The clinical study of wear between antagonist enamel and polished/annealed monolithic zirconia crown on dental implant after 6-month delivery

Miss Supatsorn Benjaniratisai

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science in Prosthodontics
Department of Prosthodontics
FACULTY OF DENTISTRY
Chulalongkorn University
Academic Year 2019

การศึกษาทางคลินิกของการสึกระหว่างเคลือบฟันคู่สบกับครอบฟันเซอร์โคเนียชนิดโมโนลิธิคบนรากเทียมที่ผ่านการขัดและผ่านการอบเหนียว ภายหลังการใช้งานในผู้ป่วย 6 เดือน

น.ส.สุภัสสร เบญจนิรัติศัย

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
สาขาวิชาทันตกรรมประดิษฐ์ ภาควิชาทันตกรรมประดิษฐ์
คณะทันตแพทยศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2562

Thesis Title	The clinical study of wear between antagonist enamel and polished/annealed monolithic zirconia crown on dental implant after 6-month delivery
By	Miss Supatsorn Benjaniratisai
Field of Study	Prosthodontics
Thesis Advisor	Associate Professor VIRITPON SRIMANEEPONG, D.D.S., M.Sc., Ph.D.

Accepted by the FACULTY OF DENTISTRY, Chulalongkorn University in Partial Fulfillment of the Requirement for the Master of Science

.... Dean of the FACULTY OF DENTISTRY
(Assistant Professor SUCHIT POOLTHONG, D.D.S., M.Sc., Ph.D.)

THESIS COMMITTEE

.... Chairman
(Assistant Professor PRAROM SALIMEE, D.D.S., M.Sc., Ph.D.)

.... Thesis Advisor
(Associate Professor VIRITPON SRIMANEEPONG, D.D.S., M.Sc., Ph.D.)

.... Examiner
(Assistant Professor JAIJAM SUWANWELA, D.D.S., Ph.D.)

.... External Examiner
(Naruporn Monmaturapoj, Ph.D.)

สุภัสสร เบญจนิรัติศัย : การศึกษาทางคลินิกของการสึกระหว่างเคลือบฟันคู่สบกับครอบฟันเซอร์โคเนียชนิดโมโนลิธิคบนรากเทียมที่ผ่านการขัดและผ่านการอบเหนียว ภายหลังการใช้งานในผู้ป่วย 6 เดือน . (The clinical study of wear between antagonist enamel and polished/annealed monolithic zirconia crown on dental implant after 6-month delivery) อ.ที่ปรึกษาหลัก : รศ.ทพ. ดร.วิริทธิ์พล ศรีมณีพงศ์

ศึกษาการสึกของฟันธรรมชาติที่สบกับครอบฟันเซอร์โคเนียชนิดโมโนลิธิคบนรากเทียม เมื่อผ่านการขัดและผ่านการอบเหนียว ภายหลังการใช้งานในผู้ป่วยเป็นระยะเวลา 6 เดือน ผู้ป่วย 7 รายที่เข้ารับการรักษาบูรณะด้วยครอบฟันบนรากฟันเทียมถูกเลือกมาอย่างสุ่มเพื่อรับการบูรณะด้วยครอบฟันเซอร์โคเนียชนิดโมโนลิธิค(VITA YZ HT^{White}, VITA Zahnfabrik, Germany)ครอบฟันที่จะบูรณะทั้งหมด 10ซี่จะถูกแบ่งเป็น 2กลุ่มเท่าๆกันตามการปรับสภาพพื้นผิวก่อนใส่ให้ผู้ป่วย คือ กลุ่มที่ขัด (Po)และ กลุ่มที่ขัดแล้วผ่านการอบเหนียว (An)โดยในการศึกษานี้จะศึกษาฟันธรรมชาติคู่สบทั้งในฟันกรามและ ฟันกรามน้อย กลุ่มควบคุมจะเก็บข้อมูลจากฟันธรรมชาติในโค้งขากรรไกรฝั่งตรงข้ามซึ่งคู่สบเป็นฟันธรรมชาติ (CPo, CAn) เมื่อนำครอบฟันใส่ให้ผู้ป่วยจะใช้เครื่องสแกนภายในช่องปากในการเก็บข้อมูลฟันธรรมชาติคู่สบเพื่อเป็นข้อมูลพื้นฐาน ภายหลังการใช้งานในผู้ป่วยเป็นระยะเวลา 6 เดือน จะนัดหมายผู้ป่วยกลับมาติดตามผลการรักษาและเก็บข้อมูลอีกครั้ง นำข้อมูลที่ได้มาเปรียบเทียบปริมาณของฟันที่สึกโดยอาศัยโปรแกรมช่วยวิเคราะห์ (Dental System 2018, 3Shape, Denmark) ค่าเฉลี่ยของปริมาณของฟันที่สึกในกลุ่มPo,กลุ่มAn, กลุ่มCPoและ กลุ่มCAnมีค่าเท่ากับ28.08, 29.86, 31.76, 35.18 mตามลำดับ เมื่อนำไปวิเคราะห์ทางสถิติพบว่าปริมาณการสึกของฟันธรรมชาติคู่สบที่สบกับครอบฟันเซอร์โคเนียชนิดโมโนลิธิคบนรากเทียม เมื่อผ่านการขัดและผ่านการอบเหนียวน้อยกว่ากลุ่มควบคุมอย่างมีนัยสำคัญทางสถิติ ($p<0.05$) สรุปได้ว่าครอบฟันเซอร์โคเนียชนิดโมโนลิธิคบนรากเทียม เมื่อผ่านการขัดและผ่านการอบเหนียวทำให้ฟันธรรมชาติคู่สบสึกน้อยกว่าการสึกของฟันธรรมชาติที่สบกัน

สาขาวิชา ทันตกรรมประดิษฐ์	ลายมือชื่อนิสิต ....
ปีการศึกษา 2562	ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

6075840932 : MAJOR PROSTHODONTICS

KEYWORD: Antagonist wear, CAD/CAM, Dental implant, Intraoral scanner, Monolithic zirconia

Supatsorn Benjaniratisai : The clinical study of wear between antagonist enamel and polished/annealed monolithic zirconia crown on dental implant after 6-month delivery. Advisor: Assoc. Prof. VIRITPON SRIMANEEPONG, D.D.S., M.Sc., Ph.D.

This study aimed to examine the opposing natural tooth wear between polished and annealed monolithic zirconia crownon the dental implantafter 6-month delivery. Seven patients who needed the dental implant treatment were randomized to receive monolithic zirconia crowns (VITA YZ HT^{White}, VITA Zahnfabrik, Germany). Total 10 zirconia crowns in 7 patients were included in this study. The samples of zirconia crown were categorized into two groups based on occlusal surface modifications of the zirconia crowns before delivery, including: Polished (Po) and Annealed (An). Each group contained 5 samples of zirconia crowns limited to either molar and premolar restorations. Control teeth were chosen from the opposite quadrant in the same dental arch. After delivery, Full-arch were scanned for baseline data and rescan after 6 months of delivery. The wear is quantified as the loss in height. The value was determined by subtracting two scanned surface images using analysis software (Dental System 2018, 3Shape, Denmark). The mean amount of tooth structure loss for polished, annealed, and the controls (CPo and CAn) were 28.08, 29.86, 31.76, 35.18 m, respectively. Wilcoxon Signed Rank Test was used for statistical analysis. The results suggested the amount loss of natural tooth structure opposed to either the polished or annealed groups were significantly decreased when compared to the control teeth in each group ($p<0.05$). In conclusion, both the polished and annealed monolithic zirconia crown on dental implant can cause the antagonist wear of enamel less than the wear of natural dentition against natural dentition.

Field of Study: Prosthodontics Student's Signature ....

Academic Year: 2019 Advisor's Signature ....

ACKNOWLEDGEMENTS

I would like to express my special thanks of gratitude to my advisors Asst. Prof. Viritpon Srimaneepong, Dr. Kamolporn Wattanasirmkit and Dr. Pimrumpai Rochanakit Sindhavajiva for giving me constant support and invaluable advices. I would also like to thank Graduate Prosthodontic Clinic, Faculty of Dentistry, Chulalongkorn University that gave me a golden opportunity to do this wonderful clinical research on the topic "The comparison of opposing natural tooth wear between polished and annealed monolithic zirconia crown on dental implant after 6-month delivery".

Secondly I would also like to thank my parents and friends who helped me a lot in finishing this research within the limited time.

Supatsorn Benjaniratisai

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Chapter I Introduction

Background

Zirconia or zirconium dioxide (ZrO_2) ceramic has gained its popularity in restorative dentistry because it can provide both esthetics and strength. Zirconia is the type of ceramic that does not contain glass. The zirconia atoms are packed into a regular crystalline arrangement granting high mechanical strength.(1) Due to opacity of zirconia, veneering ceramic was required for mimicking natural tooth. The chipping of veneering ceramic has become a major clinical problem. Therefore, monolithic zirconia was introduced to avoid this problem.(2) Although monolithic zirconia demonstrates superior mechanical properties and comparable esthetics compared to conventional ceramic, its hardness can cause wear of opposing restoration and/or tooth.(3) The wear behavior of a material depends upon the type, microstructure, surface roughness, strength of the restorative material and chewing force.(4, 5) The hardness and roughness of the material greatly exceeds that of natural dentition which may cause the wear of opposing restoration and/or natural tooth structure. Excessive wear can be caused by several factors such as the patients' parafunctional habit or the mismatch between hardness of the restorative material and the natural tooth structure. Excessive wear may lead to supra eruption, traumatic occlusion, loss of vertical dimension, periodontal breakdown and temporomandibular joint dysfunction.(6) According to the previous clinical studies, the amount of wear of natural enamel against zirconia crown is controversial. Many authors believed that well-polished restoration would result in lower wear to natural tooth structure(7, 8) while others disagree.(3)

Although there were several studies focused on the wear potential of the zirconia restoration to the natural dentition, none of the studies has yet investigated the amount of wear of natural tooth structure opposing zirconia crown on dental implant. The crowns on dental implants can be easily retrieved or replaced, therefore, the restorations can be prepared in ways that cannot be performed in routine clinical settings such as annealing the zirconia crown after the restorations have been adjusted intraorally. The purpose of this study was to investigate the wear behavior of an antagonist tooth opposing zirconia crown on dental implant and to test the hypothesis that there is no significant difference in the change of enamel loss when the occluding surface is polished or annealed monolithic zirconia crown on the dental implant after 6-month delivery.

Research objective

To compare the amount of wear caused by enamel-enamel and polished/annealed monolithic zirconia crown on dental implant-enamel after 6-month delivery.

Research question

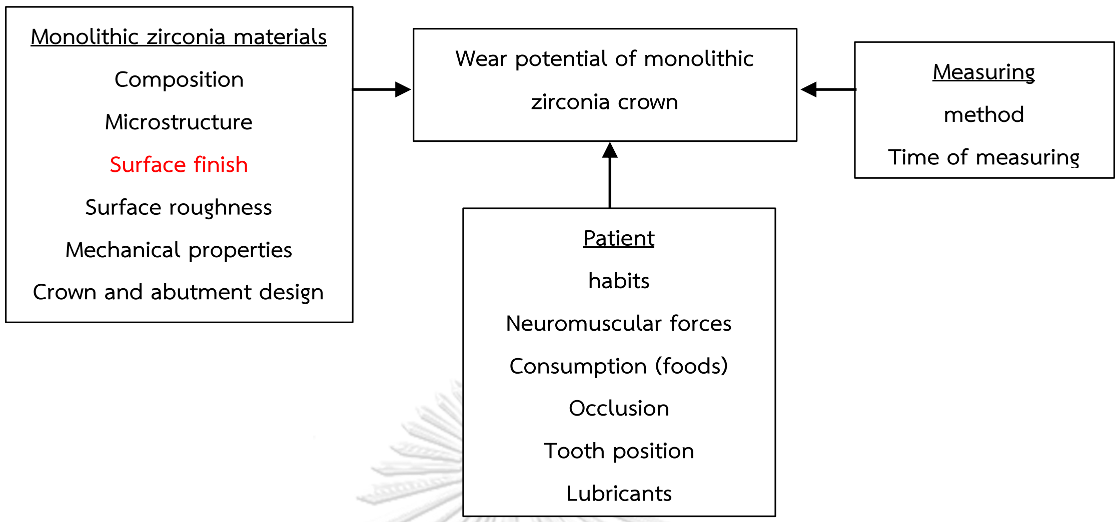
Is there a difference between the amount of wear caused by enamel-enamel and polished/annealed monolithic zirconia crown on dental implant-enamel after 6-month delivery?

Hypothesis

H_0: There is no significant difference in the amount of wear caused by enamel-enamel and polished/annealed monolithic zirconia crown on dental implant-enamel after 6-month delivery.

H_a: There is a significant difference in the amount of wear caused by enamel-enamel and polished/annealed monolithic zirconia crown on dental implant-enamel after 6-month delivery.

Conceptual framework



Research design

The selected opposing tooth of monolithic zirconia crowns on implant would be examined the wear using intraoral scanner after delivery to the patient for 6 months to evaluate the amount of wear.

Expected outcome

The outcomes of this research could provide clinical explanations and better understanding the effects of polishing and re-firing on the surface topography of zirconia restorations to wear potential after being exposed to the oral environment for a period of 6 months.

Research limitations

The sample size is limited by the variation in the patients' intraoral conditions. The results from both the polished and annealed group cannot be compared to one another since the restorations were not placed in the same subject. However, this research may serve as a guide for better understanding of the wear potential in vivo.

Chapter II Literature review

In the past, metal-ceramic restorations had been the first choice for esthetic, durable, and fitted prostheses. Although metal ceramic restorations had been popular from their predictable performance and reasonable esthetics, it had not answered the demand for improved esthetics and biocompatibility of materials. Because they have the bluish appearance problem of the surrounding tissue. All-ceramic reconstructions have been introduced and have gained popularity, together with a new processing technology i.e. computer-assisted fabrication systems [dental computer-assisted design/ computer-assisted manufacturing (CAD/CAM)] that has come to help the dentist to save the time. Because the optical appearance of ceramic resembles the natural tooth substance. It is suitable for the crown in the anterior regions of the jaws because of its low mechanical stability and brittleness.[6, 9]

Nowadays, high-strength ceramics have been developed for dental reconstructions. Zirconia is the most high-strength ceramics not only flexural strength but also fracture toughness. It has been used in the molar region.[9, 10]

Zirconia restorations

Dental ceramics are classified into three categories by determining the main composition. First is predominantly glass which has a high glassy content. It is the best in mimicking the natural tooth appearance. Second is particle-filled glass. There are filler particles added to the glass matrix for improving the mechanical properties. Last is polycrystalline. This type has no glass. Zirconia is one of the polycrystalline ceramics which have been developed for dental reconstructions.[11] Zirconia has three Crystallographic phases. According to the temperature change, there are three crystallographic phases of zirconia that can be found. It is monoclinic at room temperature - 1,170°c. It is tetragonal at 1,170 – 2,370°c and it is cubic at 2,370°c – melting point. The transformation of crystallographic phases causes the volumetric change. The changes are increased about 2.31% and 4.5% on cooling from C to T and T to M respectively (Figure 1).[12-14]

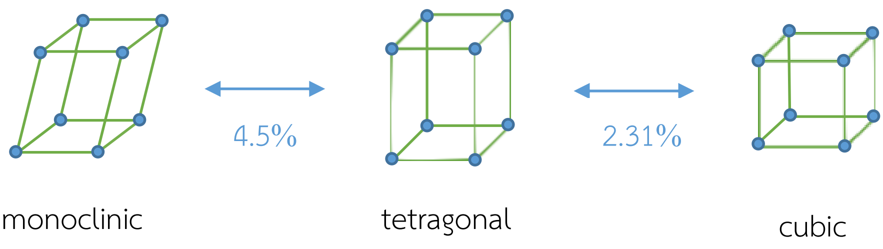


Figure 1 The transformation of crystallographic phases causes the volumetric change.

