EFFECT OF DIFFERENT POLISHING SYSTEMS, FORCES, AND DURATIONS ON SURFACE ROUGHNESS AND PHASE TRANSFORMATION OF MONOLITHIC ZIRCONIA

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ผลของชนิดหัวขัด แรงกด และระยะเวลาในการขัดต่อความหยาบพื้นผิวและการเปลี่ยนวัฏภาคของโมโนลิธิคเซอร์โคเนีย

นายทรงศักดิ์ มั่นคงสุจริต

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต

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Thesis Title: EFFECT OF DIFFERENT POLISHING SYSTEMS, FORCES, AND DURATIONS ON SURFACE ROUGHNESS AND PHASE TRANSFORMATION OF MONOLITHIC ZIRCONIA

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ทรงศักดิ์ มั่นคงสุจริต : ผลของชนิดหัวขัด แรงกด และระยะเวลาในการขัดต่อความหยาบพื้นผิวและการเปลี่ยนวัฏภาคของโมโนลิธิคเซอร์โคเนีย. (EFFECT OF DIFFERENT POLISHING SYSTEMS, FORCES, AND DURATIONS ON SURFACE ROUGHNESS AND PHASE TRANSFORMATION OF MONOLITHIC ZIRCONIA) อ.ที่ปรึกษาหลัก : ผศ. ทญ. ดร.ปรารมภ์ ซาลิมี

งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาเปรียบเทียบความหยาบพื้นผิว (Ra) ของโมโนลิธิคเซอร์โคเนียจากการขัดด้วยชนิดของหัวขัด แรงกด และระยะเวลาต่างๆกัน รวมถึงการเปลี่ยนวัฏภาคของเซอร์โคเนีย มีวิธีการโดยนำเซอร์โคเนียมาขึ้นรูปได้ชิ้นงานขนาด 7 x 5 x 4 มม.^{3} จำนวน 72 ชิ้น แบ่งเป็น 9 กลุ่ม กลุ่มละ 8 ชิ้น ตามชนิดหัวขัดและแรงที่ใช้ในการทดสอบ นำชิ้นงานมากรอผิวหน้าด้วยหัวกรอกากเพชรละเอียดเป็นเวลา 15 วินาที ทำการวัดค่า Ra เพื่อใช้เป็นค่าอ้างอิง จากนั้นนำชิ้นงานในแต่ละกลุ่มมาทำการขัดด้วยหัวขัดสำหรับพอร์ซเลน (เซรามาสเตอร์) หรือหัวขัดสำหรับเซอร์โคเนีย (ไดอะเซอร์คอน, โคเม็ตซีอาร์) ด้วยแรง 1, 2 หรือ 3 นิวตัน ตามลำดับ ด้วยหัวขัดหยาบ 15 วินาที 2 ครั้ง ตามด้วยหัวขัดละเอียด 15 วินาที อีก 2 ครั้ง โดยทำการวัดค่า Ra ทุก 15 วินาที วิเคราะห์การเปลี่ยนแปลงวัฏภาคของเซอร์โคเนียโดยใช้วิธีการวิเคราะห์การเลี้ยวเบนของรังสีเอกซ์ ใช้สถิติการวิเคราะห์ความแปรปรวนแบบวัดซ้ำในการวิเคราะห์ปัจจัยระยะเวลาในการขัด และใช้สถิติการวิเคราะห์ความแปรปรวนแบบสองทางในการวิเคราะห์ปัจจัยแรงขัดและชนิดหัวขัด ผลการศึกษาพบว่าระยะเวลาที่ขัดเพิ่มขึ้นส่งผลให้พื้นผิวเซอร์โคเนียมีค่า Ra ลดลง ($P < 0.001$) แรงที่มากขึ้นส่งผลให้ชิ้นงานเรียบขึ้น ($P < 0.001$) ไม่มีความแตกต่างอย่างมีนัยสำคัญระหว่างชนิดหัวขัดในขั้นตอนขัดหยาบ ($P = 0.376$) ชนิดของหัวขัดมีผลต่อค่า Ra อย่างมีนัยสำคัญในขั้นตอนขัดละเอียด ($P < 0.001$) โดยโคเม็ตซีอาร์และไดอะเซอร์คอนสามารถขัดเซอร์โคเนียให้พื้นผิวที่เรียบกว่าเมื่อเทียบกับเซรามาสเตอร์ ($P < 0.001$ และ $P = 0.002$ ตามลำดับ) ชิ้นงานเซอร์โคเนียในกลุ่มที่ได้รับการขัดมีสัดส่วนของวัฏภาคโมโนคลินิกอยู่ระหว่างร้อยละ 0.62 ถึง 1.18 ซึ่งไม่มีความแตกต่างอย่างมีนัยสำคัญกับชิ้นงานเริ่มต้นซึ่งมีสัดส่วนของวัฏภาคโมโนคลินิกที่ร้อยละ 0.775

สาขาวิชา	ทันตกรรมประดิษฐ์	ลายมือชื่อนิสิต	
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Songsak Munkongsujarit : EFFECT OF DIFFERENT POLISHING SYSTEMS, FORCES, AND DURATIONS ON SURFACE ROUGHNESS AND PHASE TRANSFORMATION OF MONOLITHIC ZIRCONIA. Advisor: Asst. Prof. Dr. Prarom Salimee

This study aimed to determine the effect of polishing systems, forces and durations on the surface roughness and phase transformation of zirconia. 72 pieces of fully sintered zirconia size 7 x 5 x 4 mm were fabricated with CAD/CAM, then divided into nine groups depending on the polishing systems and forces. All specimens were ground with fine diamond bur as the control, and initial surface roughness (Ra) was measured. The samples were then polished with one of the zirconia polishing systems (Diazircon or Komet ZR) or porcelain polishing system (Ceramaster), with forces at 1, 2 and 3 newtons. The polishing procedure began with coarse grit polisher for 15 s, twice, followed by fine grit polisher for 15 s, twice. The Ra was measured after each 15 s. X-ray diffraction analysis (XRD) was used to evaluate the phase transformation of zirconia. Repeated measured ANOVA was used to assess the effect of polishing duration on Ra in each group. Two-way ANOVA were used to assess the effect of polishing systems, forces. The results found that increasing duration of polishing significant reducing the Ra ($P < 0.001$), while higher force also significantly reduced the Ra value ($P < 0.001$). There was no statistical significance among the polishing systems when polishing with coarse grit polisher ($P = 0.376$); the polishing systems had a significant effect on Ra when polishing with fine grit polisher ($P < 0.001$). Komet ZR and Diazircon created a smoother surface than Ceramaster ($P < 0.001$ and $P = 0.002$, respectively). Monoclinic phase of zirconia in polishing group varies from 0.62 to 1.18%, which had no significant difference from as-received specimen (0.775%).

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

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CHAPTER I

INTRODUCTION

Nowadays, zirconia has gained more popularity in restorative dental material because of its exceptionally high mechanical properties comparing to other ceramic materials[1]. There are two ways to use zirconia for restorations: veneered zirconia, (feldspathic porcelain with zirconia coping) and monolithic zirconia. To overcome the problem of porcelain chipping, which is often found in veneered zirconia[2], monolithic zirconia restorations have been increasingly used. Before the cementation of monolithic zirconia restoration, occlusal adjustment is usually performed, which would lead to the rough surface of zirconia. The rough surface of restoration leads to clinical problems such as wear of the antagonist tooth[3]; retention of microbial biofilm[4] and inflammation of the periodontal tissues[5]; staining; unsatisfactory esthetics and decreased resistance to cracks propagation.[1] To obtain a smooth surface, polishing of the restoration after occlusal adjustment is necessary. Due to high surface hardness of zirconia, polishing bur that contains diamond particles is recommended to carry out the procedure. Feldspathic porcelain polishing system is one of the options for polishing. However, as porcelain has lower hardness than zirconia, its effectiveness is questionable when being used with zirconia restorations. For this reason, the manufacturer has created zirconia polishing system specifically for polishing dental zirconia. Park et al.[6] investigated the effects of two zirconia polishing systems and one porcelain polishing system by polished on the zirconia specimens, polishing was carried out for two minutes, however, the researchers did not mention how to control the polishing force during the polishing process. The result showed that zirconia polishing systems created a smoother surface on zirconia than the feldspathic porcelain polishing system. However, due to less abrasive material contained, it may be possible to use porcelain polishing system to polish the zirconia by using appropriate polishing force and duration.

Many factors should be considered in the polishing process, such as polishing instrument, polishing time, polishing speed, and contact polishing force[7]. Heintz et al.[8] (2006) demonstrated that contact polishing force has an influence on surface roughness for hybrid composites. To date, there are a number of studies concerning the polishing of zirconia, but few studies concerned of duration, but no study concerned of the force in polishing dental zirconia.

High contact force while polishing restoration can generate heat. This may cause the phase transformation of zirconia, which in turn may lead to the disruption of the mechanical property of zirconia[9]. For such reason, this study will evaluate the surface roughness and phase transformation of monolithic zirconia after polishing with different polishing systems, durations, as well as contact forces in order to determine suitable duration and force of polishing monolithic zirconia

Research question

1. Is there any difference in surface roughness and phase transformation of monolithic zirconia after polishing with different polishing systems?

2. Is there any difference in surface roughness and phase transformation of monolithic zirconia after polishing with different forces?

3. Is there any difference in surface roughness and phase transformation of monolithic zirconia after polishing with different durations?

4. Is there any difference in surface roughness of monolithic zirconia after polishing with different forces combined with different polishing systems?

Objective

To determine the surface roughness and phase transformation of monolithic zirconia after polishing with different polishing systems, forces and durations.

Hypothesis

Hypothesis 1

Null hypothesis

H_0 = There is no difference in surface roughness of monolithic zirconia after polishing with different polishing systems at the same duration and force.

Alternative hypothesis

H_1 = There is the difference in surface roughness of monolithic zirconia after polishing with different polishing systems at the same duration and force.

Hypothesis 2

Null hypothesis

H_0 = There is no difference in surface roughness of monolithic zirconia after polishing with different forces at the same duration and polishing system.

Alternative hypothesis

H_1 = There is the difference in surface roughness of monolithic zirconia after polishing with different forces at the same duration and polishing system.

Hypothesis 3

Null hypothesis

H_0 = There is no difference in surface roughness of monolithic zirconia after increase duration when polishing at the same force and polishing system.

Alternative hypothesis

H_1 = There is the difference in surface roughness of monolithic zirconia after increase duration when polishing at the same force and polishing system.

Hypothesis 4

Null hypothesis

H_0 = There is no difference in surface roughness of monolithic zirconia after polishing with different forces combined with different polishing systems.

Alternative hypothesis

H_1 = There is the difference in surface roughness of monolithic zirconia after polishing with different forces combined with different polishing systems.

Keywords

1. Monolithic zirconia
2. Phase transformation
3. Polishing
4. Surface roughness

Type of research

Laboratory experimental research

CHAPTER II

LITERATURE REVIEW

Zirconia in dentistry

Zirconia (ZrO_2) is a polymorphic material that occurs in three different crystal structures, depending on the temperature[10, 11](Figure 1).

1. Monoclinic phase (room temperature to 1170°C) with brittle and low mechanical property
2. Tetragonal phase (1170°C – 2370°C) with higher mechanical property
3. Cubic phase (2370°C – up to melting point)

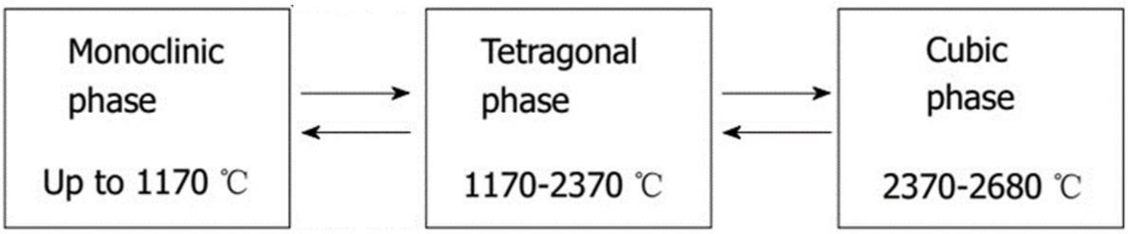

Figure 1 Temperature-related phase transformation of zirconia.

