Color Consistency of Zirconium Oxide CEREC Crowns Milled at Different Thicknesses

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Color Consistency of Zirconium Oxide CEREC Crowns Milled at Different Thicknesses

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Purpose: The purpose of this study was to evaluate the color of full-contour zirconia CEREC restorations milled at different material thicknesses which could aid dental practitioners in planning full-contour ceramic restorations.

Method and materials: Two sample crown preparations were made of an individual biogeneric copy of a left maxillary central incisor on a model scanned by means of Sirona CEREC Omnicam. One sample was prepared at a reduction of 1 mm, while the other was prepared at a 2mm reduction. A total of 60 CEREC Ivoclar ZirCad LT blocks were used to create 10 Samples of monochromic Zirconia crowns milled at 1 mm and 2 mm thicknesses in each of Vita classic shades A1, B2, and C2. The optimal thickness of 1 mm was chosen for the control groups Based on manufacturer recommendations and optimal thickness of 2 mm was chosen for the test groups. Sample crowns were sintered by means of a Sirona SpeedFire oven. No additive coloring or glaze was applied. A *Canon 80D* digital camera equipped with a *Canon MR-14EXII* ring flash and a polarized filter was used to photograph all test and control group specimens. The photographs were developed via digital software, *Photoshop CC 2019.* The CIE L*a*b* color values were measured.

Results: CIE L*a*b* data for all samples was recorded and statistically analyzed using a two sample t-test, *STATA.SE v16*. There was a statistically significant difference ($P<0.05$) in L* values when test groups (2mm) were compared with the control groups (1mm) for shades A1,

B2, and C2 with P<0.00. ΔE for shades A1, B2 and C2 groups were 3.64, 3.67, and 4.55 respectively which is higher than the clinically acceptable threshold 3.3.

Conclusion: An increase in the thickness of Zirconia from 1mm to 2mm demonstrated a $\Delta E > 3.3$ in all test groups which is detectable by untrained observers. As the thickness if Zirconia increased from 1mm to 2 mm, L* decreased in all test groups. Vita Classic shade C-2 demonstrated a more dramatic decrease in L* than shade A-1 and B-2 following the Zirconia thickness change from 1mm to 2mm.

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والله ولي التوفيق

1.0 Introduction

Production of naturally appearing ceramic restorations has been a major objective ever since their introduction (1). The opaque core of ceramo-metal restorations limits both color appearance and translucency (2). All ceramic restorations without a metal substructure allow more light transmission and consequently improved reproduction of the appearance of natural tooth structure (3). Despite the esthetic advantage of glass ceramic restorations, their lack of strength has resulted in a demand for increased durability. High strength zirconia-based restorations combined with CAD/CAM technology has broadened the range of employment of ceramics in restorative dentistry (4). Unfortunately, cohesive failures of veneering porcelain has proved to be a major drawback (5, 6). Fabrication of monolithic zirconia restorations consisting of a single zirconia material without veneering porcelain could be an alternative solution (7).

CAD/CAM technology has made it possible to provide patients with accurate, fracture resistant, full contour CEREC restorations in a single day. The aesthetics of zirconia CEREC restorations depends on multiple factors such as material thickness, color, translucency, anatomic features, and shape. Color may vary when zirconia restorations differ in thickness. Evaluation of color of full-contour zirconia CEREC restorations milled at different material thicknesses could aid dental practitioners in planning full-contour ceramic restorations.

2.0 Literature Review

2.1 Zriconia

Zirconium oxide (ZrO2) is a highly sintered polycrystalline ceramic dioxide of the transition metal zirconium (Zr) which has been utilized in restorative dentistry for approximately two decades. It has occupied a distinctive place among dental ceramic materials because of its superior mechanical properties including high flexural strength, fracture toughness, and low elastic modulus. In addition, zirconia has low corrosion potential, low cytotoxicity, and offers minimal adhesion of bacteria (8, 9). These unique properties have encouraged significant biomedical research since the 1970's for uses of zirconia in medicine and dentistry, particularly in stress-bearing roles where its strength rivals that of many alloys (8).

Zirconia is polymorphic. Its crystal structures or phases can exist as monolithic (m), tetragonal (t) or cubic (c) depending on temperature and pressure. The most stable monolithic phase is at room temperature. As the temperature rises to about 1170°C, the monolithic phase transforms into the tetragonal phase, accompanied by a volume shrinkage of approximately 4-5%. The tetragonal phase evolves into the cubic phase at about 2370°C, with only minimal additional volumetric changes (10, 11). The addition of dopants like yttrium oxide (Y_2O_3), calcium oxide (CaO) or magnesium oxide (MgO) into the ZrO_2-lattice, stabilizes the tetragonal and the cubic phases at room temperature as metastable phases (12). They can transform to the monolithic phase under the influence of crack initiation in the ceramic. This tetragonal to monolithic phase transformation is associated with 4-5 % volumetric expansion which results in compressive forces at a crack tip slowing its propagation. This unique phenomenon is termed "transformation toughening" and contributes to Zirconia's high fracture toughness compared to brittle conventional ceramics (13).

The initial generations of dental zirconia were all **y**ttrium stabilized-**t**etragonal polycrystalline **z**irconia consisting of fine grain zirconia with small amounts of Y_2O_3 as dopant. These fully crystalline 3Y-TZP ceramics (IPS e.max ZirCAD LT and MO) were composed as follows:

Table 1: Composiion of 3Y-TZP

Component	**Content**
Zirconium oxide (ZrO_2)	88.0 - 95.5 wt%
Yttrium oxide (Y_2O_3)	> 4.5 - ≤ 6.0 wt%
Hafnium oxide (HfO_2)	≤ 5.0 wt%
Aluminum oxide (Al_2O_3)	≤ 1.0 wt%
Other oxides for coloring	≤ 1.0 wt%

3Y-TZP commercially available for the fabrication of dental crowns and fixed partial dentures has been processed either by soft machining of pre-sintered blanks followed by high temperature sintering, or by hard machining of fully sintered blocks.

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2.1.1 Soft Machining.