The types of zirconia ceramics can divide into four groups. The first is zirconia toughened ceramics (ZT). This type of zirconia is combined with Alumina matrix in order that its mechanical properties are improved.[15] In-Ceram Zirconia which 33vol% of 12mol% ceria is added to In-Ceram Alumina as a stabilizer is the sample of zirconia toughened ceramics.[16] In-Ceram Zirconia can be produced either by slip casting or soft machining. Shrinkage is limited but porosity is increased when the slip casting technique is used.[12] There is more amount of porosity when compared to 3Y-TZP dental ceramics.[17] This explains why 3Y-TZP has higher mechanical properties compared to In-Ceram Zirconia. In contrast, Ce-TZP ceramics show more resistance to low-temperature degradation and thermal stability.[18] In-Ceram Zirconia from soft machining has better mechanical property than In-Ceram Zirconia from slip casting technique except for flexural strength and fracture toughness.[19] Microstructure characterized of In-Ceram Zirconia is large alumina grain with small zirconia grain. The crack pattern starts as a macrocrack. Then, the transformation from T to M occurs and causes microcrack in the alumina matrix. This increases fracture energy and causes increased toughness of In-Ceram Zirconia.[20]

The second is partially stabilized zirconia (PSZ). Tetragonal precipitates within a cubic stabilized zirconia matrix is the microstructure of partially stabilized zirconia. 8 – 10mol% MgO is added for stabilization. Transformable t-phase is precipitated after it had been sintered and cooled at a strictly controlled temperature. When T to M transformation occurs, fracture toughness is controlled by the volume fraction.[21] It causes less stability and lower mechanical properties of a material.[22]

The third is tetragonal zirconia polycrystal (TZP). To stabilize zirconia, 3mol% yttria is used (3Y-TZP).[23] This improves the mechanical property of zirconia such as fracture strength (9 – 10 MPa/m^2) and flexural strength (900 - 1,200 MPa).[24, 25] The mechanical properties depend on its grain size which can be controlled by sintering temperature and time. The appropriate grain size is 0.2 μm. If the grain size is larger than 0.2 μm, it will be less stable and have a spontaneous transformation from T to M. If the grain size is smaller than 0.2 μm, the transformation will not occur. Thus, fracture toughness is reduced. The restorations can be produced either by soft machining or hard machining.[13, 26] Soft machining gives monoclinic-free surfaces of the restorations unless they are adjusted by grinding or sandblasting. On the other hand, hard machining causes a number of monoclinic surfaces of the restorations that lead to surface microcracks, high sensitivity to low-temperature degradation and low reliability.[12, 27]

The last is zirconia-containing lithium silicate (ZLS). 10wt% zirconium oxide added to lithium silicate glass compositions acts as a nucleating agent. The microstructure has two stages. The first stage that is easy to a machine is the pre-crystallized stage. It contains only lithium metasilicate crystals. The other stage which has a dual microstructure (very fine lithium metasilicate and lithium disilicate) is the final crystalized stage. The final crystalized stage is the difference between Zirconia-containing lithium silicate (ZLS) and lithium disilicate glass ceramics. Lithium metasilicate is found only in Zirconia-containing lithium silicate (ZLS). This development of ZLS gains not only superior optical properties but also better mechanical properties.[28] Compared with leucite-reinforced glass ceramics, the mechanical properties of ZLS are three times higher.[29] Therefore, these materials are fabricated as monolithic restorations.[30]

Current status of zirconia restorations

To solve the chipping and delaminating of veneering porcelains, full-contour zirconia restorations have been developed. Not only strength but also the optical property is better. Compared with conventional Y-TZP, the translucency of monolithic zirconia has been improved. There are several ways to achieve better translucency of zirconia restorations such as modifying the microstructure of the ceramic. The modifications include increasing in the density, increasing in cubic zirconia, decreasing in alumina content, decreasing in grain size and decreasing in structural defects and the number of impurities.(31, 32) In the past, large grains were preferred. The Larger grains size, the smaller number of grain boundaries. That means reducing of light scattering. In contrast, large grains of Y-TZP result in the weakness of its mechanical properties and the stability of the tetragonal phase. For Y-TZP, translucency gains from significant decreasing the grain size. When grain size is decreased until reaching a critical value, the birefringence phenomenon is reduced. This phenomenon occurs when Y-TZP has a large amount of tetragonal crystal phase (>90%).(32, 33) Tetragonal crystal phase has anisotropic behavior (different refractive indexes) that causes significant light scattering. Another way to increase the translucency is using a cubic zirconia. Since it has an optical isotropic behavior.(34) However, zirconia has a high translucency. Its esthetic is limited by the color which is a whitish shade.(35) There are two methods to coloring zirconia restorations. First is dip coating or immersion at the pre-sintered state. This method gives a non-homogeneous final shade because the penetration of pigments is a certain depth.(36) The other method is a pre-colored zirconia pre-sintered block that gives more homogeneous shade.(35) Besides the mechanical and optical properties, there are attractive topics involving the longevity of monolithic zirconia restorations. The topics are the wear of the antagonists and the marginal adaptation. There are many studies report that the antagonist wear is a physiological wear. Moreover, polished surfaces of zirconia restorations result in lesser wear of enamel than glazed surfaces.(5, 8, 37-46) The evolution of CAD-CAM with advanced five-axis milling systems improves the marginal adaptation of the monolithic zirconia. It shows an acceptable marginal discrepancy.[47]

Dental CAD/CAM as a new processing technology

In the past, a slip-casting technique was an only method to make the polycrystalline ceramics. The restorations from this technique had many defects and cracks in the microstructure.[48] Presently, CAD-CAM systems have been used in dentistry. They can produce restorations with greater reliability and better adaptation.[49, 50] There are two types of techniques for producing the restorations. The first technique is grinding of pre-fabricated blocks**.** This technique has a significant concern about the waste of materials. It causes approximately 90% of prefabricated blocks as waste. They are not reusable. According to the type of pre-fabricated blocks, this technique can divide into two methods. Two methods are soft machining and hard machining. Pre-sintered blanks are used in soft machining. Machining time of pre-sintered blanks is shorter when it is compared with hard machining. After machining, Microcracks and surface defects have occurred but they can be cured by the subsequent sintering process.[51] Because of the sintering process, it results in shrinkage of the restorations. These dimensional changes will affect the fitting of restorations.[52] In Hard machining, fully sintered blanks are used. Precise shapes and contours of restorations gain from machining of fully sintered blanks. This technique does not require additional heat treatment so the manufactural time is reduced. Since it does not have subsequent sintering procedure, the microcracks and surface defects of restorations have remained. Because of the high strength of polycrystalline ceramics, the machining tools are worn. Also, much more time is consumed in the machining process.[53] Another technique is additive manufacturing technology or addition CAD-CAM systems or solid free-form fabrication. This system is a novel technology that defeats the problem of material waste. Recently, there are three outstanding methods which are selective laser sintering or melting, direct 3D printing and stereolithography. First is selective laser sintering or melting. This technique is known as a manufacturer of metal alloys. It is still in development for producing polycrystalline ceramics. When the process starts, a thin layer of dispersed powder in the build chamber is preheated below the melting point. Then, the laser scans a cross-section of the 3D model and heats the powder to the melting point in order to fuse the particles together. The laser then scans the next cross-section.[54] This process is repeated for each layer until all parts are completed. They are left to cool down gradually. Then the excess powder is cleaned. This excess powder is able to re-use. Although unfused powder is degraded by the high temperature, it can be refreshed with new materials. Thus, this technique is one of the least wasteful manufacturing methods. Second is direct 3D printing. This technique is the direct printing of a ceramic suspension. Its procedure is similar to a traditional inkjet printer. It can create dense green bodies with high resolution and produce complicated shapes. These dense green bodies are ready for sintering.[55, 56] The third is stereolithography. This developed technique can produce more complex ceramic pieces. Stereolithography and 3D printing are alike. But the suspension that is used in this technique consists of ceramic particles and resin components (acrylates or epoxy monomers).[57] To shape the solid object, the resin part is polymerized during printing. Then, this resin part is removed in the sintering process.

Environment-induced changes of zirconia ceramics

There are two unique features that discriminate zirconia from other ceramics. These features can occur because the crystallographic phase of TZP can change at the room temperature. These are low-temperature degradation (LTD) and transformation toughening.

<u>Effect of moisture and low temperature to zirconia</u>

Kobayashi et al. (1981) described the process of low-temperature degradation (LTD) or hydrothermal degradation. Slow tetragonal to monoclinic transformation occurs at low temperature (150-400°c) which causes stress to the surrounding grains and result in crack formation. The presence of water speeds up the surface degradation by penetrating into the cracks. When the transformation progresses microcracking, grain pullout and surface roughening occur.[10, 58]

There are three factors influencing Low temperature degradation.[59] First is grain size. Critical grain size for tetragonal phase retention is depended on Y_2O_3 content. The more Y_2O_3 content, the larger critical grain size.[60] If grain size exceeds the critical value, the monoclinic phase increases. On the other hand, the grain size that is smaller than the critical grain size causes no tetragonal-monoclinic transformation to occur. Winnubst and Burggraaf reported that 3.5mol% Y-TZP with grain size 0.1 μm was resistant to phase transformation.[61] For 3Y-TZP, Tsukuma et al. reported that the critical grain size was 0.2 μm. At the surface, there are yttrium more than the interior grain. Thus, smaller grain size helps uniform yttrium distribution occurred. The stress distribution of smaller grain size decreases more rapidly so it is more stable.[62] Not only grain size but also grain-shape affects the stress levels. Spherical grains show a homogeneous stress level. In contrast, faceted grains show stress at the edge. Round-edged grains have lower stress than sharp-edged grains. Mecartney reported that glassy phase surrounding the grains reduced the residual stress. It coated the grains in order to protect the grain-boundaries from the water. The grain size is controlled by using the ultra-fine powder and lowering the sintering temperature.[63]

Second is stabilizer content**.** When Y_2O_3 level increases, the resistance to tetragonal-monoclinic phase transformation of Y-TZP ceramics is increased. The c-ZrO_2 level also increases. Because of the stability of c-ZrO_2 (do not change in content and lattice parameter), phase transformation does not occur in this phase.[64, 65] The transformation rate is depended on the concentration of t- ZrO_2 on the surface.[66] The t- ZrO_2 on the surface that is a transformable fraction of the tetragonal phase. c-ZrO_2 or t'-ZrO_2 is a non-transformable fraction of the tetragonal phase.[67] Schmauder and Schubert et al. reported that stress from thermal expansion was Y_2O_3 dependent. The free energy could change by the Y_2O_3 content in two ways. Firstly, it had less stress with higher yttria content when it was cooled. Lastly, the stress increased with lower yttria content. Wang and Stevens reported that chemically homogeneous TZP led to few nucleations and less opportunity for transformation initiation. The chemically homogeneous TZP were narrow grain size and narrow yttria distribution which came from low-temperature sintering and using a homogeneous powder respectively.[62, 68, 69]

Third is composition**.** The impurity of base materials i.g. SiO_2 and Al_2O_3 improve the aging resistance.[63] Masaki et al. reported that high purity powders inhibited transformation. The impurities that did not form solid solutions with ZrO_2 caused thermal stress and strain which were transformation initiators.[70]

Low-temperature degradation (LTD) can inhibit by increasing Chemical free energy, increasing Strain-free energy, increasing Surface free energy, Coating surface, Surface engineering, controlling non-transformable tetragonal zirconia, controlling density and controlling lattice spacing.

Increasing the yttria content also increases chemical free energy which improves the stability of Y-TZP. The mechanical properties of Y-TZP are reduced by over-stabilization of t-ZrO_2 phase. Alloying the Y-TZP with another stabilizing oxide is another method to improve its thermal stability. According to Sato and Shimada, an addition of CeO2 to the Y-TZP helps to eliminate the degradation process without reducing the mechanical properties and also increases the elastic modulus.[71-73]

For increasing strain free energy, Sato et al. found that addition of Al_2O_3 (5-10wt%) to 3mol% Y-TZP decreased the surface monoclinic content and increased the concentration of dispersed Al_2O_3. The Al_2O_3 grains restrain zirconia grains' volume expansion which leads to the tetragonal-monoclinic phase transformation. The addition of Al_2O_3 is not a total prevention of transformation. It only reduces the rate of transformation.[71-73]

For increasing surface free energy, the sintering temperature is reduced to control the grain size. The sintering additives also are used for ensuring a small grain size.[66, 74] Sato and Shimada found that smaller grain size of the CeO_2-alloyed Y-TZP decreased the surface monoclinic content and decreased the concentration of CeO_2 required for total inhibition.[73]

The surface coating i.g. Al_2O_3 is coated onto the surface of Y-TZP. It must be stable and fully dense when it contacts the environment. The fractured coating result in an attack of water vapor.[59]

For surface engineering, a very fine-grained tetragonal phase is formed as a surface layer on Y-TZP. So, the large grain sized Y-TZP which gives maximum toughness is protected from aging-induced transformation.[75]

To control Non-transformable tetragonal zirconia (t'-ZrO_2), Jue et al. reported that the aging resistance of t'-ZrO_2 was gained when its surfaces had been polished.[76] The t'-phase is more resistant to aging-induced transformation than t-phase, but the rate of the mechanism is similar.[59]

The density can be controlled because the critical density is Y_2O_3 dependence. If the density exceeds the critical value, the aging-induced transformation will not occur.[70]

Kim and Jung reported that lattice spacing can be controlled. When the critical value of lattice spacing is reached, localized lattice destabilization and transformation occur. Yoshimura et al. found that the inclusion and exclusion of OH^- in the lattice resulted in expansion and contraction of the zirconia lattice respectively.[66] Lee and Kim reported that the transformation was reversible upon annealing over 1200°c. The micro-cracks were healed but the macro-cracks still remained.[77]

Effect of moisture and stress to zirconia

Kelly JR explained the transformation toughening process. When Yttria-stabilized tetragonal zirconia polycrystal is subjected to mechanical and thermal stimuli, the tetragonal to monoclinic transformation occurs. Since the monoclinic phase occupies more volume than the tetragonal phase, this increase in volume ceases crack propagations.[78]