The transformation from the tetragonal phase to the monoclinic phase when cooling will cause the volume expansion (4%), inducing a very large stress and leading to crack formation and reduction in strength and toughness. Under this condition, pure zirconia would be useless for dental restorative material. The solution is by adding pure zirconia with oxides such as calcium oxide (CaO), magnesium oxide (MgO), yttrium oxide (Y_2O_3) and cerium oxide (CeO_2) allowing the stabilization of the tetragonal structure at room temperature. In this way the positive mechanical property of the tetragonal phase is preserved. The most common stabilizer for dental zirconia is Y_2O_3.The addition of 3% Y_2O_3 is called yttria-stabilized tetragonal zirconia polycrystals (Y-TZP).

However, when heat or stress is applied to zirconia during various treatments such as grinding, sandblasting, or autoclave, the transformation from tetragonal phase to monoclinic phase might occur and affect the mechanical property of zirconia. The transformation causes a volume expansion of 4%, creating a compressive layer. This layer opposes the propagation of cracks and increase the mechanical properties of zirconia which is called "Transformation toughening[12]" However, this advantage is lost when the depth of the defects occurred is greater than the compressive layer, resulting in higher levels of tensile stresses, susceptibility to surface damage and an increase of the surface roughness.

The fabrication of Y-TZP restoration can be performed by milling the zirconia block using CAD/CAM procedure which has two systems[11].

1. Hard machining

This system is performed by milling the fully sintered block; it is also called "hot isostatic pressing", the Y-TZP blocks are sintered and condensed at high temperatures (1400–1500°C) and under high pressure in inert gas medium. These blocks are very hard, dense and homogeneous because of the extreme hardness of sintered zirconia, a good milling system is required that needs an extended milling time compared to the soft-milling process. Fully-sintered HIP zirconia has a denser polycrystalline structure with less porosity than non-HIP material, and this should translate clinically into increased resistance to fracture. This system has the advantage of a well adaptation and marginal fit, because there is no shrinkage in the process, but has the disadvantage of high cost in production since it requires very tough and wear-resistant cutting devices.

2. Soft machining

The soft machining process is the most common manufacturing system for Y-TZP, based on milling of partially sintered blocks. CAD software programs design the enlarged framework to compensate shrinkage. In CAM procedure, the framework is machined according to the designed form. After this step, the sinterization is performed. Since volume shrinkage of restoration is about 20-30%, the zirconia framework reverses previous dimensions. The advantage of this system is relatively low cost since milling partially sintered block does not required effective cutting device as fully sintered block, the disadvantage of this system is the shrinkage of framework after final sinter. However, the CAD/CAM software calculates the final dimension to compensate shrinkage.

Clinical use of zirconia

Zirconia was introduced in dentistry in the 1990s with the high mechanical properties but opaque color. It has been used as a core material to support veneering ceramic. Zirconia veneer system can be used as a restoration for posterior single crown, posterior multiple unit fixed dental prostheses (FDPs)[10]. There were many studies about the clinical failure of veneering zirconia. Catastrophic fractures within the zirconia core ceramic are reported at 0-7% for single crowns after two years and at 1% to 8% for FDPs after 2 to 5 years[13-16]. Ten years cumulative survival rate for three-unit bridge is about 85%[17]. The rates of chipping of zirconia veneering ceramics have been reported to be 2% to 9% for single crowns after 2-3 years and 3% to 36% for FDPs after 1-5 years[16,18-20]. Implant-supported zirconia restorations revealed even higher rates at 8% for single crowns after six months and at 53% for FDPs after one year[21-23]. With the high rate of chipping of zirconia veneering ceramics, the trend of fabrication of monolithic zirconia restoration to avoid veneering failure increased. With the opaque of zirconia, different methods have been used to improve the translucency of Y-TZP, including introducing cubic phase zirconia; reducing the amount of Al_2O_3 from 0.25 to 0.1% of weight, which is added during manufacturing for aging resistance; adding 0.2 mol% of La_2O_3 to Y-TZP; modifying the sintering time and temperature; reducing the grain size, which can effectively eliminate light scattering and improve zirconia translucency[24,25]. Milling the zirconium oxide powders into smaller particles, which are then mixed with a suitable binder to increase the compaction and density, eliminates the porosity that highly affects light scattering and translucency[11,26]. Monolithic zirconia is widely used in clinical practice for single and multiple unit restorations, implant abutments, implant supported prostheses, orthodontic brackets. Sulaiman et al. (2016)[27] studied about fracture rate of monolithic zirconia restorations up to 5 years. This study found that the overall fracture rate up to 5 years for all restorations (single unit or multiple unit) was 1.09%. While the fracture rate was 0.69% for single unit crown and 2.60% for FDPs.

Polishing and Surface roughness of zirconia

A smooth surface of dental zirconia restorative material is essential for esthetic and function. Miyazaki et al. (2013)[11] showed the correlation between the glossiness and the surface roughness of dental zirconia. The glossiness increased significantly with decreasing surface roughness. The high surface roughness is susceptible to bacterial plaque retention. Bollen et al. (1997)[4] reviewed that threshold for surface roughness for plaque retention on hard surface of material is 0.2 µm. If material roughness is more than this value, the material will be susceptible for plaque accumulation. Many studies proved that highly polished zirconia shows the least wear of antagonist compared to zirconia with high surface roughness[28-30]. The strength of polishing and grinding on zirconia is still controversial. Some investigators concluded that grinding could increase the strength of zirconia[31-33] while others have reported that grinding zirconia without polishing reduced its strength[34,35].

The effectiveness of finishing or polishing device on the results of surface roughness of the restoration is determined by many factors such as polishing instrument (abrasive used in the device, type of the binder), polishing time, polishing speed, polishing pressure, etc[7]. There are several finishing and polishing systems commercially available that are specific for zirconia restoration, for example, Komet ZR (Gebr Brasseler GmbH, Germany), ZilMaster (Shofu Inc, Japan), EVE Diacera (EVE Ernst Vetter GmbH, Germany). These systems contain a series of diamond burs of various shapes. Another polisher for zirconia is the diamond polishing paste. It mainly contains diamond grains (1–6 μm) and other fine oxides (less 0.5 μm) such as anatase (TiO_2), corundum (Al_2O_3). These diamond pastes are usually used to polish with plastic or rubber cone and soft brush[1]. The diamond paste commercially available are, e.g., Diapolisher paste (GC, Japan), Dura-PolishDia (Shofu Inc, Japan). Huh et al. (2016)[36] used energy dispersive spectrometer (EDS) to analyze the zirconia polishing systems composition. Six zirconia polishing systems that were analyzed in this study were D&Z Zirconia Polishing, EVE Diacera, CeraGloss, StarGloss, LUSTER, DFS Diamond Zirconia Tools. It was confirmed that diamond was used as main abrasive in all systems, D&Z and DFS system used silica carbide as supplementary abrasive. EVE, Ceragloss, StarGloss used Al_2O_3 as supplementary abrasive. LUSTER used only diamond as abrasive. In contrast with feldspathic porcelain polishing kit such as, Ceramiste (Shofu Inc, Japan) used silica carbide as main abrasive.

Previous researches had been studied about various polishing factors. Al-Haj Husain et al.(2016) [37] reported about using several polishing systems varied in types of abrasive and showed that the highest roughness was obtained with the synthetically bonded grinder interspersed with diamond system (EVE Kit, EVE, Pforzheim, Germany) (1.11 μm) compared to other systems (0.13– 0.4μm) and monoclinic phase change was not noted in any groups. Chavali et al. (2017)[38] reported the use of two different polishing systems with different polishing speed (5,000 RPM, 15,000 RPM and 40,000 RPM) to polish dental zirconia and showed that 15,000 RPM produced higher gloss and lower roughness than the other speed. However, Ahmad et al. (2005)[39] showed that at higher rotational speed (20,000 RPM), specimens polished with the diamond polishing system produced statistically lower flexural strength specimens compared to those that had been polished at 10,000 RPM.

Surface roughness measurement

Arithmetic Average Height (Ra) is the most widely used parameter for surface roughness measurement. The roughness average is the area between the roughness profile and its central line. The determination of Ra can be calculated using the formula shown in Figure 2, where f(x) is the profile deviation from the mean line and l is the sampling length[40].

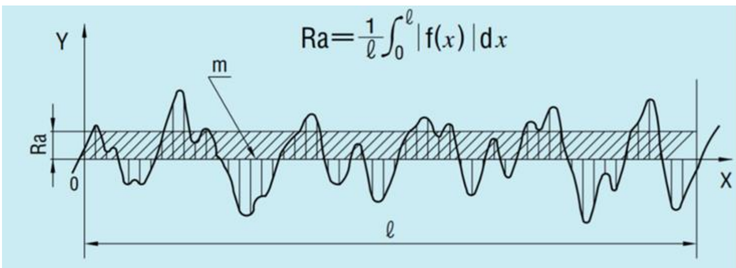

Figure 2 The calculation of Ra

The instrument for measure surface roughness can be divided into two categories.

1. Contact types

In contact-type instruments, the stylus tip makes direct contact with the surface of a sample. The detector tip is equipped with a stylus, which traces the surface of the sample. The vertical motion of the stylus is electrically detected. The electrical signals go through amplification and digital conversion process to be recorded. The stylus method is directly sensitive to surface height with little interference. One disadvantage of stylus instruments is that the stylus may damage the surface, depending on the hardness of the surface relative to the stylus, force, and tip size[41,42].

2. Non-contact types

The light is used to scan the surface texture of the object, then creating the digital profiler to measure the surface texture with digital technic. Optical methods have the advantage that they are non-contacting, non-destructive. Optical methods based on imaging and microscopy also have a higher speed than contacting techniques, which rely on mechanical scanning of a contacting probe. However, optical methods are sensitive to surface qualities besides the surface height. These include optical constants, surface slopes, fine surface features that cause diffraction, and deep valleys in which multiple scattering may occur[42].

In 2016, Melora et al.[43] study about using several techniques to measure the surface roughness of retrieved hip femoral heads affected by metallic debris, by using both a stylus contact profiler and an optical non-contact profilometer. The result showed that conventional stylus and 3D optical profilometer confirmed a satisfying agreement.

Zirconia phase transformation analysis

There are several methods to observe the phase transformation of zirconia, including X-ray diffraction (XRD)[44], Atomic force microscope (AFM)[45], Raman spectroscopy[46]. X-ray diffraction is the most common method used to identify the crystalline phase of zirconia. XRD is a tool for the investigation of the fine structure of matter[47]. This technique was discovered by German physicist Max von Laue in 1912. He found that crystal diffracted x-ray and the manner of the diffraction revealed the structure of the crystal. The three-dimensional structure of crystalline materials is defined by repeating planes of atoms that form a crystal lattice. When a focused X-ray beam interacts with these planes of atoms, part of the beam is diffracted. X-rays are diffracted by each mineral differently, depending on what atoms make up the crystal lattice and how these atoms are arranged. When an X-ray beam hits a sample and is diffracted, we can measure the distances between the planes of the atoms that constitute the sample by applying Bragg's Law (Figure 3).

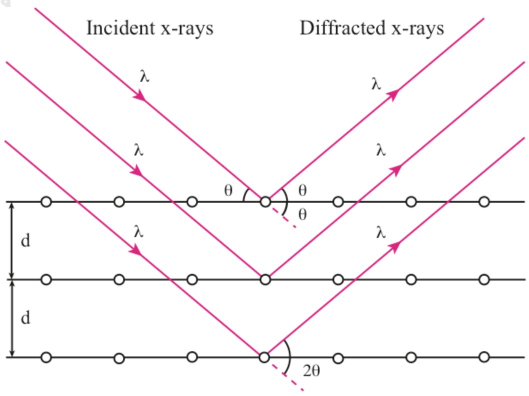

Figure 3 Bragg's Law

Bragg's Law: $n\lambda = 2d \sin\theta$, where n is the order of the diffracted beam, λ is the wavelength of the incident X-ray beam, d is the distance between adjacent planes of atoms (the d-spacings), and θ is the angle of incidence of the X-ray beam. Since we know the wavelength and we can measure angle of incidence of the X-ray beam, we can calculate the d-spacings. The geometry of an XRD unit is designed to accommodate this measurement. The characteristic set of d-spacings generated in a typical X-ray scan provides a unique "fingerprint" of the mineral[48].