Since its development in 2001(14), direct ceramic machining of pre-sintered 3Y-TZP has become increasingly popular and has now been offered by an increasing number of manufacturers. The die or a wax pattern is initially scanned, followed by a computer designed enlarged restoration (CAD). Finally, a pre-sintered ceramic blank is milled by computer aided machining (CAM). The restoration is then sintered at high temperature. Several variations of this process exist depending on the scanning process and compensation for the considerable sintering shrinkage of 3Y-TZP (∼25%). This approach has the advantages of rapid milling, reduced cutting forces, increased tool life, potentially better surface quality, and prevention of moisture absorption by the zirconia blanks eliminating the need for drying the milled zirconia prior to sintering (15, 16).

Typically the 3Y-TZP powder used in the fabrication of zirconia blanks contains a binder that enables cold isostatic pressing. The binder is later eliminated during the pre-sintering phase. It also contains about 2% by weight HfO2, classically difficult to separate from ZrO2. These powders have only minor variations in chemical composition. The powders consist of spray-dried agglomerates of much smaller crystals that are about 40nm in diameter. The blanks are manufactured by cold isostatic pressing. The mean pore size of the compacted powder is very small and in the order of 20–30nm with a very narrow pore size distribution (14).

Binder elimination during pre-sintering heat treatment has to be carefully controlled. If the temperature increase is too rapid, the elimination of binder and associated burn out products can lead to cracking of the blanks. The pre-sintering temperature of the blanks affects the hardness and machinability. Adequate hardness is needed for the handling of the blanks but if the hardness is too great, it might adversely affect machinability. The pre-sintering heat treatment temperature also affects the surface roughness of a machined blank. Since higher pre-sintering temperatures lead to rougher surfaces, slower heating rates are preferred. The density of each blank is carefully measured so that the appropriate compensating shrinkage occurs during final sintering. The final density of the pre-sintered blanks is approximately 40% of the theoretical density (6.08 g/cm3). The density gradient within the blanks is less than 0.3% of the theoretical density in all directions (14).

2.1.2 Hard Machining

Pre-sintered Y-TZP blocks are processed in a high pressure inert gas atmosphere at temperatures between 1400 and 1500 ◦C (17, 18). The result is a very high density exceeding 99% of the theoretical density. The blocks can then be machined using a milling system specially designed to handle the increased hardness and difficult machinability of fully sintered Y-TZP (19, 20).

2.1.3 Colour in Dentistry

Achieving natural optical properties using artificial materials is one of the main challenges in restorative dentistry. Color is undoubtedly one of the major parameters considered by patients when judging the esthetics of a restoration (21).

The Munsell Color Order System and the International Commission on Illumination System (CIE) are two principle systems used to describe color. The Munsell system is based on three color coordinates: value describes lightness, hue describes the nature of the color, and chroma describes color saturation. The CIE system is based on the coordinates L*, a*, b*. The

L* coordinate represents the brightness of an object. The a* coordinate represents the red (positive value) or green (negative value) chromacity. The b* coordinate represents the yellow (positive value) or blue (negative value) chromacity (22-24). Among these color parameters, it is generally accepted that the value (L) is the most critical for shade matching. It has been reported that a ΔL of [±2] is the clinically acceptable change threshold (25). Changes related to the a* and/or b* coordinates are better tolerated when clinically assessing color match (26).

A 50:50% perceptibility threshold refers to a situation where 50% of observers notice a difference in colour between two objects while the other 50% perceive no difference. The difference in colour that is acceptable for 50% of observers corresponds to a 50:50% acceptability threshold (AT). If 50% of observers consider a dental restoration to require colour correction while the other 50% consider the colour difference to be acceptable, the difference between those two thresholds is considered the industry tolerance limit and indicates how much perceptible difference can be tolerated while still considering a colour match to be acceptable (27).

It is widely agreed that ΔE > 1 is perceptible (22, 25, 28-49). The acceptability threshold in the literature ranges from ΔE 2.0 to 4.0. The majority of the studies have determined that the 50% acceptability threshold is ΔE= 3.7 (27, 30, 32-35, 41, 43, 44, 46, 48, 50-52). One-third of clinical studies reporting ΔE= 3.7 as a 50% acceptability threshold in the literature refer to the clinical study by Johnston and Kao(30) in 1989. The systematic review stated that recent dental literature is lacking and most of the recent clinical studies refer to studies that have been done three decades ago where the aesthetic demands have been changed.

Color formulas are designed to provide a quantitative representation of color differences between two objects. The most extensively used ΔE formula is derived from the CIE L*a*b* system, which approximates uniformed distances between color coordinates:

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

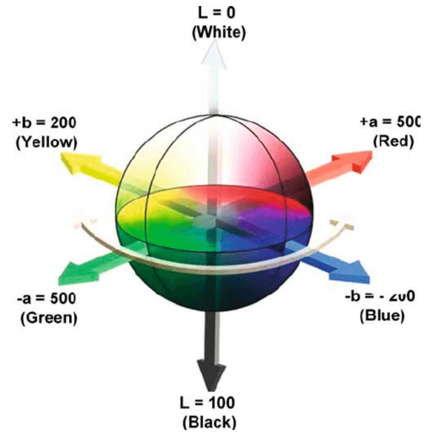

Figure 1:The cubical CIE Lab color space(53)

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2.1.4 REVIEW OF COMPUTER-AIDED DESIGN/COMPUTER- AIDED MANUFACTURING (CAD/CAM) SYSTEMS

CAD/CAM fabrication along with the development of new ceramic systems has been replacing conventional lost wax restoration fabrication in restorative dentistry. (54) Duret et al. introduced the commercial Sopha system, in the early 1970's. However, it did not gain popularity due to limitations of the computer systems of that time (54, 55).

By the mid 1980's, the chairside CEREC system was developed by Mormann and colleagues for fabrication of ceramic inlays and onlays (56).

In 1987, Swiss dentist, Dr. Werner Mörmann, and Italian electrical engineer, Marco Brandestini, introduced the first digital intraoral scanner which evolved into CEREC® by Sirona Dental Systems LLC (Charlotte, NC) which was the first commercially available CAD/CAM system for dental restorations (57, 58). Since then many different digital impression and CAD/CAM milling systems have been introduced. With the availability of systems capable of capturing 3D virtual images from the tooth preparation, chairside restorations can be made either directly via CAD/CAM systems or remotely at a dental laboratory from an accurate master model of the tooth preparation(57).

