

Mechanical fatigue of monolithic all-ceramic crowns in vitro

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Abstract

Purpose: The objective of this study was to investigate the effects of thermal stresses and cyclic fatigue on the mechanical properties of monolithic resin-interpenetrating phase ceramic restorations comparing with other monolithic all-ceramic restorations. **Materials and Methods:** A design of full anatomical crown was performed digitally and a crown was milled to fit on a standardized prefabricated acrylic die. Specimens were divided into 5 groups based upon the material used; experimental resin-interpenetrating phase composites, feldspathic porcelain, lithium disilicate, leucite-reinforced glass-ceramic, zirconia-reinforced composite resin. All crowns were cemented with adhesive resin cement according to manufacturers' recommendations. Cemented crowns were fatigued for 150,000 cycles with a maximum load of 450 N and minimum load of 0 N and subjected to the load to failure test by compressive loading in a universal testing machine. The load required to cause failure was recorded for each specimen. Two-way ANOVA and Tukey HSD were used for statistical analysis. Modes of failure after testing were evaluated using scanning electron microscopy (SEM). **Results:** Two-way ANOVA showed that material, cyclic fatigue and interaction between them had a significant effect on load to failure of the CAD/CAM crowns. Multiple comparisons test results recorded significant differences between load to failure of the fatigued and non-fatigued crowns of lithium disilicate, leucite-reinforced glass-ceramic groups

Keywords: Monolithic, Cyclic fatigue, load to failure

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Introduction

Due to the chipping and crack or veneering porcelain in the core-veneer all-ceramic system, the monolithic all-ceramic based restorations are increasingly promoted for single-crown and full-mouth rehabilitation. Monolithic all-ceramic crowns are made from the same ceramic throughout. The fabrication of monolithic restorations can be from either cast-press technique or CAD/CAM technique.¹ For the castable/pressable ceramic systems, a wax pattern of the restoration is made. The lost wax technique is used to fabricate molds for pressable ceramics. Pressable ceramics are available from manufacturers as prefabricated ingots made of crystalline particles distributed throughout a glassy matrix.² Microstructure of pressable ceramics shows not much porosity in the material compared to conventional firing porcelain.^{2, 3} IPS Empress is an injection molding system which uses 40-50% leucite to reinforce the glass matrix. Empress restorations are translucent and have reported flexural strength of about 120-140 MPa.⁴ However, some studies reported increased failure rates of restorations when used in the posterior region. IPS e.max Press (Figure 4) was introduced in 2005 as an improved press-ceramic material compared to IPS Empress 2. It consists of lithium disilicate crystals as appears in IPS Empress2 but its physical properties and translucency are improved through a different firing process.⁵ Due to the time-consuming fabrication by pressed restoration. Computer-assisting/computer-designed milled restorations became more interesting. Since CAD/CAM systems have been developed, chair-side fabricated restorations can be made.⁶

An attempt to reduce error from the laboratory processing led to the development of a new sophisticated computerized system that can fabricate restorations at the chair side. Computer-aided designing/ computer-aided manufacturing (CAD/CAM) technology has been introduced in dentistry since 1980 and has been developing rapidly.⁷ A digital impression is made directly in the patient's mouth and the restorations are designed and fabricated either in the laboratory or chair side by using chair-side milling facilities. Many materials are available for CAD/CAM milled monolithic restorations. These materials must be able to be milled rapidly, resist machining damage, and be finished easily before final placement.⁸ CAD/CAM ceramics are available as prefabricated blocks and can be milled by computer-controlled tools. The prefabricated blocks for fabricating monolithic crowns are already fully sintered with nearly pore-free microstructure. The ceramics have more uniformity inside the material because of controlled fabrication by manufacturers.⁸

Recently, a novel resin-interpenetrating phase ceramic has been introduced in dentistry. An interpenetrating network material in which a porous ceramic is infused by a polymer has been developed by the Vita company (Vita Zahnfabrik, Bad Sackingen, Germany) based on the glass infiltrated ceramic (In-Ceram) system. He and Swain investigated the elastic modulus, fracture toughness and microhardness of resin-interpenetrating phase ceramic and the results showed the lower hardness values of the resin-interpenetrating phase ceramic than those in conventional veneering porcelain.⁹ Several wear test studies have indicated that dental ceramics generated

greater wear of the antagonist than other restorative materials because of the high hardness values of those ceramics.^{10, 11, 12} Therefore, the significantly lower hardness value of resin-interpenetrating phase ceramic could be of considerable advantage to protect the opposing teeth from excessive wear. However, they did not study the flexural strength of the resin-interpenetrating phase ceramic.