CHAPTER III

MATERIALS AND METHODS

Material used in this study

1. Monolithic zirconia: Zirlux16+ (Henry Schein Inc, NY, USA)

2. Diamond bur grit size 46 µm: Komet (Gebr Brasseler GmbH & Co KG, Germany)

3. Zirconia polishing systems:

   - Komet ZR (coarse, fine) (Gebr Brasseler GmbH & Co KG, Germany)

   - Diazircon (coarse, fine) (Diaswiss, Switzerland)

4. Porcelain polishing system: Ceramaster (coarse, fine) (Shofu, Kyoto, Japan)

Equipment

1. Custom made device for control polishing force

2. High speed handpiece (NAKANISHI INC, Japan)

3. Micromotor (NAKANISHI INC, Japan)

4. Digital Vernier caliper (Digimatic, mitutoyo, Japan)

5. Ultra-sonic cleaner (Bransonic model 5210, Branson, USA)

6. Optical profilometer (Alicona infinitefocusSL, Graz, Austria)

7. X-ray diffractometer (Bruker AXS D8, Karlsruhe, Germany)

8. Scanning electron microscope (SEM) (JSM 5410L, JEOL, Japan)

Table 1 Polishing system used in this study

instrument	Manufacturer	Product code	Composition		Manufacturer's Usage Recommendations
			Grit	Binder	
Komet ZR	Komet Dental, Lemgo, Germany	94018C	Diamond	Silicone and polyurethane	Pre-polish zirconia
		94018F			High shine polish zirconia
Diazircon	Diaswiss, Nyon, Switzerland	9502-060	Diamond	N/A	Abrasion, pre-polish zirconia
		9507C-050			Fine polish zirconia
Ceramaster	Shofu, Kyoto, Japan	126 C	Diamond	Silicone	Finish and polish porcelain
		0126			Super polish porcelain

Zirconia used in this study is Zirlux 16+ (Figure 4). which is partially sintered block with 20% shrinkage after final sinter. The composition of Zirlux 16+ consists of zirconium dioxide 94-95%, aluminum oxide 0–0.5% and; yttrium oxide 5.0–5.5 %. It has flexural strength about 1100 MPa, and the density after sintering is 6.08±0.01 g/cm^3.

Figure 4 Zirlux 16+ block

Specimen preparation

Seventy-two pieces of zirconia specimen Zirlux16+ (Henry Schein Inc, NY, USA) were prepared by milling machine (VHF S2, VHF, Germany) with compensation for sintering shrinkage about 20 percent by computer-aided design (CAD) software. The specimens were sintered according to manufacturer’s recommendation. The final dimension of sintered specimen was 7 x 5 x 4 mm (Figure 5). For simulating the occlusal adjustment, the sample was ground with a fine diamond bur (Komet, Gebr Brasseler GmbH & Co KG, Germany) by using a high-speed handpiece by grinding with 200,000 RPM at the speed of 1 mm per second in one direction. The diamond bur was changed after grinding every after four specimens. Specimens were cleaned in an ultrasonic device with distilled water for 5 minutes. The Ra was measured by using a non-contact optical profilometer (Alicona infinitefocusSL, Graz, Austria) with 50X magnification as an initial value which the normal distribution of the data was also confirmed for all specimens.

Figure 5 Zirconia specimen

All specimens were randomly separated into nine groups for three polishing systems and three levels of force (Table 2). The zirconia polishing systems used in this study were Komet ZR (Gebr Brasseler GnbH & Co KG, Germany, Figure 6) and Diazircon (Diaswiss, Switzerland, Figure 7). The porcelain polishing system used in this study was Ceramaster (Shofu corp, Japan, Figure 8). All polishing systems had two steps of coarse and fine grit polisher (Table 1).

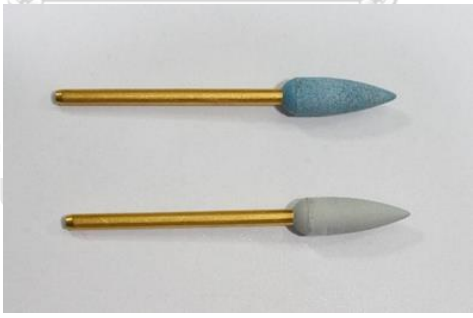

Figure 6 Komet ZR polishing system

Figure 7 Diazircon polishing system

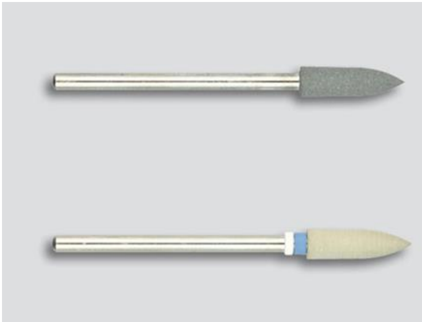

Figure 8 Ceramaster polishing system

Polishing procedure

The specimen was mounted in a customized device (Figure 9) which was developed to control the polishing process in this study. The machine equipped with load-cell and force gauge to monitor the press-on force during the polishing procedure. The tool allowed the handpiece to move in the vertical and horizontal axis with an electronic controller. By using this device, it can reduce error from the uneven force of an investigator with a controlled constant force. All samples were polished in the same direction in the back and forth movement, with a slow-speed handpiece (Volvere V8, NSK, Japan). The rotary speed was set following the manufacturer's recommendation (Table 2). The polishing process began by using a coarse grit polisher for 15 s and repeat for more 15 s, followed by fine grit polisher with the same protocol. At each 15 s, the specimens were cleaned in an ultrasonic device with distilled water for 5 min and the Ra was measured. Diagram of the process in the experiment was shown in Figure 11. The polisher was changed after polishing every group.

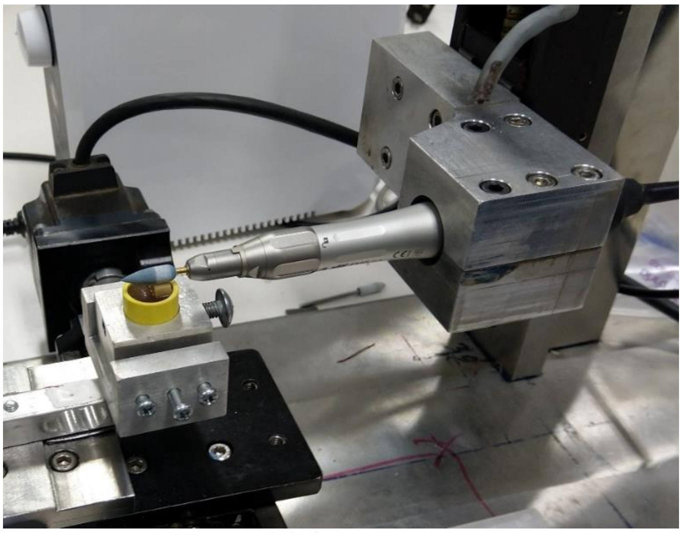

Figure 9 Zirconia specimen mounted in the holder of the custom-made device.

Table 2 Specimen groups according to polishing systems and forces

Brand	Polishing system	Polishing speed (RPM)*	
		Coarse polisher	Fine polisher
Komet ZR	Zirconia	8000	8000
Diazircon	Zirconia	10000	8000
Ceramaster	Porcelain	15000	15000

*polishing speed as per the manufacturer's recommendation.

Surface roughness measurement

The Ra value of each specimen was measured after grinding and after polishing at each 15 s by a non-contact optical profilometer (Alicona infinitefocusSL, Graz, Austria) with 50X magnification. This profilometer has the LASER to assist focusing and controlling the position for measurement the same location. The length for roughness evaluation was 4 mm, perpendicularly to the polished direction, following recommended ISO 4288 standards[40]. Five measurements were done at the area of 0.5 x 0.5 mm, at the center, and 1 mm from the center in four directions

(Figure 10). The average Ra value was calculated from these five measurements at each time.

One specimen from each group in each step was randomly examined by scanning electron microscopy (SEM, JSM-IT500, JEOL, USA) which the specimen was coated with gold dust in a vacuum sputter coater. The polishing systems used in this study were also observed.

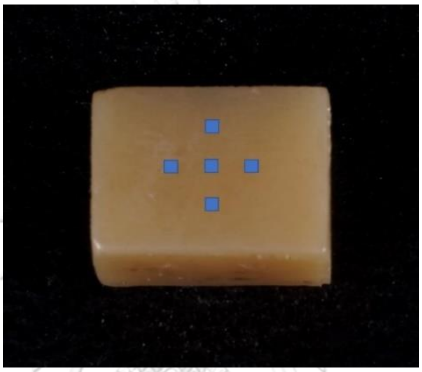

Figure 10 Position for measured Ra of the specimen

Phase transformation analysis

The zirconia phase transformation was determined by x-ray diffraction (XRD) method. The XRD patterns of the as received, the ground, and the polished samples were analyzed by randomly measuring three specimens in each group (n=3 per group). The XRD data were obtained with a diffractometer (Bruker AXS D8, Karlsruhe, Germany) using an x-ray setting at 40 kV, and 40 mA with a step size of 0.01° per step and a scan time of 1 s per step. Diffractograms were measured at positions from 1° to 60° 2θ. The interpretation of the zirconia phase and ratio between tetragonal and monoclinic phase were calculated based on the Rietveld refinement technique by software Difracplus Topas Version 2.1 (Bruker, Karlsruhe

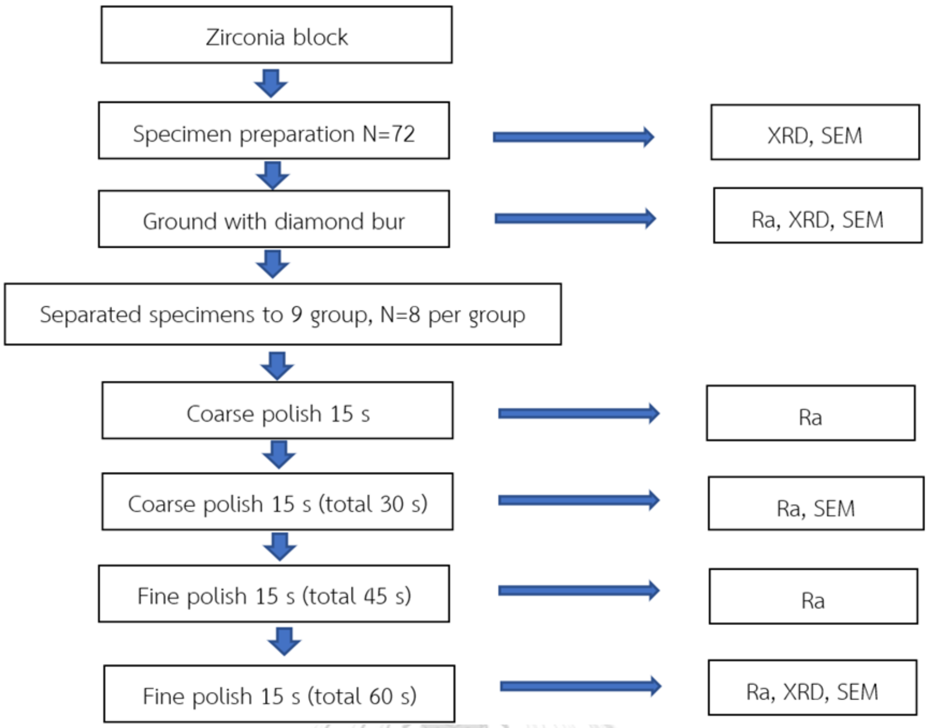

Figure 11 Diagram of the process in the experiment

Statistical analysis

Two-way ANOVA was used to assess the effect of polishing systems, forces, and the interaction between polishing systems and forces on surface roughness in each step. Post-hoc comparisons accounting for multiple testing were conducted using Tukey's honestly significant difference (HSD) test. Repeated measured ANOVA was used to assess the effect of polishing duration on surface roughness in each group by analyzed in each step. Data were analyzed using SPSS Statistics for Windows, Version 22.0 (IBM, Armonk, NY). A P-value < 0.05 was considered statistically significance.