3.0 Null Hypothesis

. There is no change in color consistency of CEREC Zirconia crowns milled at 1 mm and 2 mm thicknesses using Vita Classic shades A 1, B 2 and C2

4.0 Method and Materials

Using *Sirona CEREC Omnicam*, a dental model was scanned and an individual biogeneric copy of the maxillary left central incisor was generated (figure 2). Two sample crown preparations were made using depth cut and diamond chamfer burs. One sample was prepared with a 1 mm reduction while the second sample was prepared with a 2 mm reduction. The crown preparations were scanned by means of a *Sirona CEREC Omnicam.* Preparation thicknesses were verified by superimposing the bigeneric individual copy and utilizing preparation analysis tools (Figure 3, 4, 5). Ivoclar ZirCad LT was used as the fabrication material of choice. A total of 60 CEREC MC XL blocks were used to create 10 Samples of monochromic Zirconia crowns milled at 1 mm and 2 mm thicknesses in each of Vita classic shades A 1, B 2, and C 2 (Figure 4, 5, 6). In addition, all sample blocks had the same LOT number. Crowns were sintered by means of a SpeedFire oven (Figure 7), *Sirona*. No additive coloring or glaze was applied. Each sample crown was inserted into the prepared dental models with the identical stump shade.

Figure 2: Biogeneric Individual copy of tooth #9

Figure 3: Biogeneric Copy Supperimposed with Crown Preparation

Figure 4: Verifying 1 mm Middle Thrid Crown Thickness

Figure 5: Verifying 2 mm Middle Thrid Crown Thickness

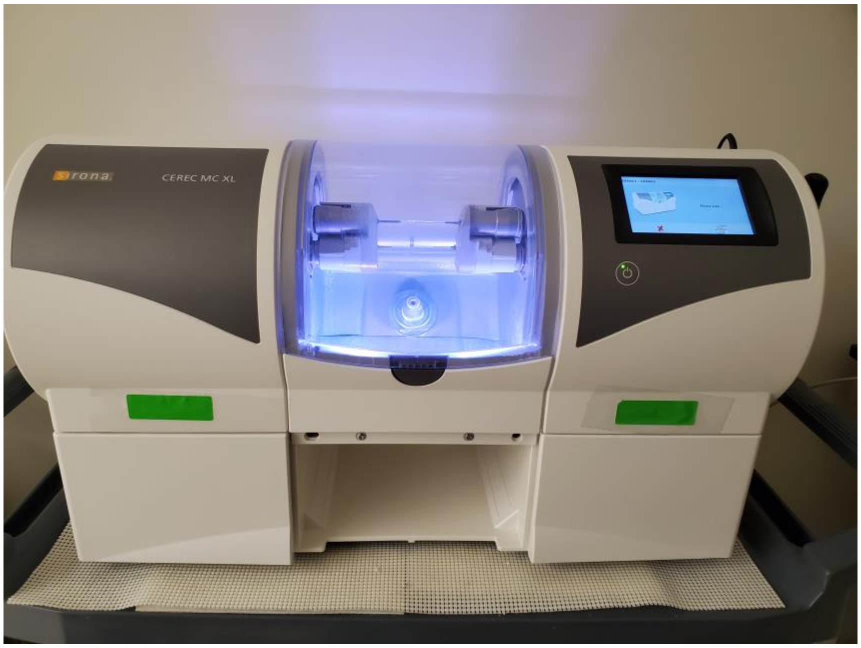

Figure 6: CEREC MC XL Milling Machine

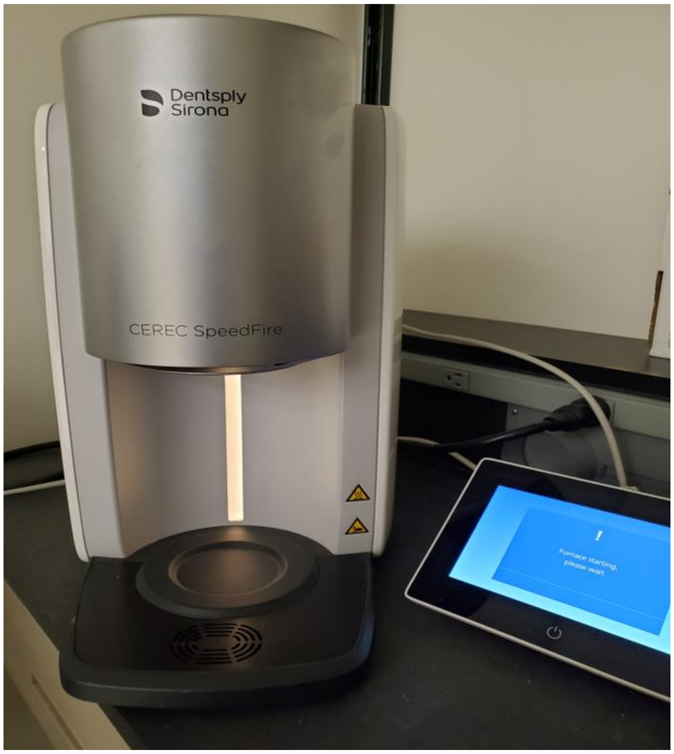

Figure 7: Crown Sintered in Sirona Speed Fire Furnace

4.1 Control and Test Groups

Based on manufacturer recommendations for Ivoclar ZirCad LT, the optimal thickness of 1 mm was chosen for the control groups for shades A 1, B 2, and C 2. The optimal thickness of 2 mm was chosen for the ZirCad crowns of the test groups for shades A 1, B 2, and C 2.

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Table 2: Control and test groups of sample

Group	A 1	B 2	C 2
Control (1 mm)	10	10	10
Test (2 mm)	10	10	10

4.2 Color Measurements

A *Canon 80D* digital camera equipped with a *Canon MR-14EXII* ring flash was used to photograph all test and control group specimens. All the photographs were exposed using the same camera settings: ISO 100, Shutter Speed 1/125, F 22. The camera was mounted on a tripod to control object to lens distance (Figure 9). A polarized filter, *Polar_eyes*, was employed to remove any flash glare as (Figure 10 and 11). Photographs were taken one minute apart to allow the ring flash to fully recharge. The photographs were developed via digital software, *Photoshop CC 2019*. The CIE L*a*b* color values were measured as shown in Figure 12.