The surface finish of zirconia restorations

Because hardness of zirconia is high (H_V 1,160-1,300), someone can misunderstand that it is the cause of opposing enamel wear. This wear is depended on the crystal grain size and surface roughness of zirconia which are in line with its microstructure.[6] However, Seghi et al. suggested that the wear potential of a material was not related to the hardness value of the material. Crystalline phase might be responsible for the material's abrasiveness.[79] Seghi et al. (1991) and Won-suck et al. (2002) also reported that there was a poor correlation between hardness and abrasive potential.[4, 79] Seghi et al. (1991) suggested that a lack of significant crystalline phase of zirconia decreased the abrasiveness in spite of its high hardness value. While pressable lithium disilicate material which was composed of higher crystalline content (70% volume) caused increasing the abrasive potential of the material.[79] Mirror-polished zirconia can be done because zirconia has a fine and homogeneous microstructure. The degree of polishing indicates the amount of antagonist's wear. Highly surface finish means the least wear.[6]

Smooth surface will be gained when zirconia has been polished. The more diamond grain size decreases, the more glossiness increases. Glossiness implies enough polishing. It increases rapidly when zirconia's roughness is decreased less than 0.3 μm.[6] Grinding rotary instruments and Diamond polishing paste are used to grind and polish of zirconia restoratives. The hardness of alumina and diamond are higher than zirconia's hardness. Therefore, they are used as abrasive grains. Diamond abrasive grains used for coating the grinding rotary instruments are fixed with metal, glass, artificial rubber to a stainless-steel shaft i.e. Super Course, SinterDia, VitrifiedDia, Aadva Point Zr, CeramDia, Porcelain Hi-glaze.[6] The larger diamond grain size is used, the higher grindability achieved.[80] The diamond grain size should be used from large to small respectively.[6] Diamond grains and fine other oxides are also included in diamond polishing paste such as DirectDia paste, Diapolisher paste that can be used in the oral cavity and Other pastes that are used in laboratories. Plastic or rubber cone and a soft brush are used with diamond polishing paste for polishing i.e. Super snap buff disk, PTC Cup, Robinson brush. Super snap buff disk consists of TiO_2 and polyester. PTC Cup consists of TiO_2, ZnO and artificial rubber. Robinson brush consists of hard (horse hair) or soft fibers (sheep hair).[6]

Occlusal wear

Wear is a process that occurs when surfaces abrade against each other and a load is applied.[37, 44] This process causes the loss of surface material. Wear can be divided into two types. First is two-body wear which occurs when there are two surfaces abrade against each other. Another is three-body wear which occurs when there are abrasive particles between two surfaces. Lubricants are important factors that reduce the unintentional changes not only from two-body to three-body wear but also from three-body to two-body wear. The amounts of lubricant affect the efficiency of abrasion. Too much lubricant reduces the contact between surfaces which results in the reduction of abrasive efficiency. In contrast, too little lubricant also reduces abrasive efficiency but it increases a heat generation. The examples of lubricants are water, glycerin, and silicone.[37]

<u>Wear mechanism and biomechanical factors</u>

Delong (2006) described the wear mechanism according to the chewing cycle. Chewing cycle is divided into three phases. The first is the preparatory phase. In this phase, the jaw is positioned to contact the food bolus until the teeth contact the food bolus. Commonly, there is not the occlusal force during this phase. The second is the crushing phase. It is a three-body interaction between the teeth and food bolus. This phase starts when the teeth first contact the food bolus until there is tooth-to-tooth contact or jaw begins to open. The bolus is compressed, while the masticatory force distributes to the surface of the bolus that contacts with the maxillary and mandibular teeth. The bolus entraps the particles in the two body surfaces and falls out. Thus, they become rougher and cause three-body abrasion.[81] The last is the gliding phase. This phase does not always occur. It starts with tooth-to-tooth contact which the bolus is completely penetrated. It continues until jaw begins to open. This phase represents both two- and three-body wear mechanism (Figure 2).[82] Chewing movement usually has saliva as a lubricant, the masticatory force is about 3-36 N and sliding distance between contacting teeth is about 0.9-1.2 mm.[83, 84]

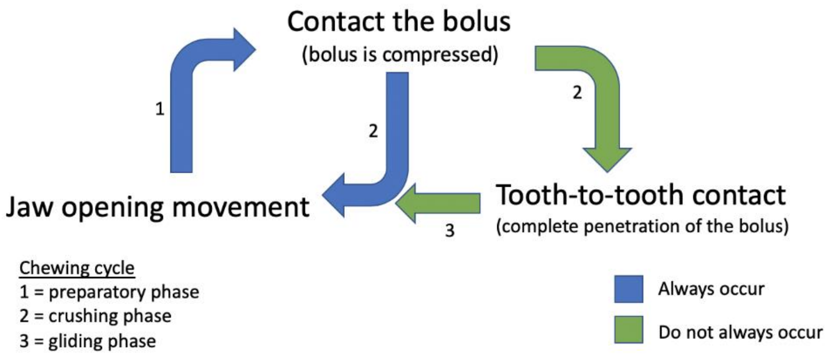


Figure 2 The wear mechanism according to the chewing cycle.

The forces that are produced by masticatory muscle may be resolved into reactive forces perpendicular and tangential to the occlusal surfaces of the teeth. These forces cause the movement of the jaw and wear of the interacting materials.[82] The width of wear scar is directly proportional to frictional coefficients.[5] The wear types between enamel and dental materials are abrasive wear, adhesive wear, fatigue wear, and corrosive wear.[85]

Firstly, abrasive wear is divided into two types. The first type is two-bodies abrasion. The two moving bodies are in direct contact. Depending on the angle of attack and the angle of the asperities, on the coefficient of friction, the speed of movement, the pressure, the distance and the difference of hardness between two surfaces there are four models of two-body abrasion (Figure 3).[86, 87] When the hardness of the two surfaces is different. The asperities of the harder surface will dig into the more ductile surface. This mechanism called microploughing. Particles create a principal furrow with symmetrical lateral borders and forms parallel grooves according to the movement of abrasive particles. Then the mechanism ends up with weakening, deforming, and removing some of the more ductile material which called microfatigue. When the hardness of two breakable materials is similar. The micro-asperities of the harder material slice cleanly through the more ductile material without causing plastic deformation. This mechanism called microcutting. With strong pressure, the asperities can be detached in a process called microcracking. The other type is three-bodies abrasion. The two bodies moving against each other with abrasive particles interposed between them. The severity depends on the size, the shape, and the hardness of the particles. There are two models of three-body abrasion. (Figure 4) When the two bodies are far apart, the particles are free to spread overall the two surfaces. Small particles can attack the two bodies because they are not in contact. When the two bodies are close, the abrasive particles are entrapped and fall out of suspension. If the particles integrated into the surfaces, the wear will be the two-body model.[81]

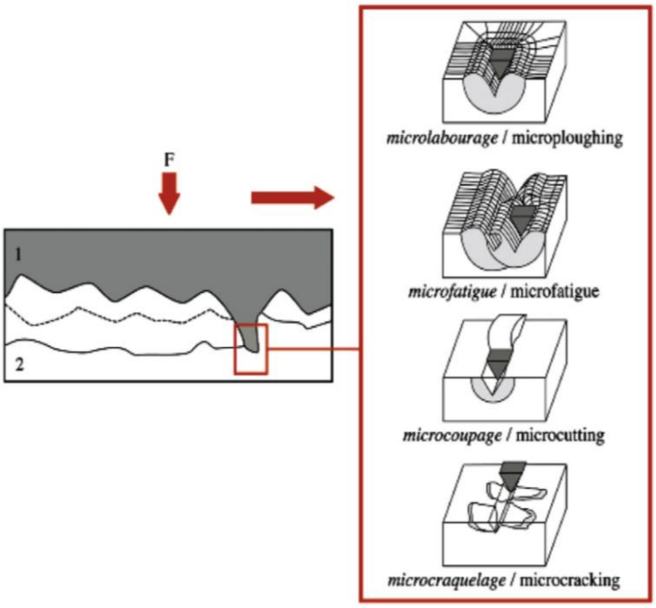


Figure 3 Two-bodies abrasion (Zum Gahr KH. Wear by hard particles. Tribology Int 1998; 31(10):587-96)

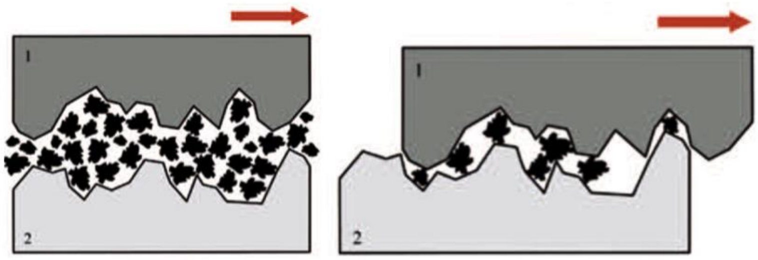


Figure 4 Three-bodies abrasion (Mair LH, Understanding wear in dentistry, Compend Contin Educ Dent 1999;20(1):19-30)

Secondly, adhesive wear can occur when two bodies slide against each other with strong pressure. (Figure 5) It is found in metal and composite restoration. The plastic deformation occurs when the surface asperities interact with each other. After deformation, they can fuse with each other by a process analogous to cold welding. Amounts of the transferred materials depend on the distance between the materials, their rugosity, the pressure, the temperature or the environment.(88) If the transferred materials interpose itself between two bodies, a three-body abrasion process occurs. Parafunctions produce this type of wear. The saliva acts as the lubricant. It reduces the coefficient of friction. Furthermore, the bolus in three-body abrasion tends to remove the fine covering of the transferred materials.(81)

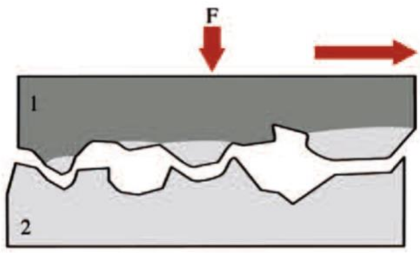


Figure 5 Adhesive wear (Mair LH, Understanding wear in dentistry, Compend Contin Educ Dent 1999;20(1):19-30)

Thirdly, fatigue wear occurs when one surface slides along another surface with strong pressure (Figure 6). There are a compression zone and a tension zone. The tension zone develops beneath it. This deformation causes inter-molecular micro-cracks which spread in the sub-surface. When the fracture propagation reaches the surface. The potions of material may break off and interpose themselves between the two bodies, a three-body abrasion process occurs. Fatigue wear relates to enamel contact with strong pressure. It does not relate to mastication. Enamel is harder than dentin because it has a high degree of calcification. However, high modulus of elasticity of enamel and its low elastic limit bring it at a greater risk of fracture. Prismatic organization of enamel tends to block the propagation of microcracks especially at occlusal where the prisms are perpendicular to the surface and the calcification is maximal.[89-92] When the microcracks provoke the delamination of inter-prismatic and intra-prismatic substance.[93] It will be stopped at the dentinoenamel junction which acts as a barrier.[94] This type of wear can be found in abfraction at cervical enamel.[81]

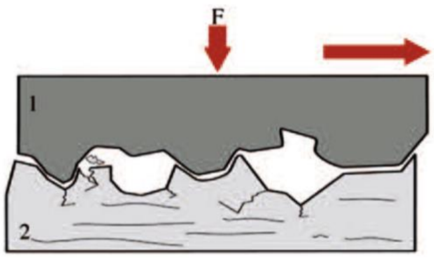


Figure 6 Fatigue wear (Mair LH, Understanding wear in dentistry, Compend Contin Educ Dent 1999;20(1):19-30)

Fourthly, corrosive wear or erosion occurs when a chemical attack of acid or chelation breaks inter-molecular bonds of dental tissue or restorative materials. It is not a wear modality but it allows other wear mechanisms to occur. Then the surface molecules will be swept away and the new surface will expose the corrosive environment (Figure 7). The corrosive agents are both intrinsic and extrinsic. The extrinsic agents such as foodstuffs, some medications and chemical elements in the environment. The intrinsic agents are regurgitation, gastro-esophageal reflux, and spontaneous vomiting provoked by chronic alcoholism or anorexia-bulimia. Saliva carries phosphate and bicarbonate ion which help to increase the pH and form a protein pellicle over the teeth. This protein pellicle can re-calcify the affected tooth surfaces and limit the wear.[81]

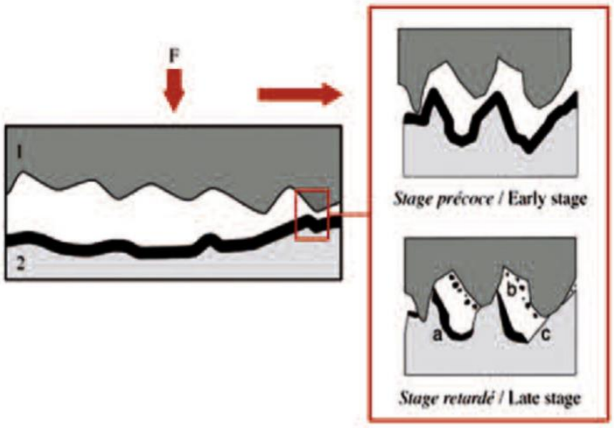


Figure 7 Corrosive wear (Mair LH, Understanding wear in dentistry, Compend Contin Educ Dent 1999;20(1):19-30).

a: Corroded areas not affected by surface friction.

b: Debris from corroded surfaces immediately after wear occurred.

c: Area just after wear occurred, susceptible to additional corrosion if re-subjected to corrosive agent when surfaces separate.

Wear can occur when there are force and friction. Only crushing and gliding phases of the chewing cycle have force and friction. Reduced contact area leads to the increase of shear stress on enamel which causes enamel wear.[82] The wear between enamel mainly shows abrasive wear.[95] Abrasive wear has rough parallel furrows with granular debris in the wear scar, while adhesive wear shows smooth and narrow wear scar. Moreover, fatigue wear shows the chipping flake and pit-like structure in the wear scar (Figure 8).[5]

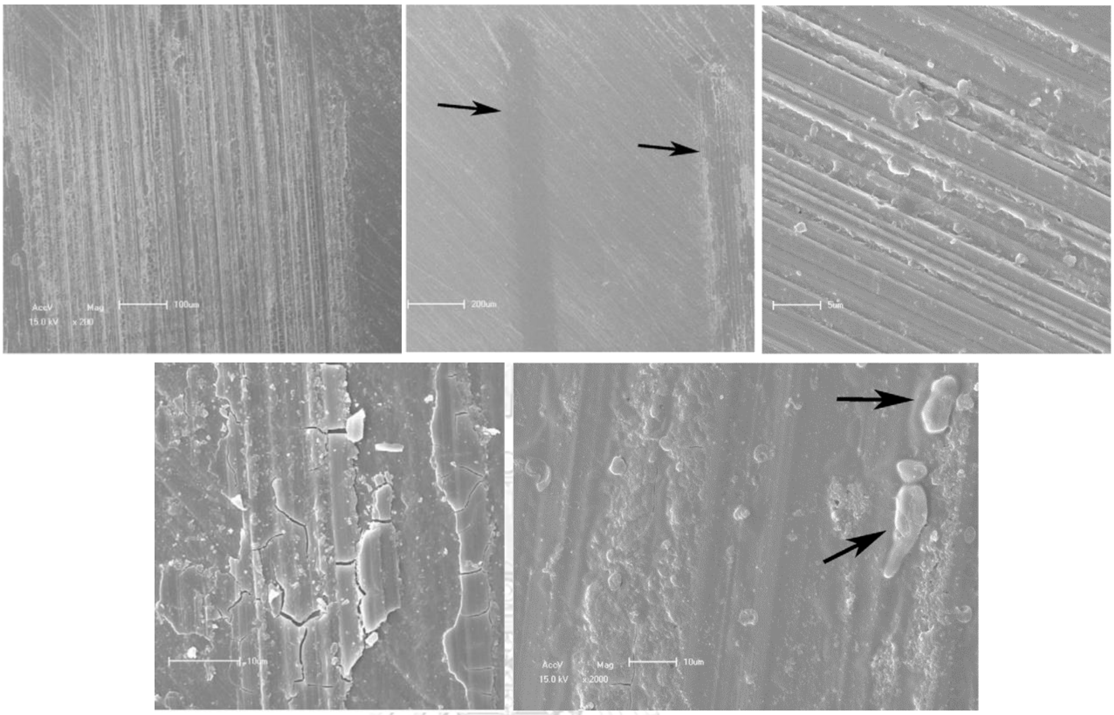


Figure 8 SEM images of the worn surface of enamel after wear test
Arrows show parallel furrows with granular debris, chipping flake and pit-like structure in the wear scar.