Interpenetrating phase ceramics (IPCs) contain at least two different phases, which are having the different coefficient of thermal expansion. When the IPCs are subjected to abrupt changes in temperature, thermal stresses occur.¹³ Thermal stresses develop because of the thermal contraction mismatches of the multiphase ceramics including IPCs. These stresses can result in the formation of micro-cracks that can strongly influence the strength of the multiphase ceramic composites. Dental restorative materials are required to maintain their properties in the challenging environment of the oral cavity where they experience contact with saliva, pH changes and thermal changes. Evaluation of dental materials; especially multiphase composites, often includes testing of property of interest after a sequence of thermal stressing in which the sample is moved between high and low temperature surrounding for predetermined number of cycles (thermocycles). Even though the thermocycling protocol does not really simulate the oral environment, it can provide information on the behavior of the materials.¹⁴

In addition, another desired property of dental ceramics is fatigue

resistance. In the oral environment, restorative materials are exposed to repeated cyclic chewing force under wet condition. This can accelerate the failure of the restorations.¹⁵ Single-load tests determined the maximal stress that a ceramic can tolerate before failure, however, these results may not be valid for predicting clinical failure for dental restorations.¹⁶ Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading.¹⁷ Therefore, the object of this study was to investigate the effects of thermal stresses and cyclic fatigue on the mechanical properties of monolithic resin-interpenetrating phase ceramic restorations comparing with other monolithic all-ceramic restorations.

Materials and Methods

Standardized prefabricated acrylic dies were prepared with a 5-degree convergence angle and a 1-mm shoulder finish line to serve as master dies. The axio-occlusal line angle and axio-gingival line angle were rounded (Figure 1). A master die was scanned using extraoral digital scanner (New D750, 3Shape, Copenhagen, Denmark). A design of full anatomical crown was performed using Dental Designer software (3Shape, Copenhagen, Denmark) to fit on the master die and the design was sent for milling process. The monolithic all-ceramic crowns were wet-milled using wet-milling machine (CoriTEC 250i, Imes Icore, Eiterfeld, Germany). The all-ceramic materials used and groups of specimen for fatigue resistance evaluation are listed in Table 1.



Figure 1 A standardized acrylic die with a 5-degree convergence angle and 1-mm shoulder

The intaglio surfaces of crowns made of composites resin and resin-interpenetrating phase materials (ER, LU) were air-borne particle abraded using 50- μ m aluminium oxide at a pressure of 0.5 MPa, sonicated with an ultrasonic cleaner (BRANSON 2210, BRANSON, Connecticut, USA) washed thoroughly with water and dried. The air-abraded surfaces were then applied with ceramic primer (Clearfil Ceramic Primer, Kuraray, Japan) and air-dried. For crowns made of glass-ceramic materials (MK, EC, EM), the intaglio surfaces were etched with 9.6% Hydrofluoric acid (PULPDENT, MA, USA), sonicated, rinsed with water, air-dried, and applied with Clearfil Ceramic Primer. Self-curing adhesive resin cement (Panavia 21, Kuraray, Japan) was used to cement CAD/CAM milled crowns according to manufacturer recommendations with the application of forces of 30 N. All cemented crowns were

stored in room temperature water for 24 hours prior to load to failure testing and cyclic fatigue loading. For the cyclic fatigue groups, cemented crowns were fatigued prior to load to failure test. Specimens were tested in a wet environment by placing the specimens in a custom-made cup, which could position the specimen at the center of the apparatus. Water was filled in the cup to the level above the top of the specimen. The specimens in the water-filled cup were subjected to cyclic loading using a custom-manufactured cyclic fatigue apparatus. Load was applied to a specimen with a hardened 4.5-mm stainless steel ball, which rested on the occlusal surface with 3 points of contact (Figure 60). Specimens were fatigued for 150,000 cycles with a maximum load of 450 N and minimum load of 0 N. The cycles were run at room temperature. After 150,000 cycles, cemented crowns were subjected to the load to failure test by compressive loading in a universal testing machine (Instron Model 4202; Instron Co., Canton, MA) with the 10 KN load cell at a crosshead speed of 0.5 mm/min. The load was applied to the center of the crown by a 6.5-mm-diameter stainless steel ball. The load required to cause failure was recorded for each specimen. Two-way ANOVA was used to detect significant difference of the load to failure between the non-fatigued group and fatigued group. Tukey HSD was used for multiple comparisons. Modes of failure after testing were evaluated using scanning electron microscopy (SEM).