The CIE color space of each reading was measured and recorded in terms of the 3 coordinate values (L*, a*, b*). Mean coordinate values and the standard deviations (SD) were calculated for each group by means of two-sample t-test. ΔE (color difference value) was calculated between the control group and test groups' means, according to the formula:

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

Figure 8: Polar_eyes Cross Poliralization Filter

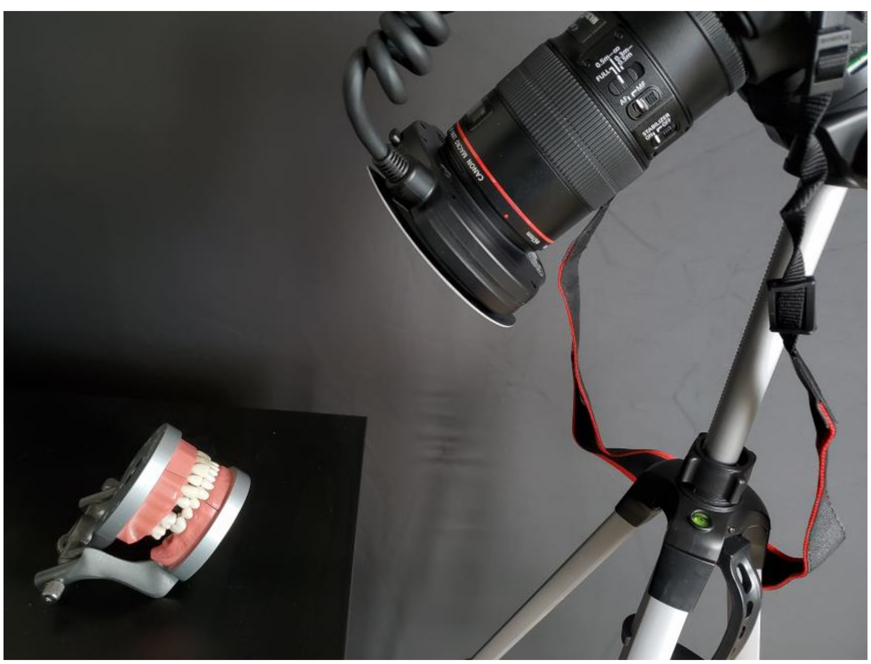

Figure 9: Camera Mounted on Tripod with a Fixed Lens-to-Object Distance

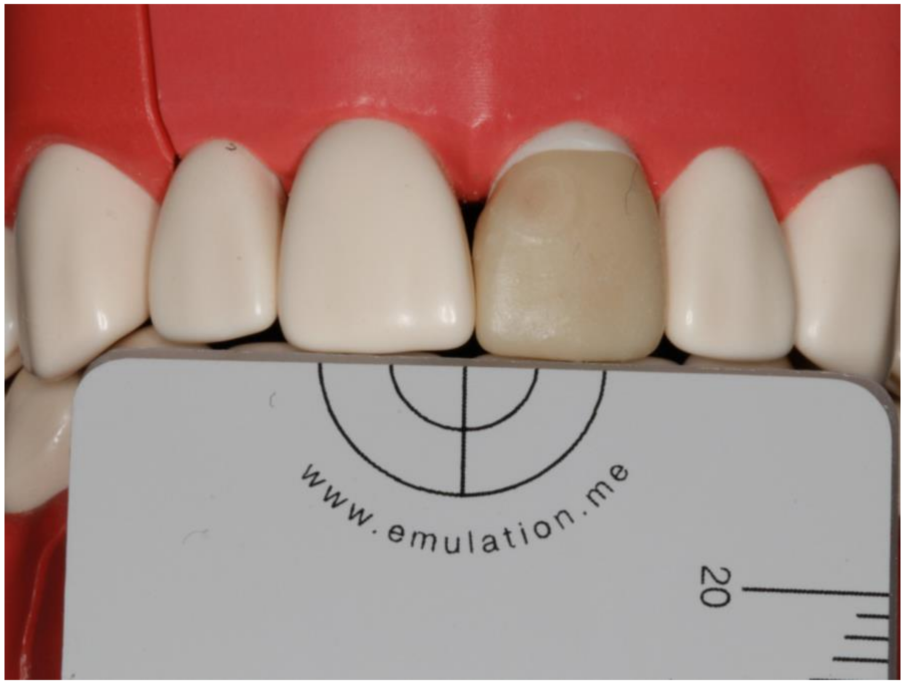

Figure 10: Photo Taken Without Poliraization Showing Light Reflection

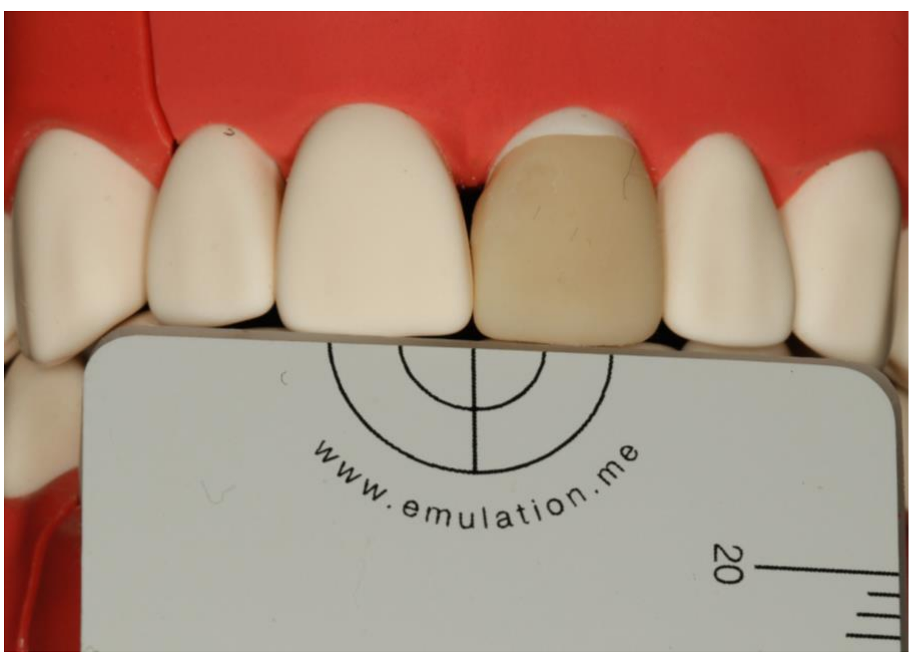

Figure 11: Photo Taken With Poliraization to Remove Glare and Light Reflection

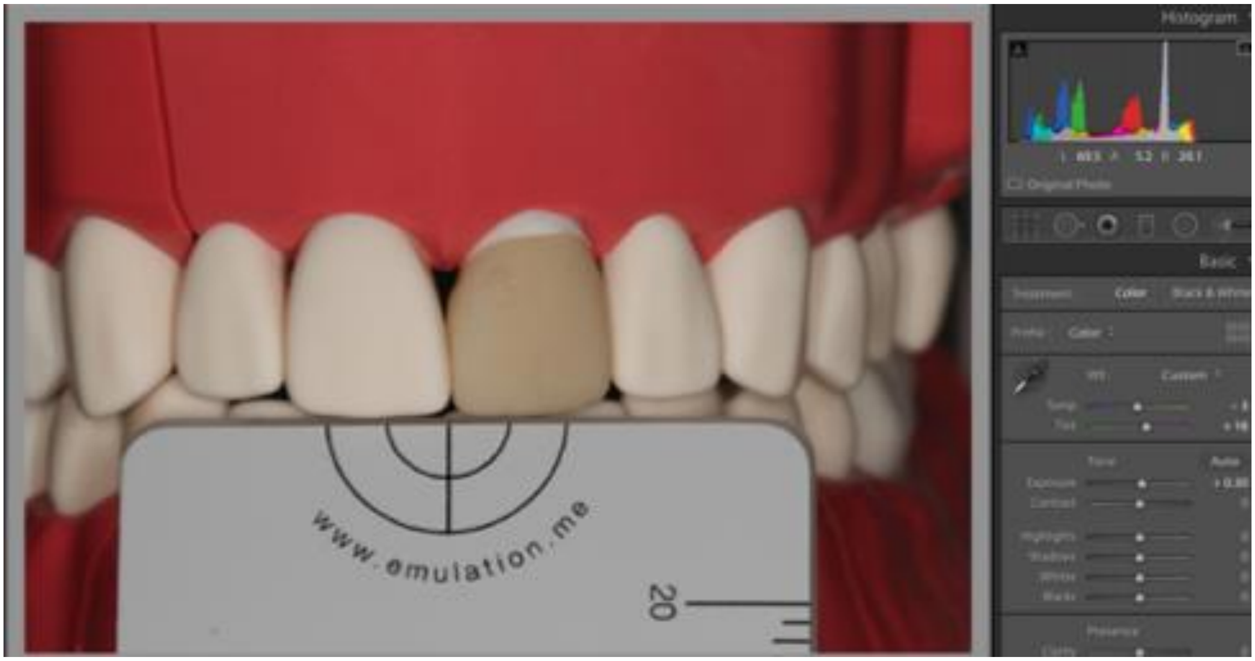

Figure 12: : CIE L*a*b* Analysis Using Adbobe Lightroom CC

5.0 Results

CIE L*a*b* data for all samples was recorded and statistically analyzed using a two-sample t-test, *STATASE v16*. ΔE mean values and standard deviations of the test and control groups are listed in (table 3). There was a statistically significant difference ($P<0.05$) in L* values when test groups (2mm) were compared with the control groups (1mm) for shades A1, B2, and C2 with $P< 0.00$. The a* values showed a statistically significant difference when the test groups were compared with control groups for shades A1 and B2 with $P< 0.00$. However, for shade C2 there was no statistically