Mastication is a three-body phenomenon. The diet acts as a lubricant so the friction is lower than for enamel-to enamel. The properties of food can affect the frictional coefficient and wear behavior of the teeth.(82)

Li and Zhou (2002) suggested that saliva is an important factor that greatly reduces the depth and severity of the wear scars by decreasing the frictional coefficient.(5, 96) According to their study, the surface hardness of glass or ceramic decreases in a wet environment.(96)

Factors affecting enamel and ceramic wear

Mahalick et al. (1971) reported that the wear potential depended on neuromuscular forces, lubricants, foreign bodies, patient habits and type of restorative material used.[97]

In 2002, Won et al. suggested that hardness, frictional resistance, fracture toughness, porosity, crystals, chemical degradation, and surface finish affected the wear potential of the ceramic.[4] Wang et al. also reported that frictional coefficients of enamel related to hardness, elastic modulus andsurface finishing of the materials, while Seghi et al. suggested that the wear potential of a material was not related to the hardness value of the material. Crystalline phase might be responsible for the material's abrasiveness.[79] Wang et al. showed Empress glass ceramic, which has a needle-shaped lithium disilicate crystalline grains embedded in a glass matrix, has a high frictional coefficient. When the glass matrix is worn, lithium disilicate crystalline grains are exposed. Thus, the surface roughness is increased.[5] Seghi et al. (1991) and Won-suck et al. (2002) also reported that there was a poor correlation between hardness and abrasive potential.[4, 79]

The position in the tooth and its histological structure of enamel affected its properties. The direction of enamel rods referred to the strength of enamel. The direction of enamel rods which parallel to the forces was better than the perpendicular direction. Thus, cuspal enamel would stronger and could withstand the force in a direction parallel to the enamel rods.[89-92, 98]

Methods of measuring wear

There are three methods for measuring wear. The first is the United States Public Health Service (USPHS) method.[99, 100] This method is the non-parametric test. Wear is classified into three categories. The first is "alpha" which means no wear. The second is "bravo" that means visible wear with clinically acceptable. The last is "Charlie" which means excessive wear and it must be restored. Advantages of this method are that it is ready to use and does not require special equipment. However, it is subjective and requires more chair-time in order to obtain the information.[82]

The second is the Leinfelder et al. method.[101, 102] This method uses calibrated standard casts that the occlusal surfaces of the casts were reduced by 0.1 mm. The prepared casts are used to compare with the replicas of the restoration. Wear-surfaces are believed to be the primary cause of the loss of vertical dimension. Advantages of this method are that it is not expensive and does not take a long time to obtain the information. But the result tends to underestimate wear.[103]

The third is 3D images. This is the best method for measuring wear. The measuring system should be both accurate and precise. The accuracy of the device should be at least one order of magnitude smaller than what is being measured.[82] Lambrechts (1987) reported the wear rate of enamel against enamel was 20–40 μm per year.[104] This means that the measurement tool should have an accuracy of 2-4 μm or better. Another way, it is more practical to use the sensitivity of people. The sensitivity of people to their occlusal changes which is described as an absolute threshold is used as a baseline. The accuracy of the measurement tool should be below this value. Jacobs et al. (1994) reported that mean absolute thresholds in different materials were a range between 0.02-0.03 mm. Many subjects could detect foils as thin as 0.01 mm.[105] Thus, this means that the measurement tool should have an accuracy of 20 μm or 10 μm is preferred. Advantages of this method are that the 3D databases are quantitative and accurate. It can be stored and used in both the clinic and the laboratory. The 3D databases can be compared with another.[102] However, this method requires specialized hardware and software which makes it expensive.[82]

Values of wear can be determined by subtracting two scanned surface images. The value is measured as a volume or depth. Volume is a function of two parameters (depth and area). Thus, Measuring the volume is indirect wear measurement. When wear occurs, the dynamic occlusal change also takes place. The centric contacts move, the orientation of teeth to each other changes and the contact areas are increased. Occlusal contact areas are different from wear region areas. They are always less than or equal to wear region areas. Wear occurs in many regions because the contact changes. Depth and area are difficult to combine many wear regions, while volume can combine them. Thus, the volume is preferred for measuring wear. Depth is not a good parameter for comparing wear. The value is depended on the measurement (where and direction). There is an effective method to determine wear. Values of wear can be determined by subtracting two scanned surface images. The shortest distance from each point is calculated. Then average the absolute values of these distances and plus or minus the standard deviation. The absolute values are used because the sign of opposite sides can cancel each other which cause underestimate of the accuracy. This method gets the accuracy of the result from the mean of multiple measures and gets precision of the result from standard deviation. The problem with this method is that half of the distances are greater than the mean. These are grouped in the region of wear. They overestimate the error of the result. There is a way to report by using "sigma" value which is related to the standard deviation. A 1 sigma value is the absolute distance that is equal to or greater than 68% of the measured absolute distance. 2 sigma is greater than 95% and 3 sigma is greater than 99%. This method is similar to confidence intervals.[82]

3D images can be divided into two groups, contact profiling system, and non-contact profiling system. Contact profiling system is used for profiling the topology of occlusal surfaces. Resolution depends upon the size of the stylus tip which has diameter 0.1 mm or larger. Advantages of this group are that this system has good accuracy. It is low cost and is not affected by surface material properties (color and transparency). However, this system takes a long time and requires a rigid surface. Another group is non-contact profiling system. This group can be further divided into point, line, area and volume scanners. Point profiling system is similar to contact profiling system but It uses light source or microscope focused on the surface as a stylus. Advantages of this system are that it does not contact the surface but it requires an opaque, diffuses reflecting surface. Resolution depends upon the focus light source (less than 0.025 mm). Non-contact line laser system scans the surface using the straight line projected on the surface. The disadvantage of this system is that It has a lower resolution because it cannot focus as a single point. Area scanner is similar to line scanner but It projects a pattern over the surface. The advantage of this system is that it is significantly faster than point profiling system. However, it has lower resolution because it cannot focus as a single point. Volume scanner is a CT based. Resolution is determined by voxel. The advantage of this system is that the shadowing is not a problem but the system is expensive and the subject is exposed to radiation.[82]

Studies on the wear of antagonist zirconia

<u>Friction study in arthroplasty</u>

This research focuses on the wear of high-density polyethylene which was used in the femoral head and cup of artificial hip joints.[6] Kumar et al. (1990) reported that hardness is not related to the susceptibility of wear. They found that polyethylene rarely wears on zirconia.[106]

<u>Wear studies in enamel</u>

In the 2000s, Zirconia came into the dental field. Although the conditions of materials and the methods of use were unclear, there were some conclusions about the antagonist wear against zirconia crown restoration.[6]

Tambra et al. (2003) suggested that the IV gold caused less enamel wear than polished zirconia.[6]

In 2008, there was the study of five materials about enamel antagonist loss using a modified Leinfelder wear testing machine. Culver et al. reported that Cercon and Lava (zirconia) caused more enamel loss than Empress (leucite-containing glass) and MZ100 and Z100 (composite resin).[6]

In the 2010s, the development in polishing instruments and materials caused the change in previous conclusions about the wear of enamel against zirconia.

Shar et al. (2010) studied enamel antagonist wear against between polished and glazed zirconia using a modified Leinfelder wear testing machine. Although, they suggested that the glazed zirconia showed less enamel loss than the polished zirconia.[6] Jung et al. reported that mirror-polished zirconia caused significantly less of enamel loss than glazed and porcelain-veneered zirconia.[38] In the same year, Albashaireh et al. studied five dental ceramics' wear against zirconia balls using dual-axis mastication simulator. The five dental ceramics were e.max ZirCAD, e.max Press, e.max ZirPress, Empress Esthetic, and e.max Ceram. They showed that zirconia caused antagonistic tooth wear less than feldspathic dental porcelain. [107]

Sorensen et al. (2011) studied the enamel wear against the seven types of materials using the Oregon Health &Science University (OHSU). These materials were Omega 900, Empress, Bovine enamel, d.sign, Lava, Aquarius and Empress 2. They showed that the polished Lava caused small enamel loss. It was similar to the gold alloy (Aquarius).[6] In the same year, Basunbul et al. found that the polished Wieland zirconia caused significantly less enamel loss than the glazed Wieland zirconia, Ceramco porcelain, and Cerec Mark II. They concluded that this occurred because of loss of the glazed layer in the glazed zirconia, while the polished zirconia did not change.[39]

Wang et al. (2012) listed the wear potential of the dental materials against enamel surface from highest to lowest by determined the frictional coefficient. The wear potential decreased from zirconia with a rough surface, Empress glass ceramics, veneer porcelain, zirconia with the well-polished surface, Ni-Cr alloy and Au-Pd alloy, respectively. There was no significant difference in wear potential between veneer porcelain and zirconia with the well-polished surface, as well as, Ni-Cr alloy and Au-Pd alloy. Moreover, they found that Empress glass ceramics and veneer porcelain showed abrasive wear style, while zirconia and Ni-Cr alloy showed fatigue wear style.[5] In this year, Yang et al. studied the loss of enamel against Zirkonzahn Y-TZP (polished, stained, stained then glazed), Acura Y-TZP, Wieland Y-TZP, a feldspathic porcelain by using the University of Alabama wear-testing device. The results showed that three Y-TZP products caused significantly less antagonist wear than veneering porcelain. This resulted from the homogeneous surface of Y-TZP. Moreover, they found that stained and glazed Zirkonzahn Y-TZP was significantly more abrasive than Y-TZPs without glazing.[6] Kim et al. (2012) also reported that polished zirconia caused less enamel wear than feldspathic porcelain and heat-pressed ceramics. The wear rate was associated with the roughness of the zirconia.[108]

In 2013, Janyavula et al. studied the loss of enamel against four types of surface-treated zirconia (Lava). They found that highly polished zirconia caused less enamel loss than glazed zirconia. They suggested that the surface of porcelain restoration should be polished prior to glazing in the area where aesthetics is crucial.[40] In this year, Stawarczyk et al. also studied the enamel loss against the three types of surface-treated zirconia (ZENOTEC Zr Bridge Translucent) and a base alloy (Denta NEM, CoCr alloy) using a chewing simulator. They found that polished zirconia had a lower wear rate than glazed zirconia, veneered zirconia and base alloy. Not only enamel antagonists but also the material itself.[41]

In 2014, Park et al. reported that polished zirconia caused the least volume loss of enamel antagonist. In contrast to the stained and glazed zirconia which caused the highest volume loss.[42] Lawson et al. (2014) suggested that zirconia caused less wear of opposing enamel than lithium disilicate ceramic. Moreover, glazed zirconia caused more opposing enamel loss than polished zirconia.[43]

Gauri Mulay (2015) studied weight of tooth samples against zirconia using a two-body wear machine. They reported that polished porcelain inflicts lesser damage to enamel than that of glazed porcelain. Therefore, he suggested that polishing porcelain restoration might be a better option than over glazing.[44] In this year, Kwon et al. study the wear of three types of materials (zirconia, gold, enamel) against zirconia. They reported that zirconia against enamel caused the most wear compared to opposing gold or zirconia. [109]

Rupawala et al. (2017) studied the wear of enamel against the different ceramic systems using two-body wear machine and observed the phase transformation of zirconia structure. They found that polished zirconia caused the least wear to enamel antagonist when compared to lithium disilicate, porcelain fused to metal and glazed zirconia. The wear potential of restorative material increased from lithium disilicate, porcelain fused to metal and glazed zirconia, respectively. Furthermore, there was no significant change in the phase from tetragonal to monoclinic.[8]

In 2018, Esquivel-Upshaw et al. studied the wear of enamel against different surface treated monolithic zirconia (polished and glazed) and metal-ceramic in patients. They found that polished zirconia caused less enamel antagonist wear than glazed zirconia. Furthermore, there were no significant differences in wear potential of enamel, polished monolithic zirconia, and metal-ceramic to the opposing enamel.(45)

Wear studies using steatite

Due to the clinical study about wear has a large variation of measurement values and conditions. Steatite ($MgO \cdot SiO_2$) which has the wear behavior same as human enamel is used as antagonist material in the laboratory.(110-113)

In 2011, Preis et al. studied the loss of steatite and enamel against five zirconia and four veneering porcelains using a chewing simulator. They found that zirconia caused less antagonist wear than porcelain.(114) Furthermore, Kuretzky et al. studied the enamel loss against four types of surface-treated zirconia (rough, polished, glazed and veneered Lava) and e.max CAD using a longitudinal moving notch device. The study showed polished zirconia caused the least wear.(6)

Kontos et al. (2013) studied the loss of steatite against five types of surface-treated zirconia (glazed, polished, ground, sandblasted, as fired) using a chewing simulator. The result showed that out of all the materials mentioned earlier, polished zirconia caused the least wear.(46)

Digital and conventional impressions

The digital impression has many advantages compared with a conventional technique. The advantages are the elimination of laboratory and clinical steps, reducing the transport time between dental laboratory and clinic, storage of the digital file, in-office milling of the final restorations and reduced patient discomfort.(115-120) On the other hands, the disadvantages of the digital technique are a costly equipment and a personal adaptation to the new technology.(115)

According to Caputi S. and Varvara G., 2-step impression technique (putty wash) demonstrated superior result in term of accuracy when compared to the 1-step impression (double mixed, single impression) and monophase technique.[121] Moreover, Anshul Chugh et al. reported that providing a uniform and controlled wash space when taking an impression gives a better marginal accuracy of the restoration.[122] Although the conventional impression materials have an excellent dimensional stability and a precision, there are many factors that affect the accuracy such as temperature, duration before pouring, the surface wettability of the gypsum, distortion from disinfection procedure.[123, 124] Furthermore, laboratory procedures can cause errors.[125, 126]

Esquivel-Upshaw et al. (2018) suggest that the indirect technique that requires a replica for measuring wear. Every step can produce the inaccuracies. The errors come from the setting expansion of stone, the linear dimensional change of impression and the accuracy of scanners or profilometer.[45] Delong (2006) also reported that direct scanning was superior to the indirect methods due to the potential for improved accuracy and simplification in the number of steps.[82]

Paul Seelbach reported that digital and conventional impression demonstrated similar result in term of marginal accuracy. However, the study was conducted in an ideal laboratory setting where no difficulties such as leaking of gingival fluid or subgingival preparation were included.[127]

Chochlidakis et al. (2016) studied the accuracy between digital and conventional impressions by using the information from both previously in vitro and in vivo studies. They found that the restorations fabricated by digital impression showed a smaller marginal gap than those fabricated by conventional impression. This difference was not statistically significant. They also reported that a digital die gave a smaller marginal and internal gap than SLA/polyurethane die. In the conventional group, cast restorations gave the smallest internal gap compared to restorations from CAD/CAM and pressing technique. In the digital group, CAD/CAM restorations gave smaller marginal and internal gap than restoration from pressing technique. The glass-ceramic restoration showed the largest internal gap in both digital and conventional groups compared to zirconia and metal alloy restorations.