CHAPTER IV

RESULTS

The surface roughness

The Ra of each polishing group was presented in Table 3 and Figure 12. According to the repeated measured ANOVA analysis, in the coarse grit polishing, the polishing time had a significant effect on the surface roughness in all groups. Post-hoc analysis showed that with polishing at 15 s and 30 s, the Ra value decreased significantly in all groups (Table 3). In the fine grit polishing, the polishing time had a significant effect on the surface roughness in all samples. Post-hoc analysis showed that both the polishing at 15 s and 30 s gave a statistically significant decrease in Ra in all group, except the C1 group, at 15 s, did not show a statistical significant difference compared with the beginning step.

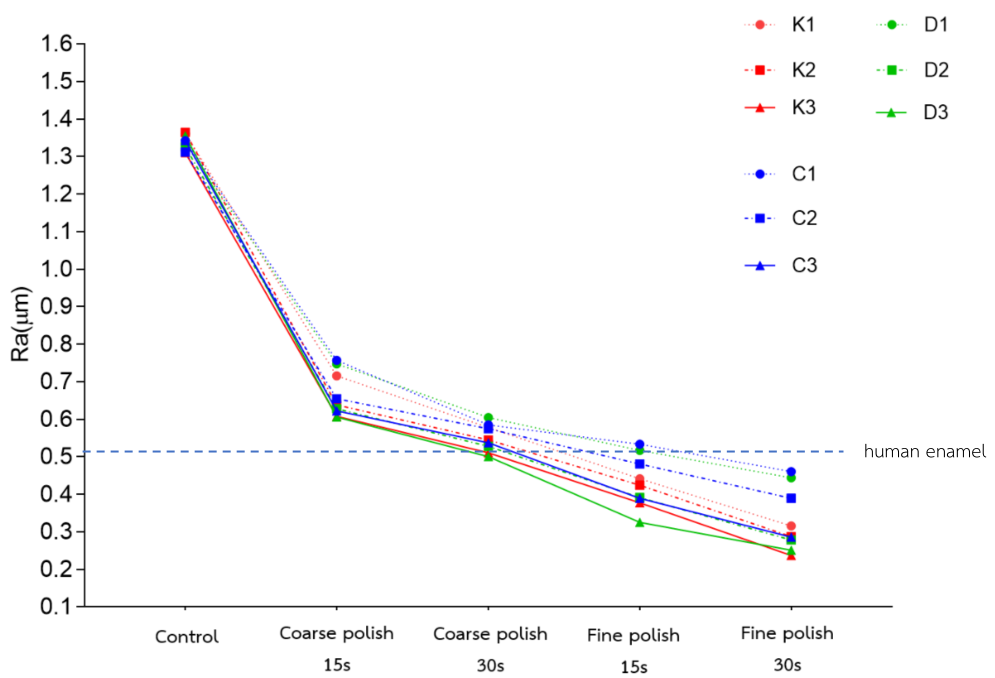

Figure 12 Ra (µm) measured at each step of force of all polishing systems. Dash line show the Ra of human enamel[49]

Table 3 Ra (μm) [mean ± SD] and the results of the repeated measures ANOVA

Group	Coarse polisher				Fine polisher			
	Time (sec)			*P* value	Time (sec)			*P* value
	0	15	30		0	15	30	
K1	1.36 ± 0.10	0.72 ± 0.05	0.58 ± 0.05	<0.001	0.58 ± 0.05	0.44 ± 0.08	0.32 ± 0.06	<0.001
K2	1.36 ± 0.08	0.64 ± 0.04	0.55 ± 0.07	<0.001	0.55 ± 0.07	0.42 ± 0.10	0.29 ± 0.04	<0.001
K3	1.31 ± 0.09	0.61 ± 0.04	0.51 ± 0.05	<0.001	0.51 ± 0.05	0.38 ± 0.08	0.24 ± 0.06	<0.001
D1	1.33 ± 0.09	0.74 ± 0.04	0.60 ± 0.06	<0.001	0.60 ± 0.06	0.52 ± 0.05	0.44 ± 0.06	<0.001
D2	1.33 ± 0.09	0.63 ± 0.08	0.53 ± 0.09	<0.001	0.53 ± 0.09	0.39 ± 0.06	0.28 ± 0.05	<0.001
D3	1.35 ± 0.09	0.61 ± 0.07	0.50 ± 0.07	<0.001	0.50 ± 0.07	0.33 ± 0.04	0.25 ± 0.04	<0.001
C1	1.34 ± 0.10	0.75 ± 0.05	0.59 ± 0.05	<0.001	0.59 ± 0.05*	0.53 ± 0.07*	0.46 ± 0.05	<0.001
C2	1.31 ± 0.10	0.65 ± 0.03	0.58 ±0.05	<0.001	0.58 ±0.05	0.48 ± 0.07	0.39 ± 0.06	<0.001
C3	1.34 ± 0.06	0.62 ± 0.04	0.54 ± 0.05	<0.001	0.54 ± 0.05	0.39 ± 0.06	0.29 ± 0.04	<0.001

* indicates no-significant difference (P = 0.200)

Table 4 *P*-value for two-way ANOVA test results

Polishing step	Interaction (System x Force)	Polishing system	Force
Coarse 15 s	0.816	0.264	<0.001*
Coarse 30 s	0.557	0.376	<0.001*
Fine 15 s	0.08	0.008*	<0.001*
Fine 30 s	0.01*	<0.001*	<0.001*

*indicates a statically significant difference *(P* < 0.05)

Table 5 *P*-values for Turkey HSD Post-Hoc test between different polishing systems

Polishing step	Ceramaster-Komet ZR	Ceramaster-Diazircon	Komet ZR-Diazircon
Coarse 15 s	0.25	0.481	0.90
Coarse 30 s	0.449	0.442	1.0
Fine 15 s	0.024*	0.015*	0.984
Fine 30 s	<0.001*	0.002*	0.01*

* indicates a statistically significant difference (*P* < 0.05)

Table 6 *P*-values for Turkey HSD Post-Hoc test between different forces

Polishing step	1N-2N	2N-3N	1N-3N
Coarse 15 s	<0.001*	0.146	<0.001*
Coarse 30 s	0.06	0.1.41	<0.001*
Fine 15 s	0.004*	0.003*	<0.001*
Fine 30 s	<0.001*	<0.001*	<0.001*

* indicates a statistically significant difference (*P* < 0.05)

Based on the two-way ANOVA statistics used to analyze the different between the polishing force and the polishing system (Table 4), in each polishing step, it was found that after coarse polishing process at 30 s, the interaction between the polishing force and the polishing system was not statistical significance (P = 0.557), zirconia polisher created a smoother surface than porcelain polisher without statistical significance (P = 0.376), and the magnitude of force had a significant effect on surface roughness (P < 0.001).

After fine polishing process, the interaction between the polishing force and the polishing system had a statistical significance (P = 0.01). The polishing system had a significant effected on Ra (P < 0.001), and the magnitude of force also had a significant effect on Ra (P < 0.001). Post-hoc analysis (table 5) compared between zirconia and porcelain polishing system showed that Komet ZR and Diazircon were more effective than Ceramaster (P < 0.001 and P = 0.002, respectively). When comparing between the zirconia polishing systems, Komet ZR was more effective than Diazircon (P = 0.01). The polishing force with 3 N created a smoother surface than 2 and 1 N (P < 0.001), whereas the force 2 N also significantly created smoother surface than 1 N (P < 0.001).

The phase transformation

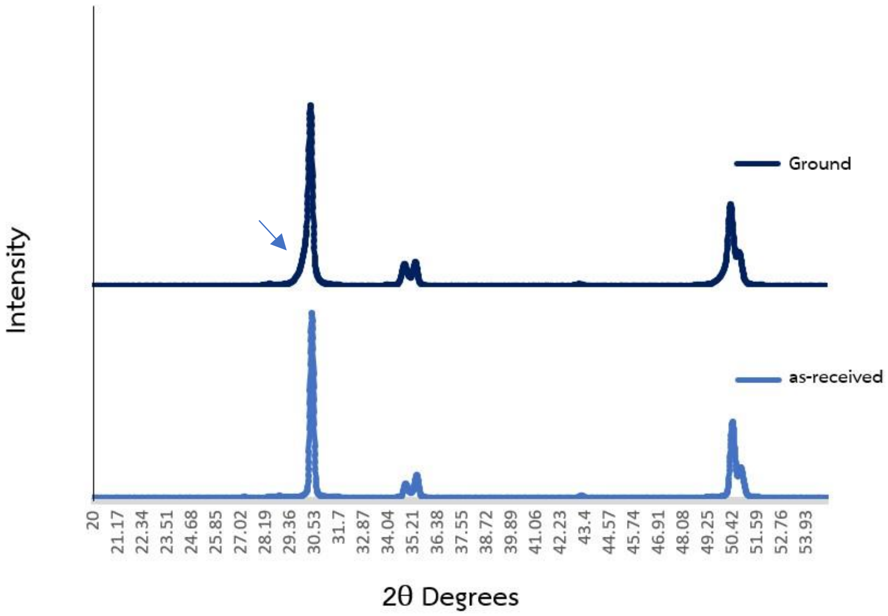

Figure 13 XRD patterns of the as received specimen and the ground specimen, the hump on the left shoulder (HLS) (arrow) was observed.

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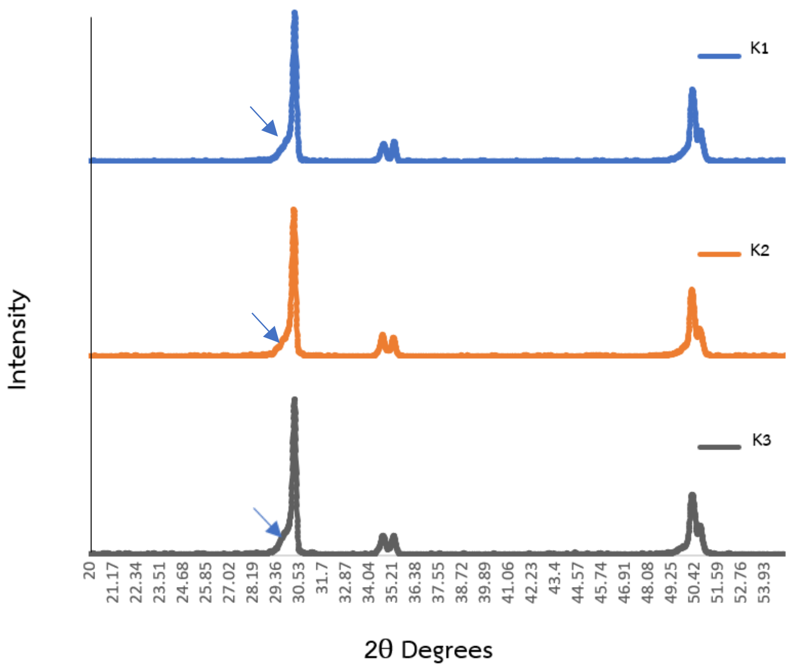


Figure 14 XRD patterns of zirconia specimen after polished by Komet ZR, the HLS (arrows) was observed.