significant difference ($P= 0.6$). The b* values showed a statistically significant difference when test groups were compared with the control groups for shade C2 with $P<0.00$ while for shades A1 and B2 there was no statistically significant difference with $P= 0.44$ and 0.55 respectively. The ΔE values for all test groups were above the perceptibility threshold $(\Delta E > 1)$. ΔE for shades A1 and B2 groups were 3.64 and 3.67 respectively which is more than the clinically acceptable range $((\Delta E) < 3.3)$, while the ΔE for C2 group was 4.55 which is significantly higher than the clinically acceptable range.

Table 3: Mean CIE L*a*b* values (standard deviation) of test group with their color differences (ΔE) compared to the control group

Control and Test Groups	**L* (SD)**	**a* (SD)**	**b* (SD)**	**ΔE**
A1 (Control) 1 mm Thickness	72.86 (0.17)	2.27 (0.42)	11.97 (0.66)	
A1 (Test) 2 mm Thickness	69.32 (0.23)	3.09 (0.34)	12.21 (0.70)	3.64
B2 (Control) 1 mm Thickness	69 (0.19)	3.64 (0.47)	17.24 (1.34)	
B2 (Test) 2 mm Thickness	65.47 (0.12)	4.58 (0.70)	17.59 (1.22)	3.67
C2 (Control) 1 mm Thicknes	63.05 (0.15)	6.17 (0.88)	20.9 (0.86)	
C2 (Test) 2 mm Thickness	59.16 (0.15)	6.16 (0.59)	18.54 (0.99)	4.55

6.0 Discussion

This study evaluated the effect that different ceramic thicknesses had on the final color of monolithic zirconia crowns. The results revealed a significant difference in CIE Lab and ΔE values related to the zirconia thickness. Therefore the null hypothesis was rejected.