Table 1 Lists of materials used in this study

Materials	Trade name	Manufacturer	Abbreviation
Experimental resin-interpenetrating phase composites	None	Vita Zahnfabrik, Bad Säckingen, Germany	ER
Feldsparthic porcelain	Vita Mark II	Vita Zahnfabrik, Bad Säckingen, Germany	MK
Zirconia-reinforced composite resins	Lava Ultimate	3M ESPE, Minnesota, USA	LU
Leucite-reinforced glass-ceramics	IPS Empress CAD	Ivoclar-Vivadent, Schaan, Liechtenstein	EC
Lithium disilicate glass-ceramics	IPS e.max CAD	Ivoclar-Vivadent, Schaan, Liechtenstein	EM

Results

The mean load to failure (N), standard deviations and coefficient of variation of CAD/CAM crowns are shown in Table 2. Two-way ANOVA showed that material, cyclic fatigue and interaction between them had a significant effect (*) on load to failure of the CAD/CAM crowns (Table 3). Within material group, multiple comparisons test results recorded significant differences between load to failure of the fatigued and non-fatigued crowns of EC and EM groups (*). Microscopic results show crack propagation microcracks inside materials of the fatigued EC and EM group (Figure 2, 3).

Discussion

In order to use resin-interpenetrating phase ceramics as a material for CAD/CAM milled crowns, this material has to resist cyclic loading. Clinically, dental restorations are subjected to masticatory forces under dry and wet conditions; therefore, these conditions

must be considered during in vitro testing of such restorations.¹⁵ All-ceramic materials tested in the laboratory should produce failures that are comparable to those in clinical situations. Several important factors that are essential to carry out a meaningful laboratory test were identified. Firstly, materials should be prepared in a crown shape because the practical crown failure usually occurs under a complex type of stresses. Secondly, the crowns should be cemented on a standardized die with modulus values close to dentin. In this study, the acrylic dies were used instead of human dentin. It was because acrylic dies could be easily milled in a standardized way. Furthermore, these materials had a low value of modulus of elasticity compared to those ceramics materials. From in vitro studies, it was evident that the lower modulus of elasticity of the abutment material the higher proportion of failure in the crown. Thirdly, crowns should be subjected to cyclic load because, clinically, all-ceramic crowns are subjected to the repeated chewing force.

Table 2 Mean, standard deviations (SD), and coefficient of variations (COV) of all experimental groups

Materials	Non-fatigued group		Fatigued group	
	Mean+SD	COV	Mean+SD	COV
ER	2266.66+108.68	4.8	2201.33+241.66	12.2
MK	1046.27+114.58	10.9	1199.05+148.69	10.9
LU	2889.99+284.93	9.8	2972.69+68.53	12.4
EC	1495.27+59.86*	4	1340.12+32.98*	2.5
EM	3128.54+267.64*	8.6	2750.12+262.12*	9.5

Table 3 Two-way ANOVA comparing differences between materials and fatigue treatment

Source	Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	38731556.451(a)	9	3521050.586	106.812	.000*
Intercept	312687543.099	1	312687543.099	9485.441	.000*
Material	35769081.207	4	7153816.241	217.012	.000*
Fatigue	274503.740	1	274503.740	8.327	.005*
material * fatigue	770857.807	4	154171.561	4.677	.001*
Error	2175689.971	66	32965.000		
Total	374309426.863	78			
Corrected Total	40907246.422	77			

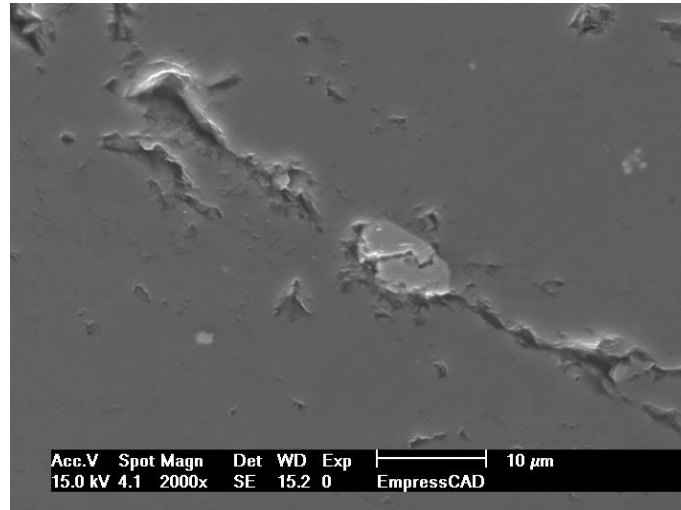


Figure 2 SEM image of fatigued IPS Empress CAD (EC) shows internal cracks and crack deviation