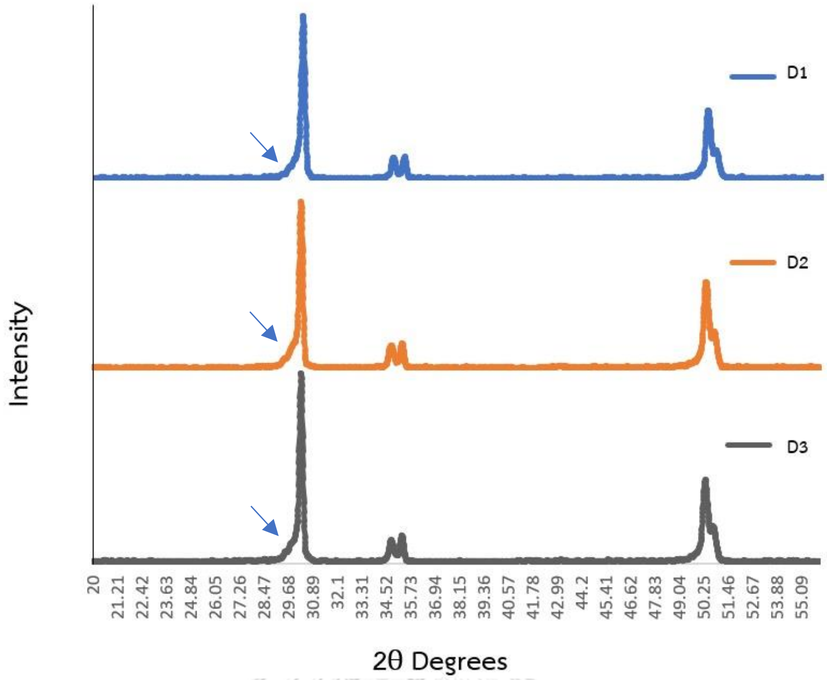


Figure 15 XRD patterns of zirconia specimen after polished by Diazircon, the HLS (arrows) was observed.

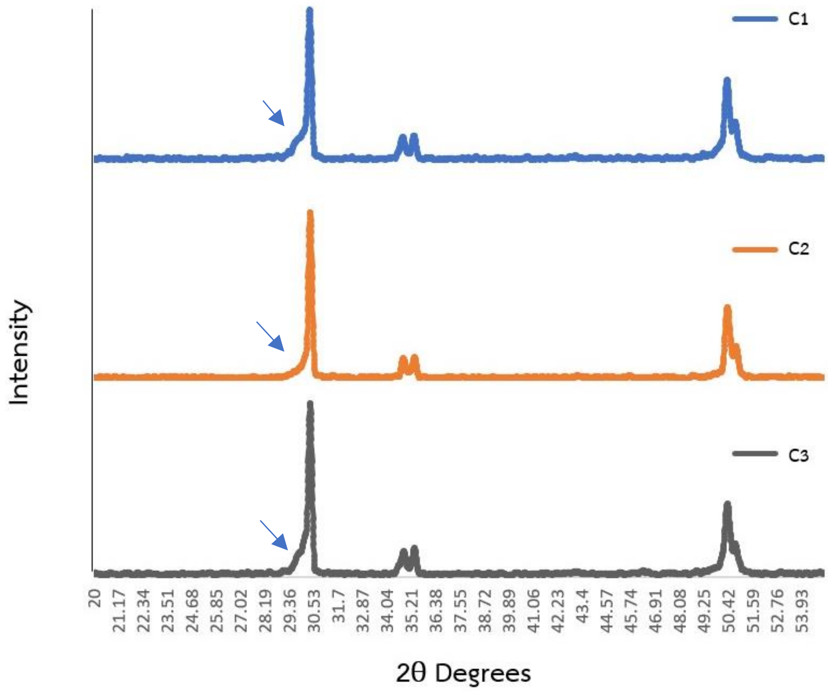


Figure 16 XRD patterns of zirconia specimen after polished by Ceramaster, the HLS (arrows) was observed.

Table 7 Percentage (%) of phase in zirconia specimens by the Rietveld refinement method.

	As received	Fine diamond	D1	D2	D3	K1	K2	K3	C1	C2	C3
Monoclinic	0.775	1.64	0.67	0.96	1.18	0.84	0.96	1.16	0.75	0.62	0.79
Tetragonal	92.22	98.36	99.33	99.04	98.82	99.16	99.04	98.84	99.25	99.38	99.21

The XRD patterns of the test group are shown in Figure 13- 16. Graphs of all specimens shown the highest peak at 30.13° 2**θ** with correlation to the tetragonal phase (JCPDS: 00-050-1089 reference pattern). None of the graphs showed the peak at 28.2°, which relates to the monoclinic phase (JCPDS: 00007-0343), which could imply that there was very few monoclinic phase. All the tested groups exhibited similar XRD patterns. However, in the ground group and all polishing groups, there was the hump on the left shoulder (from now on called HLS) of the 30°2**θ** peak.

The zirconia percentages of phase were shown in Table 7. The zirconia phase composition by the Rietveld refinement technique showed that the major content in all specimens was the tetragonal phase, with the as-received group showed monoclinic phase content only 0.775%. Meanwhile, the ground group showed monoclinic content about 1.64%, and in the polishing group, it was found that the monoclinic phase varies from 0.62 to 1.18%.

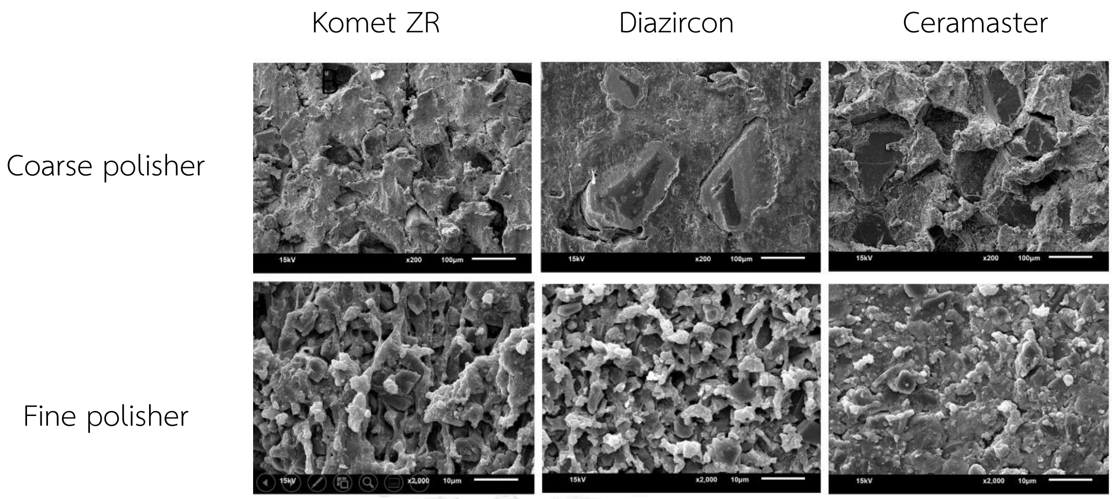


Figure 17 Scanning electron micrographs (SEM) of polishers: coarse polisher 200x, fine polisher 2000x.

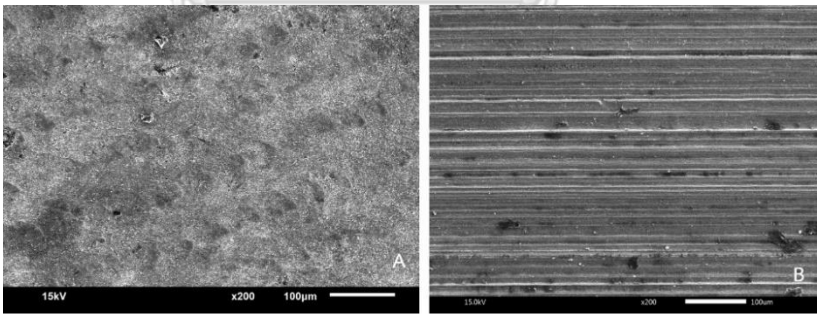


Figure 18 Scanning electron micrographs (SEM) of monolithic zirconia 200x: (A) as received, (B) after grinding with the diamond bur.

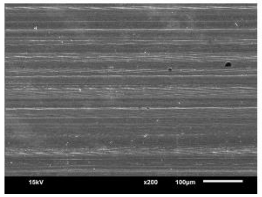
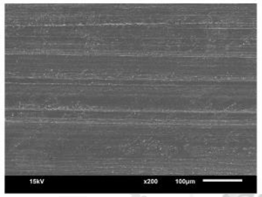
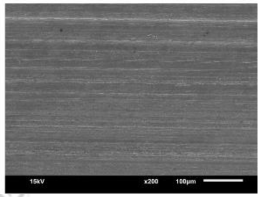
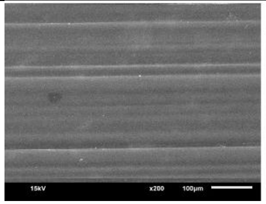
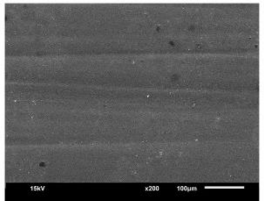
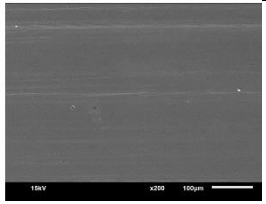
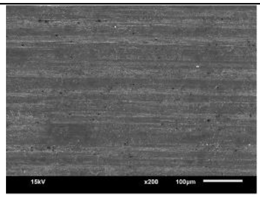
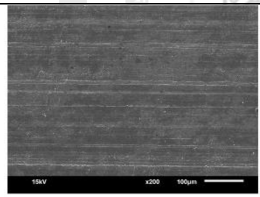
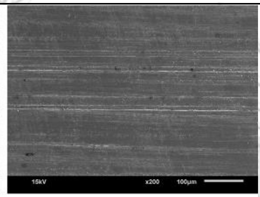
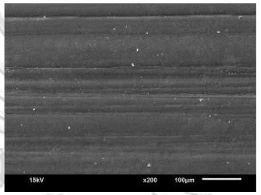
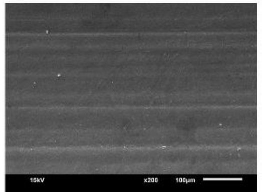
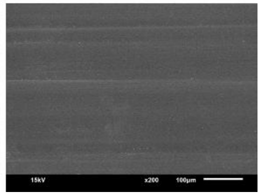
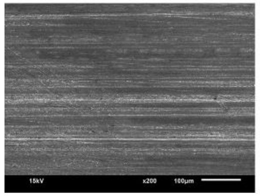
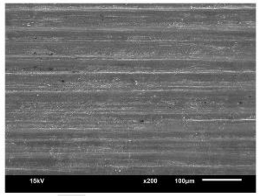
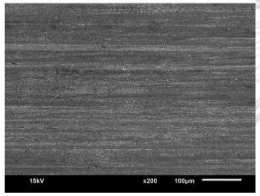
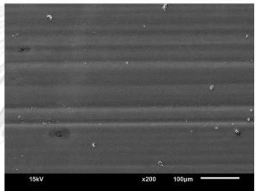
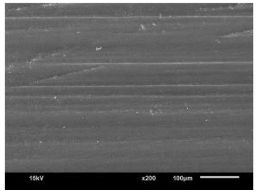
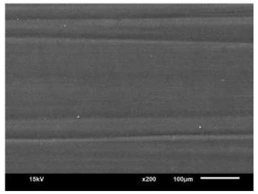
	Coarse polished after 30 s			Fine polished after 30 s		
	1 N	2 N	3 N	1 N	2 N	3 N
Komet ZR						
Diazircon						
Ceramaster						

Figure 19 Scanning electron micrographs (SEM) of zirconia after polished by different polishing systems and forces.