Different values of ΔE in terms of perceptibility and acceptability have been reported in the literature. Vichi et al.(59) divided ΔE into three ranges where ΔE less than 1 is undetectable by the human eye, ΔE values greater than 1 but less than 3.3 though detectable by a skilled operator are considered clinically acceptable, and ΔE values greater than 3.3 are observable by an untrained observer and are considered unacceptable (60-63). Accordingly, this study considerd ΔE = 3.3 as the acceptability threshold to evaluate color difference among the test samples. The increased thickness of zirconia from 1 mm to 2 mm demonstrated a color difference of $\Delta E > 3.3$ in all test groups which was detectable by untrained observers.

This study found that as the thickness of zirconia increased from 1 mm to 2 mm, L* values decreased in all test groups. The thickness of the zirconia not only affected the color, but the selected shade of test crowns. Of note in this study was the fact that shade C 2 had a more dramatic color change (ΔE = 4.55) compared to shades A 1 and B 2 (ΔE 3.64 and 3.67 respectively) when the thicknesses of the zirconia was increased. Consequently, as the value (brightness) of a selected shade decreased (from shade A 1 to C 2), increasing the thickness of a zirconia crown may exhibit an increased ΔE color change.

Tabatabaian et al (64). tested shade A-2 monolithic zirconia specimens with thicknesses of 0.7, 0.9 and 1.1 mm from 2 different manufacturers. They found that as the zirconia thickness increased the L* value decreased and the impact of the ΔE change on the final color was significant regardless of the brand of zirconia. The ideal thickness of a zirconia restoration should be 0.9 mm in order to match the targeted shade. The results of this study were similar. The zirconia crowns used in the control groups had a thickness of 1 mm. The zirconia specimens in the test groups had a thickness of 2 mm and showed a decrease in L* values along with significant changes in ΔE.

Kim et al. (65) studied the color change of 2 mm thickness zirconia specimens after being reduced 0.1 mm at a time until 1 mm thickness is reached. The study showed a noticeable color change ΔE > 3.7 even after the first 0.1 mm of reduction. They also observed that L* values decreased as the thickness of zirconia crowns increased. This can be explained by the increased absorption of light by the thicker specimens. The authors stated that using only shade A 2 was a significant limitation of their study.

Giti and Hojati (66) found that for zirconia specimens in shade A 2, a decrease in thickness from 2 to 1 mm resulted in a clinically detectable color difference (ΔE>3.7) as well as an increase in the L* values of the specimens. The authors stated that using only shade A 2 was a limitation of their study and suggested that further research was needed using different shades of zirconia specimens.

7.0 Conclusion

1. An increase in the thickness of Zirconia from 1mm to 2mm demonstrated a $\Delta E >$3.3 in all test groups which is detectable by untrained observers.
2. As the thickness if Zirconia increased from 1mm to 2 mm, L* decreased in all test groups.
3. Vita Classic shade C-2 demonstrated a more dramatic decrease in L* than shade A-1 and B-2 following the Zirconia thickness change from 1mm to 2mm.

Appendix A

Appendix Table 1: Shadde A 1 CIE L*a*b* Data

1 mm Thickness			2 mm Thickness		
L*	**a***	**b***	**L***	**a***	**b***
72.9	2.5	11.8	69.2	2.9	12
73	1.9	12.4	69.1	2.5	12.7
72.8	2.9	13	69.4	2.8	11.8
72.7	2	13.2	69.7	2.7	12.6
72.8	2.3	11.4	69.6	3.4	12
72.5	2.5	11.5	69.4	3.4	11.5
72.9	2.7	11.4	69.2	3.3	12.6
73.1	2.3	11.7	69	3.1	13.7
73	2.2	11.7	69.1	3.5	11.9
72.9	1.4	11.6	69.5	3.3	11.3

Appendix Table 2: Shade B 2 CIE L*a*b* Data

1 mm Thickness			2 mm Thickness		
L*	a*	b*	L*	a*	b*
68.8	3.6	17.8	65.5	4.8	18
69.1	4.4	16.1	65.4	5.6	15.5
68.9	3.5	19.3	65.2	4.2	19.6
69.1	3.4	16.3	65.5	3.6	18.6
69.1	3.4	19.3	65.5	5.3	17.7
68.8	4.1	16.6	65.6	4.9	18.4
68.7	3.6	16.6	65.6	4.3	16.1
69	2.7	16.6	65.6	5.3	16.7
69.2	4.1	18.3	65.4	3.7	17.3
69.3	3.6	15.5	65.4	4.1	18

Appendix Table 3: Shade C 2 CIE L*a*b* Data

1 mm Thickness			2 mm Thickness		
L*	a*	b*	L*	a*	b*
63.2	6.5	21.9	59.1	5.7	18.8
63.1	6.5	20.6	59.1	6.5	18.8
63	6.8	20.3	59.4	5.3	19
63.1	6.7	19.6	58.9	6.8	17.4
63.1	6.8	20.5	59.3	6.2	16.7
63.3	7.2	20.6	59.3	5.3	18.7
62.9	5.6	20.8	59	5.9	18.7
62.8	4.2	20.5	59.1	6.9	17.7
63.1	5.8	21.7	59.2	6.3	19.8
62.9	5.6	22.5	59.2	6.7	19.8

Bibliography

1.McLean JW. Evolution of dental ceramics in the twentieth century. *J Prosthet Dent* 2001;**85**(1):61-6.

2.Douglas RD, Przybylska M. Predicting porcelain thickness required for dental shade matches. *J Prosthet Dent* 1999;**82**(2):143-9.

3.Isgro G, Pallav P, van der Zel JM, Feilzer AJ. The influence of the veneering porcelain and different surface treatments on the biaxial flexural strength of a heat-pressed ceramic. *J Prosthet Dent* 2003;**90**(5):465-73.

4.Tinschert J, Natt G, Mautsch W, Augthun M, Spiekermann H. Fracture resistance of lithium disilicate-, alumina-, and zirconia-based three-unit fixed partial dentures: a laboratory study. *Int J Prosthodont* 2001;**14**(3):231-8.

5.Al-Amleh B, Lyons K, Swain M. Clinical trials in zirconia: a systematic review. *J Oral Rehabil* 2010;**37**(8):641-52.

6.Ha SR, Kim SH, Han JS, Yoo SH, Jeong SC, Lee JB, et al. The influence of various core designs on stress distribution in the veneered zirconia crown: a finite element analysis study. *J Adv Prosthodont* 2013;**5**(2):187-97.