While metal alloy restorations showed the smallest marginal gap followed by glass-ceramic and zirconia restorations respectively. This difference in the internal gap was not statistically significant. Moreover, they reported that fixed partial dentures showed smaller marginal and internal gap than single crowns in the digital group. In contrast to the conventional group, single crowns showed smaller internal gap than fixed partial dentures. This difference was not statistically significant. In the conventional group, the polyvinyl siloxane impression material gave a smaller internal gap value than polyether material. This difference was not statistically significant.[115]

There were two in vivo studies showed that the zirconia-based ceramic crowns fabricated using digital impression gave better marginal and internal fit than zirconia-based ceramic crowns fabricated using the conventional technique.[128, 129] Interproximal contacts and marginal gap were also better than the conventional group.[129]

Occlusal force distribution in dental implants

Rangert B. stated that implant occlusion should be biomechanically controlled to achieve good clinical success and longevity. Vertical force should be directed along the long axis of the implant body and lateral force should be minimized.[130] Improper occlusion in implants leads to biological and mechanical complications [131] such as implant failure, early crestal bone loss, screw loosening, uncemented restorations, fracture of porcelain, prosthesis fracture and peri-implant disease.[132, 133]

In natural dentition, periodontal tissues allow vertical movement range from 25-100 µm and 56-108 µm buccolingually.[134] Implants attach firmly to underlying bone which limits the vertical movement to 3-5 µm and 10-50 µm laterally.[133]

Premature contact should not be in an implant. It causes excessive lateral loads which lead to the failure of implants.[135, 136] Because the surface area of a premature contact is small, the magnitude of stress in bone increases. Moreover, the contact often on an inclined plane so it also increases the tensile crestal stress.[131] The ideally occlusal contact of the crown on implant should be on a flat surface perpendicular to the implant body and positioned over the center of the implant abutment.(132, 137) A thin articulating paper (<25 μm) is used for initial implant occlusal adjustment in centric occlusion (light tapping forces). The surrounding teeth should be greater initial contact than implant prosthesis. At heavy occlusal load position, implant and adjacent teeth are equal sharing of the load.(132, 135, 138)

Chapter III Materials and methods

Armamentarium

1. Straumann bone level and tissue level implants (Placed by Department of Oral Maxillofacial Surgery, Faculty of Dentistry, Chulalongkorn University)
2. Straumann cement-retained implant abutment (SynOcta/Variobase abutment)
3. Monolithic zirconia crowns: (VITA YZ HT^{White}, VITA Zahnfabrik, Germany)
4. Intraoral scanner (TRIOS 3, 3Shape, Denmark)
5. Analysis software (Dental System 2018, 3Shape, Denmark)

Methodology

Ethics

1. Ethical permissions should be requested and granted from the Research Ethics Committee.
2. Patients would be given an informed consent. Once the patient understood agree to the agreements of the research procedures, only then the research could be conducted with the patient as the subject.

Sample size determination

Many of the clinical studies used sample size range from 10-16 samples.[7, 45, 139, 140] Therefore, in our current study, a sample size of 10 would be used which is similar to the previous section of this study by Vatanasak W. and Wattanasermkit K.[141].

Patient Evaluation and sample collection

This study was performed at the Graduate Prosthodontic Clinic, Faculty of Dentistry, Chulalongorn University by one investigator. The protocol was approved by the Research Ethics Committee, Faculty of Dentistry, Chulalongkorn University (No.029/2019). After obtaining informed consent, 7 patients were referred for prosthodontics restorations on implants which were placed by one oral surgeon at the Department of Oral Maxillofacial Surgery, Faculty of Dentistry, Chulalongkorn University. The patients' medical history was recorded. Extraoral examination of the head, face, neck lymph nodes, TMJ, and muscles of mastication was performed to rule out the presence of factors in the exclusion criteria (Figure 9). Intraoral examination of the dental conditions, present restorations, occlusal scheme, and soft tissue conditions was conducted. The patients' data was recorded using the Department of Prosthodontic Patient's Evaluation Chart. Ten samples included in this study were categorized into 2 groups based on type of occlusal surface modification of zirconia restorations before they were delivered. Each group contained 5 samples consisting of restorations replacing either molars or premolars (Table 1).

Exclusion criteria

1. Patients with implant replacement not involving premolar and molar areas.
2. The area requiring implant placement is not able to accommodate cement-retained restoration.
3. Missing antagonist tooth or an antagonist tooth that has the dentin exposed.
4. Patients have no two non-restored or minimally restored teeth opposing each other.
5. Patients presented with symptoms of TMD.
6. Patients exhibiting or with a history of parafunctional habits.
7. Patients presented a clinical sign of tooth erosion and attrition.
8. Patients with systemic conditions at an uncontrolled stage.
9. Patients who have been administered bisphosphonate.
10. Patients who have undergone radiation therapy.
11. Patients who are mentally challenged or psychologically ill.
12. Patients who are not able and are not willing to comply with the agreement the research.
13. Patients should have a clinical sign of Xerostomia.
14. Patients whose teeth are missing or wearing removable partial denture.

Figure 9 Exclusion criteria

Table 1 Samples are divided into 2 groups based on occlusal surface modification

Subject	Tooth number (Two-digit numbering system)	Group	
		Annealed	Polished
1	15, 26	✓	
2	17, 24	✓	
3	16	✓	
4	35		✓
5	26		✓
6	16		✓
7	16, 24		✓

Examination of the zirconia restorations

All zirconia restorations were properly adjusted using Diacera pre-polishing bur (EVE, Germany) for gross adjustment. The restorations had good proximal contact when tested with dental floss and were able to hold shim stock tightly when the patients bit firmly. The occlusal and proximal contacts for the samples in Po group were further polished with Diacera (medium and fine) at the speed of 10,000 rpm. For An group, after adjustment with Diacera polishing kit at the speed of 10,000 rpm, the samples were annealed at 1000°C in Vita Vacumat Premium 4000T furnace for 15 minutes before delivery. The protocol of this procedure was presented in the previous study.[141]

Insertion and delivery visit

On the first day of delivery, full mouth Intraoral scans were taken as baseline. An intraoral scanner (TRIOS 3, 3Shape, Denmark), calibrated according to the manufacturer's instruction, was used to scan maxillary and mandibular quadrants where the restorations, opposing teeth and controlled enamel were located. Occlusion was scanned in maximum intercuspation position. The accuracy and precision of this type of scanner were reported to be 6.9±0.9 μm and 4.5±0.9 μm, respectively from the American Dental Association (professional product review). After 6 months of delivery, the patients were scheduled and recalled for an intraoral scan (Figure 10).

Wear Analysis

To determine antagonist enamel wear, the baseline and 6-month scans were superimposed using analysis software (Dental System 2018, 3Shape, Denmark). The wear was quantified as the loss in height. The data were obtained by subtracting two scanned surface images. A contact area on the occlusal surface of the opposing tooth was selected. The field observation was limited to the area of 2*2 mm^2 on the occlusal surface of targeted tooth locating the contact area at the middle of the field of interest. The total area of 4 mm^2 was divided into small grids of 0.5x0.5 mm^2 each (Figure 11). Total 25 points were measured in each samples. Analysis software was used to inspect the differences in term of total tooth structure loss (height in μm) where the lines that divided the grids met (Figure 12). The mean value was obtained by averaging the absolute values of the different distances. The mean values with standard deviations were used to calculate a sigma value (system accuracy).[82]

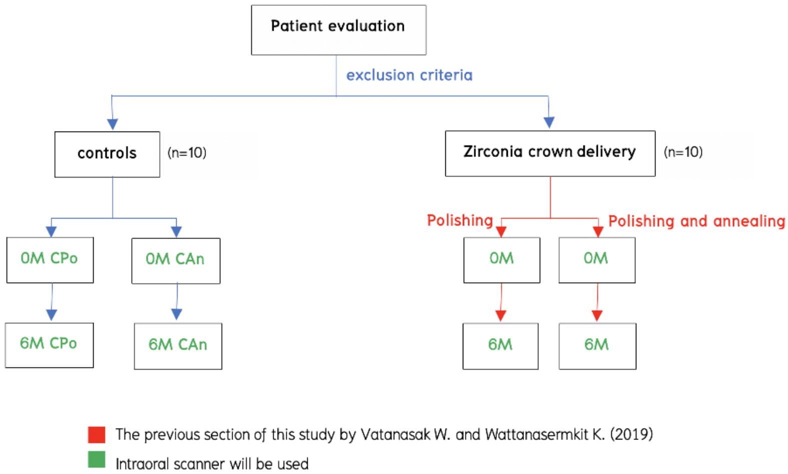


Figure 10 The diagram showing enrollment, allocation and follow up of participant

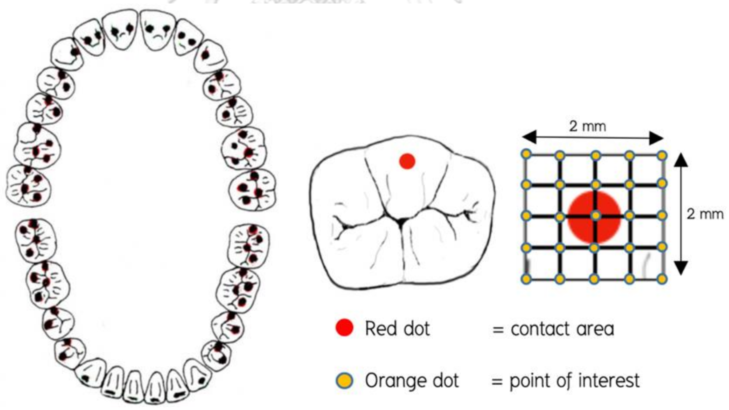


Figure 11 The field observation on the occlusal surface of targeted tooth

*The field observation was limited to the area of 2*2 mm^2 on the occlusal surface of targeted tooth locating the contact area at the middle of the field of interest. The total area of 4 mm^2 was divided into small grids of 0.5x0.5 mm^2 each*

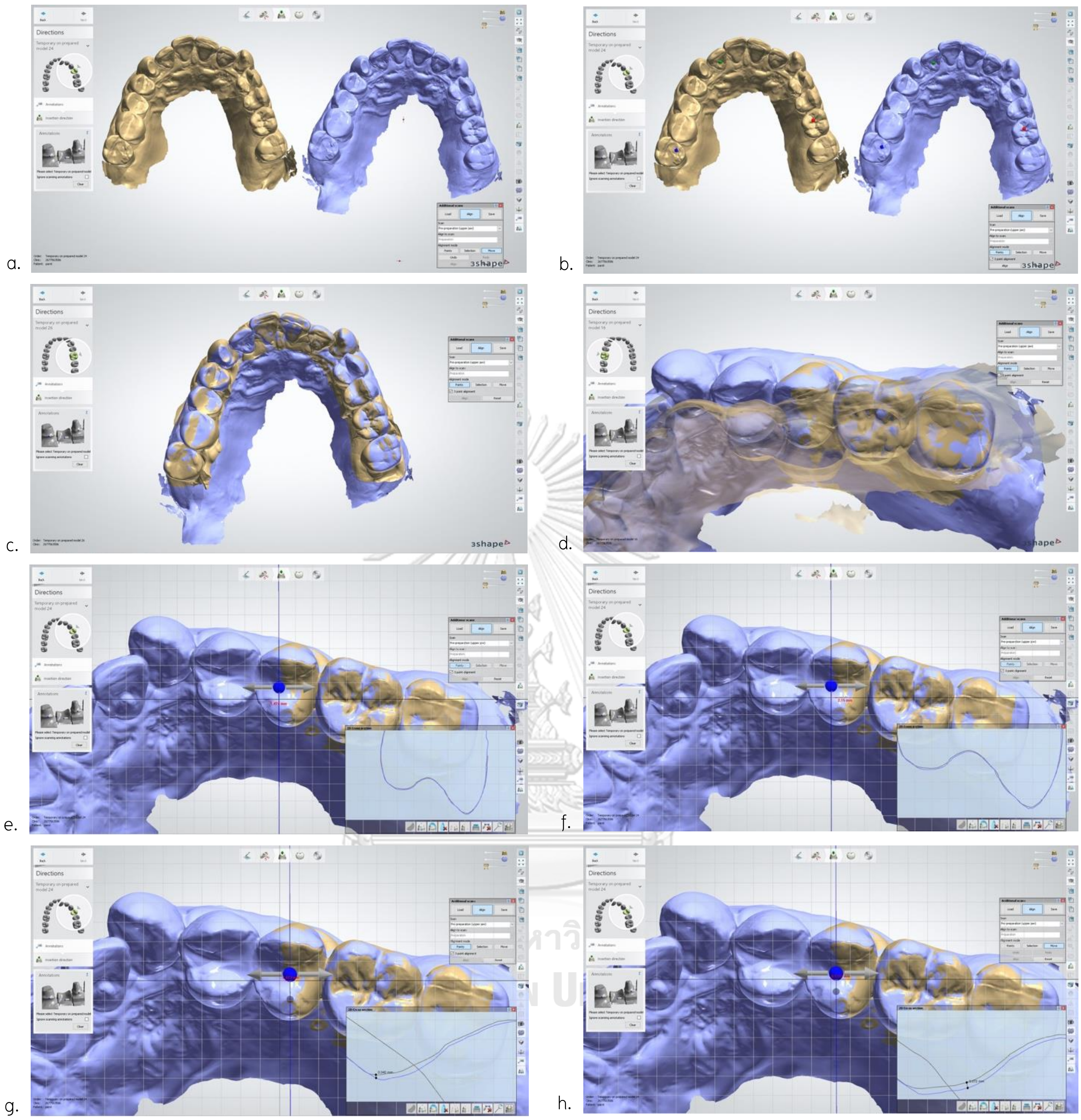


Figure 12 Analysis software was used to inspect the differences in term of total tooth structure loss

a. Two scanned surface images

b. 3-point reference were located

c. Two scanned surface images are superimposed

d. The contact area was located

e. Cross section of the targeted tooth

f. Cross section of the targeted tooth (zoom)

g-h. The different distances of superimposed images (tooth structure loss)

Statistical analysis

The mean values for each data sets were used for statistical analysis. The data were analyzed using statistical analysis software (SPSS 22.0, SPSS Inca, Chicago, IL, USA). The data were tested for normal distribution by Shapiro-Wilk test. Statistical analysis was performed using Wilcoxon Signed Rank Test with significant difference of 0.05.