The SEM images of the polisher were shown in Figure 17. Komet ZR coarse had the particle size of 60 to 100 µm, and Komet ZR fine had the particle size of 5 µm; while the Diazircon coarse had the particle size of 100 to 150 µm with the dense binder characteristic, and Diazircon fine had the particle size of 5 µm. Ceramaster coarse had the particle size of 60 to 100 µm distributed abundantly. Ceramaster fine had the diamond particle size of approximately 6 µm, which was distributed quite loosely. The as-received specimen had a rough surface texture due to the CAD/CAM process (Figure 18A), while the ground specimen showed the deep grooves on the surface from the diamond bur (Figure 18B). Figure 19 showed that the specimens polished with force 3 N displayed less scratches and grooves than specimen polished with 2 and 1 N, respectively. The surface of specimen that had been polished by Komet ZR, Diazircon or Ceramaster polishing system appeared similar when polished by coarse grit polisher. However, those polished by Komet ZR and Diazircon showed smoother surface than Ceramaster when polished by fine grit polisher.

CHAPTER V
DISCUSSION

Concerning the polishing systems, it was found that in the first 30 s of polishing with a coarse grit polisher, the two zirconia polishing systems created smoother surface than porcelain polisher with no statically significance, while in step of fine grit polisher, Ceramaster was less effective than the two zirconia polishing systems with statistically significance, as shown in Tables 3 and 4. This can be explained by the polisher particle grit, as seen in Figure 17. Ceramaster coarse had the amount of the diamond particles that were quite remarkably dense, while in the fine polisher, it had fewer diamond particles compared to the other two zirconia polishing systems. As the rotational speed set at the manufacturer's recommendation for each polishing system, Ceramaster recommend the rotational speed more than the other two zirconia polishing systems. A higher RPM might affect the Ra advantageously. However, the polishing performance of Ceramaster was still not effective than zirconia polishing systems. Goo et al.[50]compared the zirconia polisher (Komet ZR zirconia polisher, Shofu zirconia polishing kit) and porcelain polisher (Ceramiste porcelain polishers, Ceramaster porcelain polishers) for polished zirconia specimens, the Ra values after polished with the zirconia polishing systems ranged from 0.24 to 0.39 μm, while with the porcelain polishing system range from 0.42 to 0.51 μm. Park et al.[6], showed that the zirconia polisher (EVE Diacera) was more effective than the porcelain polisher (Ceramaster) when polishing zirconia specimens. This confirmed that newly developed zirconia polishing system was more effective than porcelain polishing system.

This study showed that the higher the polishing force, the more the smoothness of the surface is achieved. More polishing force created more interacted surface between the specimen and the polisher[51]. Moreover, diamond particle might dislodge from the binder and rolled across zirconia surface, created three-body wear abrasive mechanism[7]. Thus, the specimen can be polished over the entire surface. In the previous studies, the force was rarely mentioned when polishing zirconia. Few studies had reported the control of the polishing force, Happe et al.[52] used 1 N force to polish zirconia implant abutment, which the Ra ranged from 0.06 to 0.22 μm depend on their polishing protocol. Two other studies used the force 2 N for polish zirconia. Hmaidouch et al.[53] applied 2 N for ground and polished zirconia specimen but did not mention how to control the force, they used R_{MAX} for stated the surface roughness, which the R_{MAX} of polished zirconia was 2.5 μm. Chavali et al.[38] used the same operator to calibrated the force approximately 2 N to apply in the study, their results showed that the range of Ra of polished zirconia was between 0.6 - 2.3 μm, which was higher than this study. Heintz et al. (2006)[8] investigated the polishing of hybrid composites, microfilled composites, and amalgam, at 2 N and 4 N and found that the hybrid composites created more Ra when polished with 4 N force compared with 2 N. This might cause by the exposed of the filler from the resin matrix. While, for the amalgam, more polishing force provided more smoothness and grossness of the surface. It can thus be said that the increased polishing force affects the different types of material due to the differences of the surface properties of each material.

Human enamel might be used as a benchmark for the appropriate surface roughness in clinical relevance. Taha et al. (2018) [49] measured the Ra of the sound enamel in the first premolar by a non-contact profilometer, same as this study, and found that the mean Ra value was 0.52 μm. Therefore, all groups from the results from this study polished for 60 s provided the Ra value at this level. While at 45 s, every group can be polished to this level, except D1, C1, and C2. Jones et al. (2004)[54] stated that the minimum Ra that the human tongue could detect was 0.5 μm. Thus, with the Ra below 0.5 μm, the human tongue could neither irritated by the difference in the surface roughness. Compared to the results of this study, every group of the polishing systems, included porcelain polisher, can provide Ra at an that level. Park et al. (2014)[55] showed that polished zirconia to the roughness at 0.4 μm could decrease the antagonist wear significantly when compared with the glazed zirconia. Therefore with the polishing for 60 s in most of the tested groups can reach this level, except the of C1 and D1 groups. Moreover, with the polishing time of 45 s, only K3, D2, D3, and C3 groups reached this Ra value.

The zirconia phase transformation from tetragonal to monoclinic phase due to the polishing and grinding process was not significant. According to the Rietveld refinement technique, only 0.62 to 1.18% of the monoclinic phase was present. These results were the same as the previous studies which showed that grinding did not significantly lead to phase transformation of zirconia[35]. However, in the grinding and polishing process, the XRD graph pattern showed the hump on the left shoulder at 30^{o} 2θ peak. Previous studies suggested that this pattern indicated the existence of the extraordinary phase (phases other than the general phase of zirconia, which consists of monoclinic, tetragonal, and cubic phase) of zirconia. Kitano et al.[56] reported the presence of rhombohedral phase of zirconia on 5 mol% Y_2O_3 after grinding. Scherrer et al.[57] found the HLS of XRD peak in the ground and the polished groups of zirconia, matched with the face center cubic crystal structure (JCPDS-PDF: 01-077-2112 reference pattern), and the researcher described it as a pseudocubic phase. However, Kondoh[58] studied about HLS of XRD and concluded that this pattern was caused by lattice distortion in the crystal structure, which usually caused by strain of the crystal rather than phase transformation. The extraordinary phase or the lattice distortion of the crystal structure is currently still unclear for HLS of the XRD peak.

The results of this study showed that every group of the polishing systems used in this study, included porcelain polishing system, can be used to polish fine diamond ground zirconia surface. Polishing with force 2 N with a coarse grit polisher for 30 s followed by fine grit polisher for more 15 s can create a surface roughness comparable to that of human enamel by every systems. Increasing force to 3 N could create a smoother surface and did not result in the zirconia phase transformation. Further studies by increasing the range of polishing force, controlling the same speed of polishing and variation of the zirconia types may be advantageous.

Conclusion

Within the limitations of this study, it can be concluded as follow:

1. Increasing the polishing force and duration made the surface of the zirconia smoother in all polishing systems.
2. When using a coarse grit polisher, the Ra value of all systems were not significantly difference, while using a fine grit polisher, Ceramaster is significantly less effective than Komet ZR and Diazircon.
3. With increasing duration, there was a significant difference in Ra of zirconia due to an interaction between force and polishing system when using fine grit polisher.
4. Polishing process within 60 s, within polishing force of 3 N did not cause phase transformation in zirconia by any polishing system.

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APPENDIX

Test of Normality

systemXforce = k1

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC15	.878	8	.182

systemXforce = k2

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC15	.874	8	.166

systemXforce = k3

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC15	.888	8	.225

systemXforce = d1

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC15	.765	8	.112

systemXforce = d2

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC15	.978	8	.955

systemXforce = d3

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC15	.929	8	.503

systemXforce = c1

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC15	.848	8	.092

systemXforce = c2

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC15	.896	8	.267

systemXforce = c3

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC15	.891	8	.237

systemXforce = k1

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC30	.882	8	.195

systemXforce = k2

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC30	.927	8	.493

systemXforce = k3

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC30	.901	8	.294

systemXforce = d1

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC30	.959	8	.805

systemXforce = d2

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC30	.835	8	.067

systemXforce = d3

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC30	.936	8	.576

systemXforce = c1

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC30	.915	8	.392

systemXforce = c2

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC30	.871	8	.153

systemXforce = c3

	Shapiro-Wilk		
	Statistic	df	Sig.
RaC30	.808	8	.035

systemXforce = k1

	Shapiro-Wilk		
	Statistic	df	Sig.
RaF15	.950	8	.716

systemXforce = k2

	Shapiro-Wilk		
	Statistic	df	Sig.
RaF15	.886	8	.214

systemXforce = k3

	Shapiro-Wilk		
	Statistic	df	Sig.
RaF15	.757	8	.080

systemXforce = d1

	Shapiro-Wilk		
	Statistic	df	Sig.
RaF15	.988	8	.992

systemXforce = d2

	Shapiro-Wilk		
	Statistic	df	Sig.
RaF15	.939	8	.601

systemXforce = d3

	Shapiro-Wilk		
	Statistic	df	Sig.
RaF15	.961	8	.819

systemXforce = c1

	Shapiro-Wilk		
	Statistic	df	Sig.
RaF15	.956	8	.775

systemXforce = c2

	Shapiro-Wilk		
	Statistic	df	Sig.
RaF15	.942	8	.629

systemXforce = c3

	Shapiro-Wilk		
	Statistic	df	Sig.
RaF15	.829	8	.058

Repeated Measures ANOVA (Coarse polisher)

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	2.799	2	1.399	337.430	.000
	Greenhouse-Geisser	2.799	1.505	1.860	337.430	.000
	Huynh-Feldt	2.799	1.826	1.532	337.430	.000
	Lower-bound	2.799	1.000	2.799	337.430	.000
Error(time)	Sphericity Assumed	.058	14	.004		
	Greenhouse-Geisser	.058	10.532	.006		
	Huynh-Feldt	.058	12.785	.005		
	Lower-bound	.058	7.000	.008		

a. systemXforce = k1

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	3.219	2	1.610	436.850	.000
	Greenhouse-Geisser	3.219	1.537	2.095	436.850	.000
	Huynh-Feldt	3.219	1.884	1.709	436.850	.000
	Lower-bound	3.219	1.000	3.219	436.850	.000
Error(time)	Sphericity Assumed	.052	14	.004		
	Greenhouse-Geisser	.052	10.756	.005		
	Huynh-Feldt	.052	13.187	.004		
	Lower-bound	.052	7.000	.007		

a. systemXforce = k2

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	3.048	2	1.524	411.945	.000
	Greenhouse-Geisser	3.048	1.605	1.899	411.945	.000
	Huynh-Feldt	3.048	2.000	1.524	411.945	.000
	Lower-bound	3.048	1.000	3.048	411.945	.000
Error(time)	Sphericity Assumed	.052	14	.004		
	Greenhouse-Geisser	.052	11.235	.005		
	Huynh-Feldt	.052	14.000	.004		
	Lower-bound	.052	7.000	.007		

a. systemXforce = k3

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	2.387	2	1.193	341.662	.000
	Greenhouse-Geisser	2.387	1.098	2.173	341.662	.000
	Huynh-Feldt	2.387	1.150	2.075	341.662	.000
	Lower-bound	2.387	1.000	2.387	341.662	.000
Error(time)	Sphericity Assumed	.049	14	.003		
	Greenhouse-Geisser	.049	7.688	.006		
	Huynh-Feldt	.049	8.049	.006		
	Lower-bound	.049	7.000	.007		

a. systemXforce = d1

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	3.020	2	1.510	1007.819	.000
	Greenhouse-Geisser	3.020	1.578	1.914	1007.819	.000
	Huynh-Feldt	3.020	1.960	1.541	1007.819	.000
	Lower-bound	3.020	1.000	3.020	1007.819	.000
Error(time)	Sphericity Assumed	.021	14	.001		
	Greenhouse-Geisser	.021	11.047	.002		
	Huynh-Feldt	.021	13.718	.002		
	Lower-bound	.021	7.000	.003		

a. systemXforce = d2

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	3.473	2	1.737	433.207	.000
	Greenhouse-Geisser	3.473	1.262	2.753	433.207	.000
	Huynh-Feldt	3.473	1.411	2.463	433.207	.000
	Lower-bound	3.473	1.000	3.473	433.207	.000
Error(time)	Sphericity Assumed	.056	14	.004		
	Greenhouse-Geisser	.056	8.832	.006		
	Huynh-Feldt	.056	9.874	.006		
	Lower-bound	.056	7.000	.008		