7.Kim HK, Kim SH, Lee JB, Han JS, Yeo IS. Effect of polishing and glazing on the color and spectral distribution of monolithic zirconia. *J Adv Prosthodont* 2013;**5**(3):296-304.

8.Denry I, Kelly JR. State of the art of zirconia for dental applications. *Dent Mater* 2008;**24**(3):299-307.

9.Dion I, Rouais F, Baquey C, Lahaye M, Salmon R, Trut L, et al. Physico-chemistry and cytotoxicity of ceramics: part I: characterization of ceramic powders. *J Mater Sci Mater Med* 1997;**8**(5):325-32.

10.R AN, Weber KK. Biomaterials, Zirconia. StatPearls. Treasure Island (FL); 2020.

11.Chen YW, Moussi J, Drury JL, Wataha JC. Zirconia in biomedical applications. *Expert Rev Med Devices* 2016;**13**(10):945-63.

12.Kelly JR, Denry I. Stabilized zirconia as a structural ceramic: an overview. *Dent Mater* 2008;**24**(3):289-98.
13.Kosmac T, Oblak C, Jevnikar P, Funduk N, Marion L. The effect of surface grinding and sandblasting on flexural strength and reliability of Y-TZP zirconia ceramic. *Dent Mater* 1999;**15**(6):426-33.
14.Filser F, Kocher P, Weibel F, Luthy H, Scharer P, Gauckler LJ. Reliability and strength of all-ceramic dental restorations fabricated by direct ceramic machining (DCM). *Int J Comput Dent* 2001;**4**(2):89-106.
15.Sadan A, Blatz MB, Lang B. Clinical considerations for densely sintered alumina and zirconia restorations: Part 1. *Int J Periodontics Restorative Dent* 2005;**25**(3):213-9.
16.Beuer F, Schweiger J, Edelhoff D. Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. *Br Dent J* 2008;**204**(9):505-11.
17.Sundh A, Molin M, Sjogren G. Fracture resistance of yttrium oxide partially-stabilized zirconia all-ceramic bridges after veneering and mechanical fatigue testing. *Dent Mater* 2005;**21**(5):476-82.
18.Piconi C, Maccauro G, Pilloni L, Burger W, Muratori F, Richter HG. On the fracture of a zirconia ball head. *J Mater Sci Mater Med* 2006;**17**(3):289-300.
19.Blue DS, Griggs JA, Woody RD, Miller BH. Effects of bur abrasive particle size and abutment composition on preparation of ceramic implant abutments. *J Prosthet Dent* 2003;**90**(3):247-54.
20.Rekow ED, Silva NR, Coelho PG, Zhang Y, Guess P, Thompson VP. Performance of dental ceramics: challenges for improvements. *J Dent Res* 2011;**90**(8):937-52.
21.Vichi A, Ferrari M, Davidson CL. Influence of ceramic and cement thickness on the masking of various types of opaque posts. *J Prosthet Dent* 2000;**83**(4):412-7.
22.Chu SJ, Trushkowsky RD, Paravina RD. Dental color matching instruments and systems. Review of clinical and research aspects. *J Dent* 2010;**38 Suppl 2**:e2-16.
23.Falcone ME, Kelly JR, Rungruanganut P. In Vivo Color Relationships Between the Maxillary Central Incisors and Canines as a Function of Age. *Int J Prosthodont* 2016;**29**(5):496-502.
24.Niu E, Agustin M, Douglas RD. Color match of machinable lithium disilicate ceramics: Effects of cement color and thickness. *J Prosthet Dent* 2014;**111**(1):42-50.

25.Paul S, Peter A, Pietrobon N, Hammerle CH. Visual and spectrophotometric shade analysis of human teeth. *J Dent Res* 2002;**81**(8):578-82.

26.M. Melgosa MMP. Sensitivity differences in chroma, hue, and lightness from several classical threshold datasets. *Color Research & Application* 1995;**20**(4):220-25.

27.Khashayar G, Dozic A, Kleverlaan CJ, Feilzer AJ. Data comparison between two dental spectrophotometers. *Oper Dent* 2012;**37**(1):12-20.

28.Russell MD, Gulfraz M, Moss BW. In vivo measurement of colour changes in natural teeth. *J Oral Rehabil* 2000;**27**(9):786-92.

29.Kuehni RG MR. An experiment in visual scaling of small color differences. Color Research and Application. *Color Research & Application* 1979;**4**(2):83-91.

30.Johnston WM, Kao EC. Assessment of appearance match by visual observation and clinical colorimetry. *J Dent Res* 1989;**68**(5):819-22.

31.Chu SJ. Use of a reflectance spectrophotometer in evaluating shade change resulting from tooth-whitening products. *J Esthet Restor Dent* 2003;**15 Suppl 1**:S42-8.

32.Paul SJ, Peter A, Rodoni L, Pietrobon N. Conventional visual vs spectrophotometric shade taking for porcelain-fused-to-metal crowns: a clinical comparison. *Int J Periodontics Restorative Dent* 2004;**24**(3):222-31.

33.Karamouzos A, Papadopoulos MA, Kolokithas G, Athanasiou AE. Precision of in vivo spectrophotometric colour evaluation of natural teeth. *J Oral Rehabil* 2007;**34**(8):613-21.

34.Paravina RD, Johnston WM, Powers JM. New shade guide for evaluation of tooth whitening--colorimetric study. *J Esthet Restor Dent* 2007;**19**(5):276-83; discussion 83.

35.Sailer I, Holderegger C, Jung RE, Suter A, Thievent B, Pietrobon N, et al. Clinical study of the color stability of veneering ceramics for zirconia frameworks. *Int J Prosthodont* 2007;**20**(3):263-9.

36.Browning WD, Chan DC, Blalock JS, Brackett MG. A comparison of human raters and an intra-oral spectrophotometer. *Oper Dent* 2009;**34**(3):337-43.

37.Cocking C, Cevirgen E, Helling S, Oswald M, Corcodel N, Rammelsberg P, et al. Colour compatibility between teeth and dental shade guides in Quinquagenarians and Septuagenarians. *J Oral Rehabil* 2009;**36**(11):848-55.