Chapter IV Results

After 6 months of monolithic zirconia restoration delivery, the mean value for each data sets were collected and analyzed. The mean amount of tooth structure loss for Po, An, CPo and CAn were 28.08, 29.86, 31.76 and 35.18 μm, respectively. The results suggested that the amount of tooth structure loss on both the polished and annealed groups were significantly lower when compared to the control teeth of each group ($p<0.05$) (Table 2).

Table 2 Comparison of groups for the mean amount of tooth structure loss after 6-month delivery

Occlusal surface modification / Sample	Polished (Po)	Control Polished (CPo)	Annealed (An)	Control Annealed (CAn)
	The mean amount of tooth structure loss in term of height (μm.)			
1	14.08 [26]	20.80 [16]	15.44 [16]	21.40 [26]
2	28.16 [35]	40.40 [45]	26.24 [24]	33.24 [14]
3	29.76 [16]	39.80 [25]	29.48 [15]	34.32 [25]
4	29.88 [24]	38.68 [14]	29.92 [26]	31.12 [16]
5	38.52 [16]	47.80 [26]	48.24 [17]	55.80 [25]
Mean	28.08	31.76	29.86	35.18
P-value†	0.043*		0.043*	

† The results compared the mean amount of tooth structure loss on both the polished and annealed groups to the control teeth of each group

* Statistically significant.

Note: Numbers on the lower right corner of each cell indicate the number of tooth (two-digit numbering system)

Chapter V Discussion and conclusions

Discussion

After 6 months of monolithic zirconia crown delivery, the amount of tooth structure loss on both polished and annealed groups were significant lesser than that of each control group ($p<0.05$). Therefore, the null hypothesis was rejected. The result of our study was in agreement with previous clinical studies by Nakashima et al. In their study, the antagonist enamel wear of monolithic zirconia crowns was observed. The results showed that there was a significant difference between the antagonist wear of natural enamel and the ceramic restorations. The wear of the tooth enamel opposing the zirconia crown was significantly lesser than that opposing to natural dentition.(142) However, some studies concluded that there was no significant difference between the antagonist wear of natural enamel and the ceramic restorations.(140, 143) Lohbauer U. and Reich S. reported that in the first two years the monolithic zirconia restorations did not seem to be affected by wear.(140) Many clinical studies suggested that well-polished monolithic zirconia showed similar or more antagonist enamel wear than natural teeth but less than metal-ceramics.(139, 144) However, some studies have concluded that the natural tooth opposing to zirconia crowns showed less enamel wear than one opposing to feldspathic ceramics crowns.(8, 38, 142, 145) Mundhe et al. concluded that molars have greater occlusal force than premolars so the wear of molars was more than the wear of premolars.(144) However, the results were uncomparable because some studies did not have the control group and the testing methods were different. For example, there was a study used the replicas which may create errors due to many reasons such as the setting expansion of the stone (0.12%) and the linear dimensional change of the impression (1.5%) resulting in inconsistencies or inaccuracies during the data collecting process. These errors made a slight difference in the wear values measured.(45)

The wear rate of the restorative material should be equivalent to the enamel. Lambrechts (1987) reported the wear rate of enamel against enamel was approximately 20–40 μm per year.[104] Two years later, he studied the wear rate of human enamel. The author suggested that the wear rate is higher initially and maintained the same rate until the steady state is reached which resulted in a lower amount of enamel wear. For molars, the amount of enamel wear is approximately 38 μm during the initial state and 28 μm during the steady state. For premolars, the amount of enamel wear is approximately 18 μm during the initial state and 15 μm during the steady state.[146] Excessive wear can be caused by several factors such as the patients' parafunctional habit or the mismatch between hardness of the restorative material and the natural tooth structure. Excessive wear may lead to supra eruption, traumatic occlusion, loss of vertical dimension, periodontal breakdown and temporomandibular joint dysfunction.[6]

The wear behavior of a material depends upon the type, microstructure, surface roughness, strength of the restorative material and chewing force.[4, 5] The hardness and roughness of the material greatly exceeds that of natural dentition which may cause the wear of opposing restoration and/or natural tooth structure. Since surface roughness is the cause of wear, polishing is recommended to prevent antagonist enamel wear and maintain the structural strength of zirconia. The surface roughness of zirconia after polishing could be less than 0.2 μm, which is similar to glazed zirconia.[147-149] In the previous study by Vatanasak W., the surface roughness of zirconia crowns (using the same samples as this study) was recorded. The mean of surface roughness of polished and annealed groups are 0.56±0.24 μm and 0.66±0.06 μm, respectively.[141] The rate of wear is higher at the initial placement of a restoration. However, the rate of wear decreases and becomes stable over time (approximately after 2 years of placement).[146] This may be because of that the cusp height becomes shorter and flatter due to more rapid wear during the initial phase of placement. The flat occlusal surface represents a decrease in vertical height and an increase in the base surface area.[150] The larger the base surface area, the lesser the occlusal force per unit of surface area. When occlusal force per unit area is reduced, the loss in vertical height decreases.[139] However, in our study, the opposing natural tooth wear was observed for 6 months after the placement.

Based on the result obtained from the previously study by Vatanasak W.[141], the mean surface roughness of polished zirconia was higher than the mean of surface roughness suggested by Chong et al. (less than 0.2 μm)[148]. The mean amount of tooth structure loss on both the polished and annealed groups (28.08 and 29.86, respectively) were within the normal range of the wear rate of enamel against enamel (approximately 20–40 μm per year) as reported by Lambrechts.[104] According to Chen et al., the occlusal surface of the implant prosthesis should contact the patient’s natural dentition only after the patient bite with maximum force in maximum intercuspation position.[132] This may be the explanation of the result of this study. The fabricated zirconia crown on the dental implant does not contact the natural dentition in the eccentric position. Naturally, in a normal chewing cycle, the teeth rarely contact during mastication.[81] Moreover, in the case of patient with dental implants, more interocclusal space is available since the restoration only lightly contact the occluding tooth structure. This allows the food bolus to be freely moving, which reduces the chance of trapping the food bolus between the occluding surface, minimizing the wear potential.[151]

Mohammadi-Bassir et al. studied the phase transformation of yttrium-stabilized tetragonal zirconia after surface finishing. They reported that the surface roughness increased significantly after grinding. Polishing and glazing decreased the surface roughness. The authors reported that monoclinic (m) phase could be observed after grinding and polishing.[152] Park et al. reported that there were no significant changes in the phase of zirconia before and after polishing. The highest amount of m phase (0.09%) was observed after polishing for 8 minutes.[153] Many studies showed that polishing processes did not cause phase transformations in the zirconia samples.[154-156] Denry et al. studied the microstructural and crystallographic changes of zirconia-based dental ceramics surface after grinding and reported that when the surface zirconia is polished, either by grinding alone or by grinding followed by polishing, its surface and subsurface are damaged. This process resulted in the formation of microcraters, grain pullout, and an increase in the amount of rhombohedral (r) along with strained tetragonal (t) phase. Annealing the polished zirconia can reverse the zirconia phase transformation. However, the surface damage caused by grinding will remain and may lead to failure by crack propagation.(157) Vatanasak W. also supported that surface finishing and polishing can change the t phase content but annealing at 1,000 °c for 15 minutes can increase the t phase content.(141) The r phase is formed on the outer surfaces of zirconia. When zirconia experiences mechanical stress, a phase transformation of t-to-r would occur. After being annealed at 600° and 800°C for 24 h, r–to-m phase transformation could occur and the increase in annealing temperature can induce the m-to-t phase transformation. In addition, the r-to-t phase transformation will occur after annealing at 1000°C.(158) Phase transformation may result in the increase of the surface roughness due to many reasons that were previously mentioned.(157) The surface and subsurface damages caused by grinding may remain even after the restoration is well-polished or annealed. The remaining surface and subsurface damages may lead to crack propagation and result in roughening of the surface which accelerate the antagonist wear. In the current study, the mean value of the amount of tooth structure loss is similar in both polished and annealed group. However, the results could not be directly compared since the samples from each group were in different subjects.

Apart from beneficial properties of the zirconia ceramic, low-temperature degradation (LTD) is one of its disadvantages. LTD may weaken the zirconia restoration, increase the surface roughness, and promote microcracking.(159) Kobayashi et al. described the process of LTD or hydrothermal degradation. Slow t to m transformation occurs at low temperature (150-400°C) in humidity environment which causes stress to the surrounding grains and result in crack formation.(58) Rupawala et al. suggested that the zirconia showed almost no t–to-m transformation after 10,000 cycles of wear in a wet environment.(8) However, there was no evidence of the number of cycles likely to be experienced in vivo, but a provisional estimate of approximately 10,000 cycles per year was suggested.(160) The result from an in vivo study by Vatanasak W. and Wattanasermkit K., which used the same subjects as the current study, suggested that the phase transformation of zirconia (t-to-m) might not occur in the oral cavities after 6-month of usage. No significant change in the surface roughness of the zirconia crowns were observed clinically. This current study examined the opposing natural tooth wear after 6-month delivery, LTD might not be involved.

Conclusion

Within the limitation of this study we can conclude that the monolithic zirconia crown on the dental implant can cause little amount of wear of opposing enamel in 6months after delivery. The monolithic zirconia crown in both the polished and annealed groups caused lesser antagonist wear of enamel than natural teeth ($p<0.05$). However, the results from both the polished and annealed group cannot be compared to one another since the restorations were not placed in the same subject. The further study may require placing both the polished and annealed monolithic zirconia crowns in the same subject so the amount of tooth structure loss can be directly compared.

Clinical implication

Monolithic zirconia crown is one of the suitable option that can be used on dental implants in posterior teeth. However, proper polishing is necessary to reduce the wear of antagonist tooth.

REFERENCES

1. Kelly JR, Benetti P. Ceramic materials in dentistry: historical evolution and current practice. Australian dental journal. 2011;56 Suppl 1:84-96.

2. Schley J-S, Heussen N, Reich S, Fischer J, Haselhuhn K, Wolfart S. Survival probability of zirconia-based fixed dental prostheses up to 5 yr: a systematic review of the literature. European Journal of Oral Sciences. 2010;118(5):443-50.

3. Stober T, Bermejo JL, Rammelsberg P, Schmitter M. Enamel wear caused by monolithic zirconia crowns after 6 months of clinical use. Journal of oral rehabilitation. 2014;41(4):314-22.

4. Won WS, DeLong R, Kenneth JA. Effect of restorative materials on wear of human enamel. The Journal of Prosthetic Dentistry. 2002;64:194-203.

5. Wang L, Liu Y, Si W, Feng H, Tao Y, Ma Z. Friction and wear behaviors of dental ceramics against natural tooth enamel. Journal of the European Ceramic Society. 2012;32(11):2599-606.

6. Miyazaki T, Nakamura T, Matsumura H, Ban S, Kobayashi T. Current status of zirconia restoration. Journal of prosthodontic research. 2013;57(4):236-61.

7. Stober T, Bermejo JL, Schwindling FS, Schmitter M. Clinical assessment of enamel wear caused by monolithic zirconia crowns. Journal of oral rehabilitation. 2016;43(8):621-9.

8. Rupawala A, Musani SI, Madanshetty P, Dugal R, Shah UD, Sheth EJ. A study on the wear of enamel caused by monolithic zirconia and the subsequent phase transformation compared to two other ceramic systems. Journal of Indian Prosthodontic Society. 2017;17(1):8-14.

9. Sailer I, Pjetursson BE, Zwahlen M, Hammerle CH. A systematic review of the survival and complication rates of all-ceramic and metal-ceramic reconstructions after an observation period of at least 3 years. Part II: Fixed dental prostheses. Clinical oral implants research. 2007;18 Suppl 3:86-96.

10. Guess PC, Schultheis S, Bonfante EA, Coelho PG, Ferencz JL, Silva NR. All-ceramic systems: laboratory and clinical performance. Dental clinics of North America.

2011;55(2):333-52, ix.

11. Review of the Current Status of All-Ceramic Restorations [Internet]. 2007.

12. Abd El-Ghany OS, Sherief AH. Zirconia based ceramics, some clinical and biological aspects: Review. Future Dental Journal. 2016;2(2):55-64.

13. Burger W, Richter HG, Piconi C, Vatteroni R, Cittadini A, Boccalari M. New Y-TZP powders for medical grade zirconia. Journal of materials science Materials in medicine. 1997;8(2):113-8.

14. Denry I, Kelly JR. State of the art of zirconia for dental applications. Dental materials : official publication of the Academy of Dental Materials. 2008;24(3):299-307.

15. Lange FF. Transformation toughening. Journal of Materials Science. 1982;17(1):255-63.

16. Guazzato M, Albakry M, Quach L, Swain MV. Influence of grinding, sandblasting, polishing and heat treatment on the flexural strength of a glass-infiltrated alumina-reinforced dental ceramic. Biomaterials. 2004;25(11):2153-60.

17. Guazzato M, Albakry M, Swain MV, Ringer SP. Microstructure of Alumina- and Alumina/Zirconia-Glass Infiltrated Dental Ceramics. Key Engineering Materials. 2002;240-242:879-82.

18. Tsukuma K, Shimada M. Strength, fracture toughness and Vickers hardness of CeO2-stabilized tetragonal ZrO2 polycrystals (Ce-TZP). Journal of Materials Science. 1985;20(4):1178-84.

19. Guazzato M, Albakry M, Quach L, Swain MV. Influence of surface and heat treatments on the flexural strength of a glass-infiltrated alumina/zirconia-reinforced dental ceramic. Dental materials : official publication of the Academy of Dental Materials. 2005;21(5):454-63.

20. Porter DL, Heuer AH. Mechanisms of Toughening Partially Stabilized Zirconia (PSZ). Journal of the American Ceramic Society. 1977;60(3-4):183-4.

21. Hannink RHJ, Howard CJ, Kisi EH, Swain MV. Relationship between Fracture. Toughness and Phase Assemblage in Mg‐PSZ. Journal of the American Ceramic Society. 1994;77(2):571-9.