a. systemXforce = d3

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	2.522	2	1.261	420.131	.000
	Greenhouse-Geisser	2.522	1.487	1.696	420.131	.000
	Huynh-Feldt	2.522	1.795	1.405	420.131	.000
	Lower-bound	2.522	1.000	2.522	420.131	.000
Error(time)	Sphericity Assumed	.042	14	.003		
	Greenhouse-Geisser	.042	10.407	.004		
	Huynh-Feldt	.042	12.562	.003		
	Lower-bound	.042	7.000	.006		

a. systemXforce = c1

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	2.618	2	1.309	302.445	.000
	Greenhouse-Geisser	2.618	1.206	2.170	302.445	.000
	Huynh-Feldt	2.618	1.321	1.983	302.445	.000
	Lower-bound	2.618	1.000	2.618	302.445	.000
Error(time)	Sphericity Assumed	.061	14	.004		
	Greenhouse-Geisser	.061	8.445	.007		
	Huynh-Feldt	.061	9.244	.007		
	Lower-bound	.061	7.000	.009		

a. systemXforce = c2

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	3.137	2	1.568	904.817	.000
	Greenhouse-Geisser	3.137	1.241	2.527	904.817	.000
	Huynh-Feldt	3.137	1.377	2.278	904.817	.000
	Lower-bound	3.137	1.000	3.137	904.817	.000
Error(time)	Sphericity Assumed	.024	14	.002		
	Greenhouse-Geisser	.024	8.689	.003		
	Huynh-Feldt	.024	9.640	.003		
	Lower-bound	.024	7.000	.003		

a. systemXforce = c3

Post Hoc Test

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c]	
					Lower Bound	Upper Bound
1	2	.645*	.036	.000	.533	.758
	3	.783*	.037	.000	.668	.899
2	1	-.645*	.036	.000	-.758	-.533
	3	.138*	.021	.001	.072	.204
3	1	-.783*	.037	.000	-.899	-.668
	2	-.138*	.021	.001	-.204	-.072

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = k1

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c] Lower Bound	Upper Bound
1	2	.726*	.025	.000	.647	.805
	3	.819*	.038	.000	.701	.937
2	1	-.726*	.025	.000	-.805	-.647
	3	.093*	.027	.030	.010	.177
3	1	-.819*	.038	.000	-.937	-.701
	2	-.093*	.027	.030	-.177	-.010

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = k2

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c] Lower Bound	Upper Bound
1	2	.703*	.034	.000	.598	.808
	3	.800*	.034	.000	.692	.907
2	1	-.703*	.034	.000	-.808	-.598
	3	.097*	.022	.009	.029	.164
3	1	-.800*	.034	.000	-.907	-.692
	2	-.097*	.022	.009	-.164	-.029

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = k3

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c] Lower Bound	Upper Bound
1	2	.586*	.020	.000	.523	.649
	3	.729*	.041	.000	.601	.856
2	1	-.586*	.020	.000	-.649	-.523
	3	.143*	.023	.001	.070	.216
3	1	-.729*	.041	.000	-.856	-.601
	2	-.143*	.023	.001	-.216	-.070

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = d1

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c] Lower Bound	Upper Bound
1	2	.697*	.018	.000	.642	.753
	3	.798*	.024	.000	.723	.872
2	1	-.697*	.018	.000	-.753	-.642
	3	.101*	.016	.001	.051	.150
3	1	-.798*	.024	.000	-.872	-.723
	2	-.101*	.016	.001	-.150	-.051

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = d2

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c]	
					Lower Bound	Upper Bound
1	2	.749*	.017	.000	.695	.804
	3	.854*	.040	.000	.728	.981
2	1	-.749*	.017	.000	-.804	-.695
	3	.105*	.033	.045	.002	.208
3	1	-.854*	.040	.000	-.981	-.728
	2	-.105*	.033	.045	-.208	-.002

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = d3

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c]	
					Lower Bound	Upper Bound
1	2	.585*	.020	.000	.523	.648
	3	.757*	.034	.000	.651	.864
2	1	-.585*	.020	.000	-.648	-.523
	3	.172*	.026	.001	.090	.254
3	1	-.757*	.034	.000	-.864	-.651
	2	-.172*	.026	.001	-.254	-.090

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = c1

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c]	
					Lower Bound	Upper Bound
1	2	.657*	.028	.000	.568	.746
	3	.737*	.044	.000	.599	.875
2	1	-.657*	.028	.000	-.746	-.568
	3	.080*	.022	.027	.010	.150
3	1	-.737*	.044	.000	-.875	-.599
	2	-.080*	.022	.027	-.150	-.010

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = c2

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c]	
					Lower Bound	Upper Bound
1	2	.721*	.016	.000	.669	.772
	3	.806*	.028	.000	.719	.893
2	1	-.721*	.016	.000	-.772	-.669
	3	.085*	.016	.003	.035	.136
3	1	-.806*	.028	.000	-.893	-.719
	2	-.085*	.016	.003	-.136	-.035

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = c3

c. Adjustment for multiple comparisons: Bonferroni.

Repeated Measure ANOVA (Fine Polisher)

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	.275	2	.138	56.514	.000
	Greenhouse-Geisser	.275	1.485	.185	56.514	.000
	Huynh-Feldt	.275	1.791	.154	56.514	.000
	Lower-bound	.275	1.000	.275	56.514	.000
Error(time)	Sphericity Assumed	.034	14	.002		
	Greenhouse-Geisser	.034	10.394	.003		
	Huynh-Feldt	.034	12.538	.003		
	Lower-bound	.034	7.000	.005		

a. systemXforce = k1

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	.267	2	.133	28.570	.000
	Greenhouse-Geisser	.267	1.292	.206	28.570	.000
	Huynh-Feldt	.267	1.461	.182	28.570	.000
	Lower-bound	.267	1.000	.267	28.570	.001
Error(time)	Sphericity Assumed	.065	14	.005		
	Greenhouse-Geisser	.065	9.046	.007		
	Huynh-Feldt	.065	10.226	.006		
	Lower-bound	.065	7.000	.009		

a. systemXforce = k2

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	.301	2	.150	52.332	.000
	Greenhouse-Geisser	.301	1.551	.194	52.332	.000
	Huynh-Feldt	.301	1.910	.157	52.332	.000
	Lower-bound	.301	1.000	.301	52.332	.000
Error(time)	Sphericity Assumed	.040	14	.003		
	Greenhouse-Geisser	.040	10.856	.004		
	Huynh-Feldt	.040	13.368	.003		
	Lower-bound	.040	7.000	.006		

a. systemXforce = k3

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	.103	2	.052	95.001	.000
	Greenhouse-Geisser	.103	1.629	.063	95.001	.000
	Huynh-Feldt	.103	2.000	.052	95.001	.000
	Lower-bound	.103	1.000	.103	95.001	.000
Error(time)	Sphericity Assumed	.008	14	.001		
	Greenhouse-Geisser	.008	11.400	.001		
	Huynh-Feldt	.008	14.000	.001		
	Lower-bound	.008	7.000	.001		

a. systemXforce = d1

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	.249	2	.125	65.112	.000
	Greenhouse-Geisser	.249	1.556	.160	65.112	.000
	Huynh-Feldt	.249	1.920	.130	65.112	.000
	Lower-bound	.249	1.000	.249	65.112	.000
Error(time)	Sphericity Assumed	.027	14	.002		
	Greenhouse-Geisser	.027	10.893	.002		
	Huynh-Feldt	.027	13.437	.002		
	Lower-bound	.027	7.000	.004		

a. systemXforce = d2

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	.263	2	.131	70.356	.000
	Greenhouse-Geisser	.263	1.170	.225	70.356	.000
	Huynh-Feldt	.263	1.263	.208	70.356	.000
	Lower-bound	.263	1.000	.263	70.356	.000
Error(time)	Sphericity Assumed	.026	14	.002		
	Greenhouse-Geisser	.026	8.193	.003		
	Huynh-Feldt	.026	8.841	.003		
	Lower-bound	.026	7.000	.004		

a. systemXforce = d3

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	.063	2	.031	16.945	.000
	Greenhouse-Geisser	.063	1.837	.034	16.945	.000
	Huynh-Feldt	.063	2.000	.031	16.945	.000
	Lower-bound	.063	1.000	.063	16.945	.004
Error(time)	Sphericity Assumed	.026	14	.002		
	Greenhouse-Geisser	.026	12.856	.002		
	Huynh-Feldt	.026	14.000	.002		
	Lower-bound	.026	7.000	.004		

a. systemXforce = c1

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	.137	2	.069	34.538	.000
	Greenhouse-Geisser	.137	1.483	.093	34.538	.000
	Huynh-Feldt	.137	1.788	.077	34.538	.000
	Lower-bound	.137	1.000	.137	34.538	.001
Error(time)	Sphericity Assumed	.028	14	.002		
	Greenhouse-Geisser	.028	10.381	.003		
	Huynh-Feldt	.028	12.516	.002		
	Lower-bound	.028	7.000	.004		

a. systemXforce = c2

Tests of Within-Subjects Effects[a]

Measure: Ra

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
time	Sphericity Assumed	.255	2	.128	58.265	.000
	Greenhouse-Geisser	.255	1.829	.139	58.265	.000
	Huynh-Feldt	.255	2.000	.128	58.265	.000
	Lower-bound	.255	1.000	.255	58.265	.000
Error(time)	Sphericity Assumed	.031	14	.002		
	Greenhouse-Geisser	.031	12.803	.002		
	Huynh-Feldt	.031	14.000	.002		
	Lower-bound	.031	7.000	.004		

a. systemXforce = c3

Post Hoc Test

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c]	
					Lower Bound	Upper Bound
1	2	.136*	.018	.000	.081	.191
	3	.262*	.024	.000	.187	.338
2	1	-.136*	.018	.000	-.191	-.081
	3	.126*	.030	.013	.031	.222
3	1	-.262*	.024	.000	-.338	-.187
	2	-.126*	.030	.013	-.222	-.031

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = k1

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c]	
					Lower Bound	Upper Bound
1	2	.121	.045	.048	-.020	.262
	3	.258*	.025	.000	.178	.338
2	1	-.121	.045	.048	-.262	.020
	3	.137*	.029	.006	.047	.227
3	1	-.258*	.025	.000	-.338	-.178
	2	-.137*	.029	.006	-.227	-.047

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = k2

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c]	
					Lower Bound	Upper Bound
1	2	.134*	.033	.015	.030	.237
	3	.274*	.021	.000	.207	.341
2	1	-.134*	.033	.015	-.237	-.030
	3	.141*	.025	.002	.064	.217
3	1	-.274*	.021	.000	-.341	-.207
	2	-.141*	.025	.002	-.217	-.064

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = k3

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c] Lower Bound	Upper Bound
1	2	.088*	.014	.001	.044	.132
	3	.160*	.011	.000	.127	.194
2	1	-.088*	.014	.001	-.132	-.044
	3	.073*	.010	.000	.042	.103
3	1	-.160*	.011	.000	-.194	-.127
	2	-.073*	.010	.000	-.103	-.042

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = d1

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c] Lower Bound	Upper Bound
1	2	.137*	.022	.001	.067	.206
	3	.249*	.026	.000	.167	.331
2	1	-.137*	.022	.001	-.206	-.067
	3	.112*	.016	.001	.063	.162
3	1	-.249*	.026	.000	-.331	-.167
	2	-.112*	.016	.001	-.162	-.063

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = d2

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c] Lower Bound	Upper Bound
1	2	.176*	.027	.001	.092	.259
	3	.250*	.025	.000	.172	.327
2	1	-.176*	.027	.001	-.259	-.092
	3	.074*	.009	.000	.046	.101
3	1	-.250*	.025	.000	-.327	-.172
	2	-.074*	.009	.000	-.101	-.046

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = d3

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c] Lower Bound	Upper Bound
1	2	.051	.024	.200	-.023	.125
	3	.124*	.022	.002	.055	.194
2	1	-.051	.024	.200	-.125	.023
	3	.073*	.018	.015	.016	.130
3	1	-.124*	.022	.002	-.194	-.055
	2	-.073*	.018	.015	-.130	-.016

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = c1

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c] Lower Bound	Upper Bound
1	2	.094*	.028	.036	.007	.181
	3	.185*	.020	.000	.121	.249
2	1	-.094*	.028	.036	-.181	-.007
	3	.091*	.017	.003	.038	.145
3	1	-.185*	.020	.000	-.249	-.121
	2	-.091*	.017	.003	-.145	-.038

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = c2

c. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons[a]

Measure: Ra

(I) time	(J) time	Mean Difference (I-J)	Std. Error	Sig.[c]	95% Confidence Interval for Difference[c] Lower Bound	Upper Bound
1	2	.148*	.026	.002	.067	.229
	3	.251*	.024	.000	.176	.327
2	1	-.148*	.026	.002	-.229	-.067
	3	.104*	.020	.003	.042	.165
3	1	-.251*	.024	.000	-.327	-.176
	2	-.104*	.020	.003	-.165	-.042

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. systemXforce = c3

c. Adjustment for multiple comparisons: Bonferroni.