38.Li Q, Yu H, Wang Y. Colour and surface analysis of carbamide peroxide bleaching effects on the dental restorative materials in situ. *J Dent* 2009;**37**(5):348-56.

39.Ontiveros JC, Paravina RD. Color change of vital teeth exposed to bleaching performed with and without supplementary light. *J Dent* 2009;**37**(11):840-7.
40.da Costa JB, McPharlin R, Paravina RD, Ferracane JL. Comparison of at-home and in-office tooth whitening using a novel shade guide. *Oper Dent* 2010;**35**(4):381-8.
41.Karamouzos A, Athanasiou AE, Papadopoulos MA, Kolokithas G. Tooth-color assessment after orthodontic treatment: a prospective clinical trial. *Am J Orthod Dentofacial Orthop* 2010;**138**(5):537 e1-8; discussion 37-9.
42.Turkun M, Celik EU, Aladag A, Gokay N. One-year clinical evaluation of the efficacy of a new daytime at-home bleaching technique. *J Esthet Restor Dent* 2010;**22**(2):139-46.
43.Haddad HJ, Salameh Z, Sadig W, Aboushelib M, Jakstat HA. Allocation of color space for different age groups using three-dimensional shade guide systems. *Eur J Esthet Dent* 2011;**6**(1):94-102.
44.Sluzker A, Knosel M, Athanasiou AE. Sensitivity of digital dental photo CIE L*a*b* analysis compared to spectrophotometer clinical assessments over 6 months. *Am J Dent* 2011;**24**(5):300-4.
45.Lehmann KM, Devigus A, Igiel C, Wentaschek S, Azar MS, Scheller H. Repeatability of color-measuring devices. *Eur J Esthet Dent* 2011;**6**(4):428-35.
46.Alsaleh S, Labban M, AlHariri M, Tashkandi E. Evaluation of self shade matching ability of dental students using visual and instrumental means. *J Dent* 2012;**40 Suppl 1**:e82-7.
47.Forner L, Amengual J, Liena C, Riutord P. Therapeutic effectiveness of a new enzymatic bleaching dentifrice. *Eur J Esthet Dent* 2012;**7**(1):62-70.
48.Lopes Filho H, Maia LE, Araujo MV, Ruellas AC. Influence of optical properties of esthetic brackets (color, translucence, and fluorescence) on visual perception. *Am J Orthod Dentofacial Orthop* 2012;**141**(4):460-7.
49.Sarafianou A, Kamposiora P, Papavasiliou G, Goula H. Matching repeatability and interdevice agreement of 2 intraoral spectrophotometers. *J Prosthet Dent* 2012;**107**(3):178-85.
50.Hassel AJ, Grossmann AC, Schmitter M, Balke Z, Buzello AM. Interexaminer reliability in clinical measurement of L*C*h* values of anterior teeth using a spectrophotometer. *Int J Prosthodont* 2007;**20**(1):79-84.

51.Hassel AJ, Doz P, Nitschke I, Rammelsberg P. Comparing L*a*b* color coordinates for natural teeth shades and corresponding shade tabs using a spectrophotometer. *Int J Prosthodont* 2009;**22**(1):72-4.
52.Ongul D, Sermet B, Balkaya MC. Visual and instrumental evaluation of color match ability of 2 shade guides on a ceramic system. *J Prosthet Dent* 2012;**108**(1):9-14.
53.Singh B, Parwate DV, Shukla SK. Radiosterilization of fluoroquinolones and cephalosporins: assessment of radiation damage on antibiotics by changes in optical property and colorimetric parameters. *AAPS PharmSciTech* 2009;**10**(1):34-43.
54.Miyazaki T, Hotta Y. CAD/CAM systems available for the fabrication of crown and bridge restorations. *Aust Dent J* 2011;**56 Suppl 1**:97-106.
55.Preston JD, Duret F. CAD/CAM in dentistry. *Oral Health* 1997;**87**(3):17-20, 23-4, 26-7.
56.Mormann WH, Brandestini M, Lutz F, Barbakow F. Chairside computer-aided direct ceramic inlays. *Quintessence Int* 1989;**20**(5):329-39.
57.Yuzbasioglu E, Kurt H, Turunc R, Bilir H. Comparison of digital and conventional impression techniques: evaluation of patients' perception, treatment comfort, effectiveness and clinical outcomes. *BMC Oral Health* 2014;**14**:10.
58.Ahn JS, Park A, Kim JW, Lee BH, Eom JB. Development of Three-Dimensional Dental Scanning Apparatus Using Structured Illumination. *Sensors (Basel)* 2017;**17**(7).
59.Vichi A, Ferrari M, Davidson CL. Color and opacity variations in three different resin-based composite products after water aging. *Dent Mater* 2004;**20**(6):530-4.
60.Li Q, Yu H, Wang YN. In vivo spectroradiometric evaluation of colour matching errors among five shade guides. *J Oral Rehabil* 2009;**36**(1):65-70.
61.Inokoshi S, Burrow MF, Kataumi M, Yamada T, Takatsu T. Opacity and color changes of tooth-colored restorative materials. *Oper Dent* 1996;**21**(2):73-80.
62.Kim HS, Um CM. Color differences between resin composites and shade guides. *Quintessence Int* 1996;**27**(8):559-67.
63.Um CM, Ruyter IE. Staining of resin-based veneering materials with coffee and tea. *Quintessence Int* 1991;**22**(5):377-86.
64.Tabatabaian F, Motamedi E, Sahabi M, Torabzadeh H, Namdari M. Effect of thickness of monolithic zirconia ceramic on final color. *J Prosthet Dent* 2018;**120**(2):257-62.

65.Kim HK, Kim SH, Lee JB, Han JS, Yeo IS, Ha SR. Effect of the amount of thickness reduction on color and translucency of dental monolithic zirconia ceramics. *J Adv Prosthodont* 2016;**8**(1):37-42.
66.Giti R, Hojati SA. Effect of Varying Thickness and Number of Coloring Liquid Applications on the Color of Anatomic Contour Monolithic Zirconia Ceramics. *J Dent (Shiraz)* 2018;**19**(4):311-19.