22. A. Leach C. Sintering of Magnesium Partially Stabilized Zirconia–Behaviour of an

Impurity Silicate Phase1987. 321-4 p.
23. Hannink RHJ, Kelly PM, Muddle BC. Transformation Toughening in Zirconia-Containing Ceramics. Journal of the American Ceramic Society. 2000;83(3):461-87.
24. Van der Zel JM. Zirconia Ceramic in Dental CAD/CAM: How CAD/CAM Technology Enables Zirconia To Replace Metal In Restorative Dentistry. Journal of Dental Technology. 2007;2:16-24.
25. Christel P, Meunier A, Heller M, Torre JP, Peille CN. Mechanical properties and short-term in-vivo evaluation of yttrium-oxide-partially-stabilized zirconia. Journal of biomedical materials research. 1989;23(1):45-61.
26. Ruiz L, Readey MJ. Effect of Heat Treatment on Grain Size, Phase Assemblage, and Mechanical Properties of 3 mol% Y-TZP. Journal of the American Ceramic Society. 1996;79(9):2311-40.
27. Guazzato M, Albakry M, Ringer SP, Swain MV. Strength, fracture toughness and microstructure of a selection of all-ceramic materials. Part II. Zirconia-based dental ceramics. Dental materials : official publication of the Academy of Dental Materials. 2004;20(5):449-56.
28. Krüger S, Deubener J, Ritzberger C, Höland W. Nucleation Kinetics of Lithium Metasilicate in ZrO2-Bearing Lithium Disilicate Glasses for Dental Application. international Journal of Applied Glass Science. 2013;4(1):9-19.
29. Pieger S, Salman A, Bidra AS. Clinical outcomes of lithium disilicate single crowns and partial fixed dental prostheses: a systematic review. J Prosthet Dent. 2014;112(1):22-30.
30. Rinke S, Rodiger M, Ziebolz D, Schmidt AK. Fabrication of Zirconia-Reinforced Lithium Silicate Ceramic Restorations Using a Complete Digital Workflow. Case reports in dentistry. 2015;2015:162178.
31. Zhang H, Li Z, Kim B-N, Morita K, Yoshida H, Hiraga K, et al. Effect of Alumina Dopant on Transparency of Tetragonal Zirconia. Journal of Nanomaterials. 2012;2012:5.
32. Zhang Y. Making yttria-stabilized tetragonal zirconia translucent. Dental materials : official publication of the Academy of Dental Materials. 2014;30(10):1195-203.
33. Klimke J, Trunec M, Krell A. Transparent Tetragonal Yttria-Stabilized Zirconia

Ceramics: Influence of Scattering Caused by Birefringence. Journal of the American Ceramic Society. 2011;94(6):1850-8.

34. Silva LHD, Lima E, Miranda RBP, Favero SS, Lohbauer U, Cesar PF. Dental ceramics: a review of new materials and processing methods. Brazilian oral research. 2017;31(suppl 1):e58.

35. Kim HK, Kim SH. Optical properties of pre-colored dental monolithic zirconia ceramics. J Dent. 2016;55:75-81.

36. Rinke S, Fischer C. Range of indications for translucent zirconia modifications: clinical and technical aspects. Quintessence international (Berlin, Germany : 1985). 2013;44(8):557-66.

37. Anusavice KJ, Shen C, Rawls HR. Phillips' science of dental materials. 12th ed. ed. p. 237.

38. Jung YS, Lee JW, Choi YJ, Ahn JS, Shin SW, Huh JB. A study on the in-vitro wear of the natural tooth structure by opposing zirconia or dental porcelain. The journal of advanced prosthodontics. 2010;2(3):111-5.

39. Basunbul G, Nathanson D. Human enamel wear against four dental ceramics in vitro. 2011.

40. Janyavula S, Lawson N, Cakir D, Beck P, Ramp LC, Burgess JO. The wear of polished and glazed zirconia against enamel. J Prosthet Dent. 2013;109(1):22-9.

41. Stawarczyk B, Ozcan M, Schmutz F, Trottmann A, Roos M, Hammerle CH. Two-body wear of monolithic, veneered and glazed zirconia and their corresponding enamel antagonists. Acta odontologica Scandinavica. 2013;71(1):102-12.

42. Park JH, Park S, Lee K, Yun KD, Lim HP. Antagonist wear of three CAD/CAM anatomic contour zirconia ceramics. J Prosthet Dent. 2014;111(1):20-9.

43. Lawson NC, Janyavula S, Syklawer S, McLaren EA, Burgess JO. Wear of enamel opposing zirconia and lithium disilicate after adjustment, polishing and glazing. J Dent. 2014;42(12):1586-91.

44. Mulay G, Dugal R, Buhranpurwala M. An evaluation of wear of human enamel opposed by ceramics of different surface finishes. The Journal of Indian Prosthodontic Society. 2015;15(0972-4052 (Print)).

45. Esquivel-Upshaw JF, Kim MJ, Hsu SM, Abdulhameed N, Jenkins R, Neal D, et al.

Randomized clinical study of wear of enamel antagonists against polished monolithic zirconia crowns. J Dent. 2018;68:19-27.
46. Kontos L, Schille C, Schweizer E, Geis-Gerstorfer J. Influence of surface treatment on the wear of solid zirconia. Acta odontologica Scandinavica. 2013;71(3-4):482-7.
47. Hamza TA, Sherif RM. In vitro evaluation of marginal discrepancy of monolithic zirconia restorations fabricated with different CAD-CAM systems. J Prosthet Dent. 2017;117(6):762-6.
48. Anusavice KJ. Reducing the failure potential of ceramic-based restorations. Part 2: Ceramic inlays, crowns, veneers, and bridges. General dentistry. 1997;45(1):30-5.
49. Liu PR. A panorama of dental CAD/CAM restorative systems. Compendium of continuing education in dentistry (Jamesburg, NJ : 1995). 2005;26(7):507-8, 10, 12 passim; quiz 17, 27.
50. Miyazaki T, Hotta Y, Kunii J, Kuriyama S, Tamaki Y. A review of dental CAD/CAM: current status and future perspectives from 20 years of experience. Dental materials journal. 2009;28(1):44-56.
51. Wang H, Aboushelib MN, Feilzer AJ. Strength influencing variables on CAD/CAM zirconia frameworks. Dental materials : official publication of the Academy of Dental Materials. 2008;24(5):633-8.
52. Kohorst P, Junghanns J, Dittmer MP, Borchers L, Stiesch M. Different CAD/CAM-processing routes for zirconia restorations: influence on fitting accuracy. Clinical oral investigations. 2011;15(4):527-36.
53. Huang H. Machining characteristics and surface integrity of yttria stabilized tetragonal zirconia in high speed deep grinding. Materials Science and Engineering: A. 2003;345(1):155-63.
54. Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations: Current systems and future possibilities. The Journal of the American Dental Association. 2006;137(9):1289-96.
55. Özkol E, Zhang W, Ebert J, Telle R. Potentials of the "Direct inkjet printing" method for manufacturing 3Y-TZP based dental restorations. Journal of the European Ceramic Society. 2012;32(10):2193-201.

56. Ebert J, Ozkol E, Zeichner A, Uibel K, Weiss O, Koops U, et al. Direct inkjet printing of dental prostheses made of zirconia. Journal of dental research. 2009;88(7):673-6.

57. Chartier T, Chaput C, Doreau F, Loiseau M. Stereolithography of structural complex ceramic parts. Journal of Materials Science. 2002;37(15):3141-7.

58. Kobayashi K, Kuwajima H, Masaki T. Phase change and mechanical properties of ZrO2-Y2O3 solid electrolyte after ageing. Solid State Ionics. 1981;3-4:489-93.

59. Lawson S. Environmental degradation of zirconia ceramics. Journal of the European Ceramic Society. 1995;15(6):485-502.

60. Watanabe M, Iio S, Fukuura I. Ageing behaviour of Y-TZP. Advances in Ceramics. 1984;12:391-8.

61. Winnubst AJA, Burggraaf AJ. The aging behaviour of ultrafine-grained Y-TZP in hot water. Advances in Ceramics. 1988;24:39-48.

62. Schmauder S, Schubert H. Significance of Internal Stress on the Martensite Transformation in Yttria-Stabilised Tetragonal Zirconia Polycrystals During Degradation. Journal of the American Ceramic Society. 1986;69(7):534-40.

63. Mecartney ML. Influence of an Amorphous Second Phase on the Properties of Yttria-Stabilized Tetragonal Zirconia Polycrystals (Y-TZP). Journal of the American Ceramic Society. 1987;70(1):54-8.

64. Sato T, Shimada M. Crystalline Phase Change in Yttria-Partially-Stabilized Zirconia by Low-Temperature Annealing. Journal of the American Ceramic Society. 1984;67(10):c-212.

65. Sato T, Shimada M. Transformation of Yttria-Doped Teragonal ZrO2 Polycrystals by Annealing in Water. Journal of the American Ceramic Society. 1985;68(6):356.

66. Yoshimura M, Noma T, Kawabata K, Sōmiya S. Role of H2O on the degradation process of Y-TZP. In: Sōmiya S, editor. Hydrothermal Reactions for Materials Science and Engineering: An Overview of Research in Japan. Dordrecht: Springer Netherlands; 1989. p. 396-8.

67. Nakajima K, Kobayashi K, Murata Y. Phase stability of Y-PSZ in aqueous solutions. United States: American Ceramic Society, Inc; 1983.

68. Wang J, Stevens R. Surface toughening of TZP ceramics by low temperature ageing. Ceramics International. 1989;15(1):15-21.

69. Lilley E. Review of low temperature degradation in Y-TZP's. United States: American Ceramic Society Inc; 1990.

70. Masaki T. Mechanical properties of Y-PSZ after aging at low temperature. International Journal of High Technology Ceramics. 1986;2(2):85-98.

71. Sato T, Shimada M. Transformation of ceria-doped tetragonal zirconia polycrystals by annealing in water. Journal of the American Ceramic Society. 1985;64(10).

72. Sato T, Shimada M. Control of the Tetragonal-to-Monoclinic Phase Transformation of Yttria Partially Stabilized Zirconia in Hot Water. Journal of Materials Science. 1985;20(11):3988-92.

73. Sato T, Ohtaki S, Endo T, Shimada M. Improvement of thermal stability of Yttria-doped tetragonal zirconia polycrystals by alloying with various oxides. International Journal of High Technology Ceramics. 1986;2(3):167-77.

74. Lawson S, Gill C, Dransfield GP. The effects of copper and iron oxide additions on the sintering and properties of Y-TZP. Journal of Materials Science. 1995;30(12):3057-60.

75. Whalen PJ, Reidinger F, Antrim RF. Prevention of Low-Temperature Surface Transformation by Surface Recrystallization in Yttria-Doped Tetragonal Zirconia. Journal of the American Ceramic Society. 1989;72(2):319-21.

76. Jue JF, Chen J, Virkar AV. Low-Temperature Aging of t′-Zirconia: The Role of Microstructure on Phase Stability. Journal of the American Ceramic Society. 1991;74(8):1811-20.

77. Lee JK, Kim H. Monoclinic-to-tetragonal transformation and crack healing by annealing in aged 2Y-TZP ceramics. journal of materials Science letters. 1993;12(22):1765-7.

78. Kelly JR, Denryb I. Stabilized zirconia as a structural ceramic: An overview. dental materials. 2008;24:289-98.

79. Seghi RR, Rosenstiel SF, Bauer P. Abrasion of human enamel by different dental

ceramics in vitro. Journal of dental research. 1991;70(3):221-5.

80. Ohkuma K, Kazama M, Ogura H. The grinding efficiency by diamond points developed for yttria partially stabilized zirconia. Dental materials journal. 2011;30(4):511-6.

81. d'Incau E, Saulue P. Understanding dental wear. Journal of Dentofacial Anomalies and orthodontics. 2012;15(104):1-19.

82. DeLong R. Intra-oral restorative materials wear: rethinking the current approaches: how to measure wear. Dental materials : official publication of the Academy of Dental Materials. 2006;22(8):702-11.

83. Dowson D. History of tribology. 2nd ed. ed. London: Professional Engineering Publishing; 1998.

84. Rilo B, Fernandez J, Da Silva L, Martinez Insua A, Santana U. Frontal-plane lateral border movements and chewing cycle characteristics. Journal of oral rehabilitation. 2001;28(10):930-6.

85. Mair LH, Stolarski TA, Vowles RW, Lloyd CH. Wear: mechanisms, manifestations and measurement. Report of a workshop. Journal of Dentistry. 1996;24(1):141-8.

86. Abebe M, Appl FC. Theoretical analysis of the basic mechanics of abrasive processes: Part I: General model. Wear. 1988;126(3):251-66.

87. Gahr KHZ. Wear by hard particles. Tribology International. 1998;31(10):587-96.

88. Gahr KHZ. Chapter 4 Classification of Wear Processes. In: Gahr K-HZ, editor. Tribology Series. 10: Elsevier; 1987. p. 80-131.

89. Cuy JL, Mann AB, Livi KJ, Teaford MF, Weihs TP. Nanoindentation mapping of the mechanical properties of human molar tooth enamel. Archives of Oral Biology. 2002;47(4):281-91.

90. Maas MC. Enamel structure and microwear: an experimental study of the response of enamel to shearing force. American journal of physical anthropology. 1991;85(1):31-49.

91. Xu HH, Smith DT, Jahanmir S, Romberg E, Kelly JR, Thompson VP, et al. Indentation damage and mechanical properties of human enamel and dentin. Journal of dental research. 1998;77(3):472-80.

92. Zheng J, Zhou ZR, Zhang J, Li H, Yu HY. On the friction and wear behaviour of

human tooth enamel and dentin. Wear. 2003;255(7):967-74.
93. Zheng J, Zhou ZR. Study of in vitro wear of human tooth enamel. Tribology Letters. 2007;26(2):181-9.
94. Roy S, Basu B. Mechanical and tribological characterization of human tooth. Materials Characterization. 2008;59(6):747-56.
95. Smith BG, Bartlett DW, Robb ND. The prevalence, etiology and management of tooth wear in the United Kingdom. J Prosthet Dent. 1997;78(4):367-72.
96. Li H, Zhou ZR. Wear behavior of human teeth in dry and artificial saliva conditions2002. 980-4 p.
97. Mahalick JA, Knap FJ, Weiter EJ. Occlusal Wear in Prosthodontics. The Journal of the American Dental Association. 1971;82(1):154-9.
98. Phillips RW. Skinner's Science of Dental Materials 8th edition. Philadelphia: W. B Saunders Co, Harcourt Brace and Co; 1982.
99. Taylor DF, Bayne SC, Sturdevant JR, Wilder AD. Comparison of direct and indirect methods for analyzing wear of posterior composite restorations. Dental materials : official publication of the Academy of Dental Materials. 1989;5(3):157-60.
100. Cvar JF, Ryge G. Criteria for the clinical evaluation of dental restorative materials. San Francisco: U.S. Dept. of Health, Education, and Welfare, Public Health Service, National Institutes of Health, Bureau of Health Manpower Education, Division of Dental Health, Dental Health Center; 1971. vii, 39 p. p.
101. Leinfelder KF, Taylor DF, Barkmeier WW, Goldberg AJ. Quantitative wear measurement of posterior composite resins. Dental Materials. 1986;2(5):198-201.
102. Bayne SC, Taylor DF, Rekow ED, Wilder AD, Heymann HO. Confirmation of Leinfelder clinical wear standards. Dental materials : official publication of the Academy of Dental Materials. 1994;10(1):11-8.
103. Peters MCRB, Delong R, Pintado MR, Pallesen U, Qvist V, Douglas WH. Comparison of two measurement techniques for clinical wear. Journal of Dentistry. 1999;27(7):479-85.
104. Lambrechts P, Braem M, Vanherle J. Evaluation of clinical performance for posterior composite resins and dentin adhesives. Operative dentistry. 1987;12:41-88.
105. Jacobs R, van Steenberghe D. Role of periodontal ligament receptors in the

tactile function of teeth: a review. Journal of periodontal research. 1994;29(3):153-67.
106. Kumar P, Oka M, Ikeuchi K, Shimizu K, Yamamuro T, Okumura H, et al. Low wear rate of UHMWPE against zirconia ceramic (Y-PSZ) in comparison to alumina ceramic and SUS 316L alloy. Journal of biomedical materials research. 1991;25(7):813-28.
107. Albashaireh ZS, Ghazal M, Kern M. Two-body wear of different ceramic materials opposed to zirconia ceramic. J Prosthet Dent. 2010;104(2):105-13.
108. Kim MJ, Oh SH, Kim JH, Ju SW, Seo DG, Jun SH, et al. Wear evaluation of the human enamel opposing different Y-TZP dental ceramics and other porcelains. J Dent. 2012;40(11):979-88.
109. Kwon MS, Oh SY, Cho SA. Two-body wear comparison of zirconia crown, gold crown, and enamel against zirconia. Journal of the mechanical behavior of biomedical materials. 2015;47:21-8.
110. Wassell RW, McCabe JF, Walls AW. A two-body frictional wear test. Journal of dental research. 1994;73(9):1546-53.
111. Wassell RW, McCabe JF, Walls AWG. Wear characteristics in a two-body wear test. Dental Materials. 1994;10(4):269-74.
112. Mehl C, Scheibner S, Ludwig K, Kern M. Wear of composite resin veneering materials and enamel in a chewing simulator. Dental materials : official publication of the Academy of Dental Materials. 2007;23(11):1382-9.

