translucency, with thickness having the most significant effect (13). In the present study, regardless of the material type and aging, the mean TP value in 0.5 mm thickness (6.740) was statistically higher than the TP value in 1.0 mm thickness (4.826). In addition to this, all materials showed statistically significant differences between two thicknesses for all the aging periods. This result confirms the fact that thickness and translucency have a negative

correlation (13, 143, 157, 158, 160, 188). Similarly, Choi et. al. investigated different ceramic materials in 1 and 2 mm thicknesses and stated that TP values at 1 mm thickness were higher than in 2 mm thickness for all the tested ceramic materials (158). In another in *vitro study*, it was revealed that the translucency of CAD /CAM ceramics decreased with increasing thickness from 0.5 mm to 1.5 mm (157). On the other hand, in a study by Bai et. al. (196) different CAD /CAM materials were prepared in 0.7 mm thickness, placed on extracted teeth (nominal shade A2) and then TP values were measured with a spectrophotometer. The CAD/CAM slabs were then successively reduced to a thickness of 0.5 mm and 0.3 mm, and the TP measurements were repeated. As a result the aouthors concluded that reducing the thickness from 0.7 mm to 0.3 mm, increased the TP values of all the tested materials, possibly affecting the optical properties of ceramic veneer restorations. In another *in vitro* study, 9 different CAD /CAM materials were investigated in 1 and 2mm thicknesses and significant decrease in TP values for all the tested materials were reported when ceramic thickness was doubled. (143). Similarly Turgut et. al. evaluated lithium disilicate glass ceramic (IPS e.max Press) in A1 shade at 0.5mm and 1.0mm thicknesses and revealed statistically significant difference between two thicknesses regardless of the type of shade of the resin cement underneath (147). All of these findings are in accordance with the results of this study that thinner ceramics showed higher translucency.

With respect to the effect of **aging** on TP, regardless of glass material type and thickness, aging significantly decreased TP by time. In 0.5 mm, Celtra Duo, IPS e.max CAD and Initial LRF had statistically similar TP values in all aging periods, while Cerec had statistically lower TP value compared to its baseline measurements (24-hour). As discussed before, regarding the high translucency of Cerec at 0.5mm, this significant decrease can be attributed to the reflection of the underlying substrate's color change. At a thickness of 1.0 mm, all the tested materials had statistically similar TP values, with the exception of Celtra Duo, which had a significantly lower TP value compared to its baseline measurements. Consistent with this result, both Aljanobi et. al. and Choi et. al. reported lower TP values for zirconia-reinforced glass ceramics after aging and explained this behavior of the material by its 10% zirconia content (19, 158). Various *in vitro* studies investigated the translucency of glass ceramic materials without any underlying substrate and claimed that translucency of glass ceramic materials was significantly affected by aging and glass ceramics became more

opaque and dull by time (19, 43, 147, 158). However, Kurt *et. al.* indicated that lithium disilicate glass ceramic's TP (IPS e.max Press) was not affected by 1-year accelerated aging, both with glazed and polished surfaces, which is in accordance with the 1-year results of the present study (163).

When the contrast ratio (ΔCR) is greater than 0.07, the change in translucency could be percieved by visual examination, in other words by naked eye (180). Since a strong correlation between CR and TP is confirmed (34), Lee *et. al.* transformed the perceivable limit of ΔCR to ΔTP, and stated that the perceptability threshold for CIELAB (TPT_{ab}) as 2 units (184). However in the present study measurements executed with CIEDE2000 formula. More recently, Salas *et. al.* determined the perceptability (TPT_{00}) and acceptability (TAT_{00}) thresholds for CIEDE2000 formula as 0.62 units and 2.62 units, while corresponding CIELAB values were as 1.33 units and 4.43 units, respectively (206). In the present study, regardless of thickness, lithium disilicate glass ceramic and leucite-reinforced glass ceramic materials presented non-perceptible translucency change ($\Delta TP_{00}<0.62$ units) after 3-years aging, while feldspathic ceramic had an acceptable translucency change ($0.62< \Delta TP_{00}< 2.62$) in 0.5mm and non-perceptible translucency change in 1.0mm. On the contrary, zirconia-reinforced glass ceramic showed acceptable translucency change in 1.0mm and non-perceptible translucency change in 0.5mm.

From a clinical point of view, although feldspathic and zirconia-reinforced glass ceramic materials presented perceptible translucency change in certain thicknesses, despite the presence of an underlying resin composite substrate, all the tested materials maintain their translucency in clinically acceptable level after 3-years of hydrothermal aging. This result can be regarded as promising, however even minor errors in the brightness of a restoration can be noticeable, as human perception is more sensitive in detecting errors in value rather than chroma and hue (44, 45). The brightness of a restoration could appear low (greyish) when the translucency of a material is high, especially in thin layers without underlying dentin or core material such as in incisal area of a veneer restoration. When surface roughness is increased, translucency will be decreased due to the scattering of the light from the rough surface of the ceramic. With this diffuse light, value (brightness) of the restoration will increase. Therefore, in the case of a mismatch of a high translucent glass ceramic restoration

with the existing restorations or natural teeth due to it's high translucency and low brightness, tertiary morphology can be applied to the restoration surface before polishing and glazing that will increase the value of the restoration.

The limitation of the present study is the chosen method of artificial aging. Hydrothermal aging by thermocycling simulates clinical conditions in terms of water sorption and thermal changes. However, this method does not fully represent intraoral conditions and what the restorative materials are exposed to other than thermal changes and water sorption, such as masticatory forces, lateral forces, and coloring agents. Since color and translucency changes were detected in materials only by being exposed to distilled water at different temperatures, it may be possible to see color and translucency changes above these values under clinical conditions.

5. CONCLUSION

Within the limitations of the study, the following conclusions may be drawn:

1- The color stability of luted CAD /CAM ceramic veneers was influenced by the type of ceramic material, ceramic thickness and aging.

2- In 0.5 mm, feldspathic ceramic exhibited unacceptable color change after 2-years of aging, while zirconia-reinforced glass ceramic exhibited unacceptable color change after 3-years of aging.

3-Leucite-reinforced glass ceramic presented significantly higher color stability than feldspathic ceramic and zirconia-reinforced glass ceramic.

4- The translucency of luted CAD /CAM materials was also influenced by the type of ceramic material, ceramic thickness, and aging, with ceramic thickness having the greatest effect.

5- In 0.5mm thickness, feldspathic ceramic showed the lowest translucency, while in 1.0 mm zirconia-reinforced glass ceramic exhibited the lowest translucency after 3-years of aging.

6- Luted CAD /CAM ceramic materials showed acceptable changes in translucency after 3-years of aging, regardless of thickness.

7- In terms of optical properties, leucite-reinforced glass-ceramic showed similar results to lithium disilicate, while zirconia-reinforced glass-ceramic was comparable to feldspathic ceramic.

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