TWO WAY ANOVA

Tests of Between-Subjects Effects

Dependent Variable: RaC15

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.229[a]	8	.029	10.621	.000
Intercept	31.795	1	31.795	11804.273	.000
polishingsystem	.007	2	.004	1.361	.264
force	.217	2	.109	40.343	.000
polishingsystem * force	.004	4	.001	.389	.816
Error	.170	63	.003		
Total	32.194	72			
Corrected Total	.399	71			

a. R Squared = .574 (Adjusted R Squared = .520)

Tests of Between-Subjects Effects

Dependent Variable: RaC30

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.081[a]	8	.010	2.884	.008
Intercept	21.925	1	21.925	6209.442	.000
polishingsystem	.007	2	.004	.993	.376
force	.064	2	.032	9.030	.000
polishingsystem * force	.011	4	.003	.757	.557
Error	.222	63	.004		
Total	22.229	72			
Corrected Total	.304	71			

a. R Squared = .268 (Adjusted R Squared = .175)

Tests of Between-Subjects Effects

Dependent Variable: RaF15

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.303[a]	8	.038	8.092	.000
Intercept	13.402	1	13.402	2863.137	.000
polishingsystem	.049	2	.024	5.200	.008
force	.213	2	.107	22.790	.000
polishingsystem * force	.041	4	.010	2.188	.080
Error	.295	63	.005		
Total	14.000	72			
Corrected Total	.598	71			

a. R Squared = .507 (Adjusted R Squared = .444)

Tests of Between-Subjects Effects

Dependent Variable: RaF30

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.440[a]	8	.055	20.789	.000
Intercept	7.747	1	7.747	2926.376	.000
polishingsystem	.117	2	.059	22.122	.000
force	.269	2	.134	50.732	.000
polishingsystem * force	.055	4	.014	5.151	.001
Error	.167	63	.003		
Total	8.354	72			
Corrected Total	.607	71			

a. R Squared = .725 (Adjusted R Squared = .690)

Post Hoc Test

Multiple Comparisons

Dependent Variable: RaC15

Tukey HSD

(I) polishingsystem	(J) polishingsystem	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
komet	diazircon	-.00654	.014982	.900	-.04250	.02942
	ceramaster	-.02392	.014982	.255	-.05988	.01204
diazircon	komet	.00654	.014982	.900	-.02942	.04250
	ceramaster	-.01737	.014982	.481	-.05334	.01859
ceramaster	komet	.02392	.014982	.255	-.01204	.05988
	diazircon	.01737	.014982	.481	-.01859	.05334

Based on observed means.

The error term is Mean Square(Error) = .003.

Multiple Comparisons

Dependent Variable: RaC15

Tukey HSD

(I) force	(J) force	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1 newton	2 newton	.09963*	.014982	.000	.06366	.13559
	3 newton	.12817*	.014982	.000	.09221	.16413
2 newton	1 newton	-.09963*	.014982	.000	-.13559	-.06366
	3 newton	.02854	.014982	.146	-.00742	.06450
3 newton	1 newton	-.12817*	.014982	.000	-.16413	-.09221
	2 newton	-.02854	.014982	.146	-.06450	.00742

Based on observed means.

The error term is Mean Square(Error) = .003.

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

Multiple Comparisons

Dependent Variable: RaC30

Tukey HSD

(I) polishingsystem	(J) polishingsystem	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
komet	diazircon	.00021	.017154	1.000	-.04097	.04138
	ceramaster	-.02083	.017154	.449	-.06201	.02034
diazircon	komet	-.00021	.017154	1.000	-.04138	.04097
	ceramaster	-.02104	.017154	.442	-.06222	.02013
ceramaster	komet	.02083	.017154	.449	-.02034	.06201
	diazircon	.02104	.017154	.442	-.02013	.06222

Based on observed means.

The error term is Mean Square(Error) = .004.

Multiple Comparisons

Dependent Variable: RaC30

Tukey HSD

(I) force	(J) force	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1 newton	2 newton	.03983	.017154	.060	-.00134	.08101
	3 newton	.07279*	.017154	.000	.03162	.11397
2 newton	1 newton	-.03983	.017154	.060	-.08101	.00134
	3 newton	.03296	.017154	.141	-.00822	.07413
3 newton	1 newton	-.07279*	.017154	.000	-.11397	-.03162
	2 newton	-.03296	.017154	.141	-.07413	.00822

Based on observed means.

The error term is Mean Square(Error) = .004.

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

Multiple Comparisons

Dependent Variable: RaF15

Tukey HSD

(I) polishingsystem	(J) polishingsystem	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
komet	diazircon	.00333	.019751	.984	-.04407	.05074
	ceramaster	-.05342*	.019751	.024	-.10082	-.00601
diazircon	komet	-.00333	.019751	.984	-.05074	.04407
	ceramaster	-.05675*	.019751	.015	-.10416	-.00934
ceramaster	komet	.05342*	.019751	.024	.00601	.10082
	diazircon	.05675*	.019751	.015	.00934	.10416

Based on observed means.

The error term is Mean Square(Error) = .005.

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

Multiple Comparisons

Dependent Variable: RaF15

Tukey HSD

(I) force	(J) force	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
1 newton	2 newton	.06533*	.019751	.004	.01793	.11274
	3 newton	.13333*	.019751	.000	.08593	.18074
2 newton	1 newton	-.06533*	.019751	.004	-.11274	-.01793
	3 newton	.06800*	.019751	.003	.02059	.11541
3 newton	1 newton	-.13333*	.019751	.000	-.18074	-.08593
	2 newton	-.06800*	.019751	.003	-.11541	-.02059

Based on observed means.

The error term is Mean Square(Error) = .005.

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

Multiple Comparisons

Dependent Variable: RaF30

Tukey HSD

(I) polishingsystem	(J) polishingsystem	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
komet	diazircon	-.04492*	.014853	.010	-.08057	-.00926
	ceramaster	-.09867*	.014853	.000	-.13432	-.06301
diazircon	komet	.04492*	.014853	.010	.00926	.08057
	ceramaster	-.05375*	.014853	.002	-.08940	-.01810
ceramaster	komet	.09867*	.014853	.000	.06301	.13432
	diazircon	.05375*	.014853	.002	.01810	.08940

Based on observed means.

The error term is Mean Square(Error) = .003.

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

Multiple Comparisons

Dependent Variable: RaF30

Tukey HSD

(I) force	(J) force	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
1 newton	2 newton	.08829*	.014853	.000	.05264	.12394
	3 newton	.14875*	.014853	.000	.11310	.18440
2 newton	1 newton	-.08829*	.014853	.000	-.12394	-.05264
	3 newton	.06046*	.014853	.000	.02481	.09611
3 newton	1 newton	-.14875*	.014853	.000	-.18440	-.11310
	2 newton	-.06046*	.014853	.000	-.09611	-.02481

Based on observed means.

The error term is Mean Square(Error) = .003.

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

Ra of ground specimens (control)

	N	Mean	Std. Deviation	Std. Error	Minimum	Maximum
k1	8	1.36162	.096530	.034128	1.225	1.532
k2	8	1.36488	.081873	.028947	1.232	1.467
k3	8	1.31100	.090048	.031837	1.175	1.475
d1	8	1.33388	.088557	.031310	1.195	1.457
d2	8	1.32588	.082581	.029197	1.189	1.436
d3	8	1.35550	.097330	.034411	1.189	1.519
c1	8	1.34237	.095946	.033922	1.234	1.511
c2	8	1.31225	.104214	.036845	1.198	1.524
c3	8	1.34338	.060625	.021434	1.247	1.423
Total	72	1.33897	.086359	.010177	1.175	1.532

ANOVA

Ra0

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.025	8	.003	.398	.918
Within Groups	.504	63	.008		
Total	.530	71			

One-way ANOVA

p-value for one-way ANOVA test in polishing system factor

Polishing Step	Force		
	1 N	2N	3N
Coarse 15s	0.236	0.652	0.767
Coarse 30s	0.589	0.400	0.412
Fine 15 s	0.025*	0.087	0.107
Fine 30 s	<0.001*	<0.001*	0.120

* indicates a statistically significant difference (p<0.05)

p-values for Turkey HSD Post-Hoc test between different polishing system when polishing with 1 N

Polishing step	Ceramaster-Komet ZR	Ceramaster-Diazircon	Komet ZR-Diazircon
Coarse 15s	0.237	0.926	0.409
Coarse 30s	0.964	0.739	0.584
Fine 15s	0.873	0.029*	0.080
Fine 30s	<0.001*	0.844	0.001*

* indicates a statistically significant difference (p<0.05)

p-values for Turkey HSD Post-Hoc test between different polishing system when polishing with 2 N

Polishing step	Ceramaster-Komet ZR	Ceramaster-Diazircon	Komet ZR-Diazircon
Coarse 15s	0.839	0.629	0.931
Coarse 30s	0.670	0.375	0.869
Fine 15s	0.326	0.075	0.676
Fine 30s	0.001*	0.001*	0.938

* indicates a statistically significant difference (p<0.05)

p-values for Turkey HSD Post-Hoc test between different polishing system when polishing with 3 N

Polishing step	Ceramaster-Komet ZR	Ceramaster-Diazircon	Komet ZR-Diazircon
Coarse 15s	0.825	0.784	0.997
Coarse 30s	0.615	0.401	0.928
Fine 15s	0.919	0.114	0.226
Fine 30s	0.112	0.318	0.809

* indicates a statistically significant difference ($p<0.05$)

p-value for one-way ANOVA test in polishing force factor

Polishing step	Komet ZR	Diazircon	Ceramaster
Coarse 15s	<0.001*	0.001*	<0.001*
Coarse 30s	0.063	0.026*	0.115
Fine 15 s	0.311	<0.001*	0.001*
Fine 30 s	0.029*	<0.001*	<0.001*

* indicates a statistically significant difference ($p<0.05$)

p-values for Turkey HSD Post-Hoc test between different force, polish with Komet polishing system

Polishing step	1N-2N	1N-3N	2N-3N
Coarse 15s	0.005*	<0.001*	0.351
Coarse 30s	0.451	0.051	0.418
Fine 15s	0.908	0.301	0.523
Fine 30s	0.566	0.024*	0.184

* indicates a statistically significant difference ($p<0.05$)

p-values for Turkey HSD Post-Hoc test between different force, polish with Diazircon polishing system

Polishing step	1N-2N	1N-3N	2N-3N
Coarse 15s	0.005*	0.001*	0.780
Coarse 30s	0.111	0.025*	0.741
Fine 15s	<0.001*	<0.001*	0.037*
Fine 30s	<0.001*	<.0.001*	0.508

* indicates a statistically significant difference (p<0.05)

p-values for Turkey HSD Post-Hoc test between different force, polish with Ceramaster polishing system

Polishing step	1N-2N	1N-3N	2N-3N
Coarse 15s	<0.001*	<0.001*	0.292
Coarse 30s	0.915	0.159	0.305
Fine 15s	0.227	0.001*	0.031*
Fine 30s	0.028*	<0.001*	0.001*

* indicates a statistically significant difference (p<0.05)

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