113. Ghazal M, Yang B, Ludwig K, Kern M. Two-body wear of resin and ceramic denture teeth in comparison to human enamel. Dental materials : official publication of the Academy of Dental Materials. 2008;24(4):502-7.
114. Preis V, Behr M, Kolbeck C, Hahnel S, Handel G, Rosentritt M. Wear performance of substructure ceramics and veneering porcelains. Dental materials : official publication of the Academy of Dental Materials. 2011;27(8):796-804.
115. Chochlidakis KM, Papaspyridakos P, Geminiani A, Chen C-J, Feng IJ, Ercoli C. Digital versus conventional impressions for fixed prosthodontics: A systematic review and meta-analysis. The Journal of Prosthetic Dentistry. 2016;116(2):184-90.e12.
116. Joda T, Bragger U. Digital vs. conventional implant prosthetic workflows: a cost/time analysis. Clinical oral implants research. 2015;26(12):1430-5.
117. Lee SJ, Betensky RA, Gianneschi GE, Gallucci GO. Accuracy of digital versus

conventional implant impressions. Clinical oral implants research. 2015;26(6):715-9.

118. Papaspyridakos P, Gallucci GO, Chen CJ, Hanssen S, Naert I, Vandenberghe B. Digital versus conventional implant impressions for edentulous patients: accuracy outcomes. Clinical oral implants research. 2016;27(4):465-72.

119. Lin WS, Harris BT, Elathamna EN, Abdel-Azim T, Morton D. Effect of implant divergence on the accuracy of definitive casts created from traditional and digital implant-level impressions: an in vitro comparative study. The International journal of oral & maxillofacial implants. 2015;30(1):102-9.

120. Ting-Shu S, Jian S. Intraoral Digital Impression Technique: A Review. Journal of prosthodontics : official journal of the American College of Prosthodontists. 2015;24(4):313-21.

121. Caputi S, Varvara G. Dimensional accuracy of resultant casts made by a monophase, one-step and two-step, and a novel two-step putty/light-body impression technique: an in vitro study. J Prosthet Dent. 2008;99(4):274-81.

122. Chugh A, Arora A, Singh VP. Accuracy of different putty-wash impression techniques with various spacer thickness. International journal of clinical pediatric dentistry. 2012;5(1):33-8.

123. Thongthammachat S, Moore BK, Barco MT, 2nd, Hovijitra S, Brown DT, Andres CJ. Dimensional accuracy of dental casts: influence of tray material, impression material, and time. Journal of prosthodontics : official journal of the American College of Prosthodontists. 2002;11(2):98-108.

124. Rodriguez JM, Bartlett DW. The dimensional stability of impression materials and its effect on in vitro tooth wear studies. Dental materials : official publication of the Academy of Dental Materials. 2011;27(3):253-8.

125. Campagni WV, Preston JD, Reisbick MH. Measurement of paint-on die spacers used for casting relief. J Prosthet Dent. 1982;47(6):606-11.

126. Gorman CM, McDevitt WE, Hill RG. Comparison of two heat-pressed all-ceramic dental materials. Dental materials : official publication of the Academy of Dental Materials. 2000;16(6):389-95.

127. Seelbach P, Brueckel C, Wostmann B. Accuracy of digital and conventional impression techniques and workflow. Clinical oral investigations. 2013;17(7):1759-64.

128. Pradies G, Zarauz C, Valverde A, Ferreiroa A, Martinez-Rus F. Clinical evaluation comparing the fit of all-ceramic crowns obtained from silicone and digital intraoral impressions based on wavefront sampling technology. J Dent. 2015;43(2):201-8.
129. Syrek A, Reich G, Ranftl D, Klein C, Cerny B, Brodesser J. Clinical evaluation of all-ceramic crowns fabricated from intraoral digital impressions based on the principle of active wavefront sampling. J Dent. 2010;38(7):553-9.
130. Rangert B, Krogh PH, Langer B, Van Roekel N. Bending overload and implant fracture: a retrospective clinical analysis. The International journal of oral & maxillofacial implants. 1995;10(3):326-34.
131. Verma M, Nanda A, Sood A. Principles of occlusion in implant dentistry. Journal of the International Clinical Dental Research Organization. 2015;7(3):27-33.
132. Chen YY, Kuan CL, Wang YB. Implant occlusion: biomechanical considerations for implant-supported prostheses. J Dent Sci. 2008;3(2):65-74.
133. Kim Y, Oh TJ, Misch CE, Wang HL. Occlusal considerations in implant therapy: clinical guidelines with biomechanical rationale. Clinical oral implants research. 2005;16(1):26-35.
134. Gross MD. Occlusion in implant dentistry. A review of the literature of prosthetic determinants and current concepts. Australian dental journal. 2008;53 Suppl 1:S60-8.
135. Isidor F. Loss of osseointegration caused by occlusal load of oral implants. A clinical and radiographic study in monkeys. Clinical oral implants research. 1996;7(2):143-52.
136. Isidor F. Histological evaluation of peri-implant bone at implants subjected to occlusal overload or plaque accumulation. Clinical oral implants research. 1997;8(1):1-9.
137. Kaukinen JA, Edge MJ, Lang BR. The influence of occlusal design on simulated masticatory forces transferred to implant-retained prostheses and supporting bone. J Prosthet Dent. 1996;76(1):50-5.
138. Miyata T, Kobayashi Y, Araki H, Ohto T, Shin K. The influence of controlled occlusal overload on peri-implant tissue. Part 3: A histologic study in monkeys. The International journal of oral & maxillofacial implants. 2000;15(3):425-31.
139. Gou M, Chen H, Kang J, Wang H. Antagonist enamel wear of tooth-supported

monolithic zirconia posterior crowns in vivo: A systematic review. J Prosthet Dent. 2018.

140. Lohbauer U, Reich S. Antagonist wear of monolithic zirconia crowns after 2 years. Clinical oral investigations. 2017;21(4):1165-72.

141. Vatanasak W, Wattanasermkit K. The comparison of crystalline phase, surface roughness and surface morphology after polishing ahd annealing of monolithic zirconia implant crowns. Chulalongkorn University Dental Journal. 2019.

142. Nakashima J, Taira Y, Sawase T. In vitro wear of four ceramic materials and human enamel on enamel antagonist. Eur J Oral Sci. 2016;124(3):295-300.

143. Cardelli P, Manobianco FP, Serafini N, Murmura G, Beuer F. Full-Arch, Implant-Supported Monolithic Zirconia Rehabilitations: Pilot Clinical Evaluation of Wear Against Natural or Composite Teeth. Journal of prosthodontics : official journal of the American College of Prosthodontists. 2016;25(8):629-33.

144. Mundhe K, Jain V, Pruthi G, Shah N. Clinical study to evaluate the wear of natural enamel antagonist to zirconia and metal ceramic crowns. J Prosthet Dent. 2015;114(3):358-63.

145. Sripetchdanond J, Leevailoj C. Wear of human enamel opposing monolithic zirconia, glass ceramic, and composite resin: An in vitro study. The Journal of Prosthetic Dentistry. 2014;112(5):1141-50.

146. Lambrechts P, Braem M, Vuylsteke-Wauters M, Vanherle G. Quantitative in vivo wear of human enamel. Journal of dental research. 1989;68(12):1752-4.

147. Aldegheishem A, Alfaer A, Brezavšček M, Vach K, Eliades G, Att W. Wear behavior of zirconia substrates against different antagonist materials. The international journal of esthetic dentistry. 2015;10(3):468-85.

148. Chong BJ, Thangavel AK, Rolton SB, Guazzato M, Klineberg IJ. Clinical and laboratory surface finishing procedures for zirconia on opposing human enamel wear: A laboratory study. Journal of the mechanical behavior of biomedical materials. 2015;50:93-103.

149. Passos SP, Torrealba Y, Major P, Linke B, Flores-Mir C, Nychka JA. In vitro wear behavior of zirconia opposing enamel: a systematic review. Journal of prosthodontics : official journal of the American College of Prosthodontists. 2014;23(8):593-601.

150. Woda A, Gourdon AM, Faraj M. Occlusal contacts and tooth wear. The Journal

of Prosthetic Dentistry. 1987;57(1):85-93.
151. Gates JD. Two-body and three-body abrasion: A critical discussion. Wear. 1998;214(1):139-46.
152. Mohammadi-Bassir M, Babasafari M, Rezvani MB, Jamshidian M. Effect of coarse grinding, overglazing, and 2 polishing systems on the flexural strength, surface roughness, and phase transformation of yttrium-stabilized tetragonal zirconia. J Prosthet Dent. 2017;118(5):658-65.
153. Park C, Vang M-S, Park S-W, Lim H-P. Effect of various polishing systems on the surface roughness and phase transformation of zirconia and the durability of the polishing systems. The Journal of Prosthetic Dentistry. 2017;117(3):430-7.
154. Al-Haj Husain N, Camilleri J, Ozcan M. Effect of polishing instruments and polishing regimens on surface topography and phase transformation of monolithic zirconia: An evaluation with XPS and XRD analysis. Journal of the mechanical behavior of biomedical materials. 2016;64:104-12.
155. Caglar I, Ates SM, Yesil Duymus Z. The effect of various polishing systems on surface roughness and phase transformation of monolithic zirconia. The journal of advanced prosthodontics. 2018;10(2).
156. Huh Y-H, Park C-J, Cho L-R. Evaluation of various polishing systems and the phase transformation of monolithic zirconia. The Journal of Prosthetic Dentistry. 2016;116(3):440-9.
157. Denry IL, Holloway JA. Microstructural and crystallographic surface changes after grinding zirconia-based dental ceramics. J Biomed Mater Res B Appl Biomater. 2006;76(2):440-8.
158. Kitano Y, Mori Y, Ishitani A, Masaki T. Rhombohedral Phase in Y2O3-Partially-Stabilized ZrO2. Journal of the American Ceramic Society. 2005;71:C-34-C-6.
159. Pereira GKR, Venturini AB, Silvestri T, Dapieve KS, Montagner AF, Soares FZM, et al. Low-temperature degradation of Y-TZP ceramics: A systematic review and meta-analysis. Journal of the mechanical behavior of biomedical materials. 2015;55:151-63.
160. Gale MS, Darvell BW. Thermal cycling procedures for laboratory testing of dental restorations. J Dent. 1999;27(2):89-99.

161. Koenig V, Wulfman CP, Derbanne MA, Dupont NM, Le Goff SO, Tang ML, et al. Aging of monolithic zirconia dental prostheses: Protocol for a 5-year prospective clinical study using ex vivo analyses. Contemp Clin Trials Commun. 2016;4:25-32.

APPENDIX

STATISTICAL ANALYSIS

Descriptives

	group			Statistic	Std. Error
enamel_wear	Po	Mean		28.0800	3.94374
		95% Confidence Interval for Mean	Lower Bound	17.1304	
			Upper Bound	39.0296	
		5% Trimmed Mean		28.2778	
		Median		29.7600	
		Variance		77.766	
		Std. Deviation		8.81848	
		Minimum		14.08	
		Maximum		38.52	
		Range		24.44	
		Interquartile Range		13.08	
		Skewness		-.969	.913
		Kurtosis		2.400	2.000
	An	Mean		29.8640	5.28684
		95% Confidence Interval for Mean	Lower Bound	15.1854	
			Upper Bound	44.5426	
		5% Trimmed Mean		29.6444	
		Median		29.4800	
		Variance		139.753	
		Std. Deviation		11.82173	
		Minimum		15.44	
		Maximum		48.24	
		Range		32.80	
		Interquartile Range		18.24	
		Skewness		.796	.913
		Kurtosis		2.079	2.000
	CPo	Mean		31.7600	6.07194
		95% Confidence Interval for Mean	Lower Bound	14.9016	
			Upper Bound	48.6184	
		5% Trimmed Mean		31.7511	
		Median		33.9200	
		Variance		184.342	

				Statistic	Std. Error
		Std. Deviation		13.57728	
		Minimum		15.44	
		Maximum		48.24	
		Range		32.80	
		Interquartile Range		26.20	
		Skewness		-.089	.913
		Kurtosis		-1.941	2.000
	CAn	Mean		35.1760	5.63941
		95% Confidence Interval for Mean	Lower Bound	19.5185	
			Upper Bound	50.8335	
		5% Trimmed Mean		34.7956	
		Median		33.2400	
		Variance		159.015	
		Std. Deviation		12.61011	
		Minimum		21.40	
		Maximum		55.80	
		Range		34.40	
		Interquartile Range		18.80	
		Skewness		1.264	.913
		Kurtosis		2.738	2.000

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	group	Statistic	df	Sig.	Statistic	df	Sig.
enamel_wear	Po	.304	5	.148	.892	5	.368
	An	.298	5	.167	.921	5	.535
	CPo	.190	5	.200*	.955	5	.770
	CAn	.327	5	.086	.878	5	.302

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
CPo - Po	Negative Ranks	0[a]	.00	.00
	Positive Ranks	5[b]	3.00	15.00
	Ties	0[c]		
	Total	5		
CAn - An	Negative Ranks	0[d]	.00	.00
	Positive Ranks	5[e]	3.00	15.00
	Ties	0[f]		
	Total	5		

a. CPo < Po

b. CPo > Po

c. CPo = Po

d. CAn < An

e. CAn > An

f. CAn = An

Test Statistics[a]

	CPo - Po	CAn - An
Z	-2.023[b]	-2.023[b]
Asymp. Sig. (2-tailed)	.043	.043

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

VITA

NAME	Supatsorn Benjaniratisai
DATE OF BIRTH	10 January 1990
PLACE OF BIRTH	Thailand
INSTITUTIONS ATTENDED	Chulalongkorn University
HOME ADDRESS	132/4 soi.3 Bangkruai-sainoi Rd., Bangkruai, Bangkruai, Nonthaburi 11130