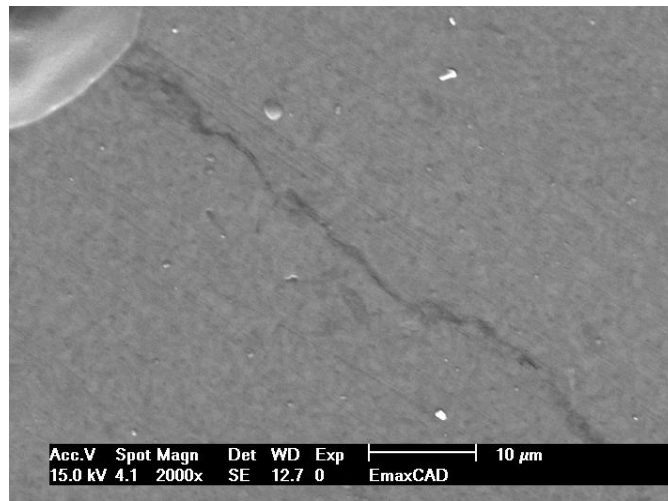


Figure 3 SEM image of fatigued IPS e.max CAD (EM) shows internal crack propagation

Finally, the test condition should be wet in order to simulate oral environment.¹⁸

In this study, the experimental design followed the criteria mentioned above. The crown specimens were fabricated from different types of CAD/CAM ceramics including an experimental resin-interpenetrating phase ceramics. The applied force was 450 N which is the average maximum biting force in the first molar area.^{19, 20} However, this value could vary depending on

individuals. The specimens were exposed to 150,000 cycles of load. After completion of cyclic fatigue loading, none of the specimens fractured.

The experimental resin-interpenetrating phase ceramics was not affected by the cyclic fatigue loading. The load to failure of the crowns made of Vita Mark II, Lava Ultimate and experimental resin-interpenetrating phase ceramic after cyclic fatigue showed no difference compared to the load to failure without

cyclic fatigue. IPS Empress Esthetic and IPS e.max CAD showed slightly reduced loads to failure after being fatigued by 10% and 12% respectively. This could be explained by the subcritical crack growth in those two materials.²¹ However, many studies showed the high cumulative survival probability of those two all-ceramic systems (more than 90% success rate).²² Therefore, the laboratory results were somewhat in contrast to the clinical results.

Conclusion

Within the limitation of this in vitro study, the following conclusions can be drawn:

1. There is no significant effect of the cyclic fatigue on the load to failure of ER, MK, and LU group.
2. The load to failure of the fatigued crowns in EE and EM significantly decreased by 10, and 12 %, respectively compared to without cyclic fatigue group.
3. The loads to failures of all testing groups were higher than the maximum average biting force in a patient mouth. Therefore, it may be assumed that all materials used in this study could withstand the maximum intraoral masticatory forces.

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ความต้านทานการแตกหักของครอบฟันเซรามิกล้วนแบบชั้นเดียว

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บทคัดย่อ

วัตถุประสงค์: เพื่อทำการศึกษาความต้านทานการแตกหักของครอบฟันเซรามิกล้วนแบบชั้นเดียวภายใต้แรงซ้ำๆ
วิธีการทดลอง: ทำการออกแบบครอบฟันแบบกายวิภาคเต็มซี่ (full contour) โดยใช้การออกแบบด้วยเครื่องดิจิทัลหลังจากนั้นทำการกลึงครอบฟันเพื่อให้พอดีกับฟันหลักอะคริลิกมาตรฐานสำเร็จรูป กลุ่มตัวอย่างถูกแบ่งออกเป็น 5 กลุ่มขึ้นอยู่กับวัสดุที่ใช้ทดลองคือ เรซินคอมโพสิต interpenetrating-phase ceramic ลิเทียมไดซิลิเกต กลุ่มที่มีผลึกดูไลต์เสริมแก้ว และเซรามิกเซอร์โคเนียเสริมแรงคอมโพสิตเรซิน ครอบฟันทั้งหมดถูกยึดด้วยเรซินซีเมนต์ตามคำแนะนำของผู้ผลิต ครอบฟันถูกนำไปผ่านการให้แรงซ้ำๆจำนวน 150,000 รอบกับแรงสูงสุด 450 นิวตัน และแรงต่ำสุดของ 0 นิวตัน หลังจากนั้นนำไปทดสอบความล้มเหลวโดยแรงอัดในเครื่องทดสอบสากล แรงที่ทำให้เกิดความล้มเหลวได้รับการบันทึกในแต่ละชิ้นงานและนำไปทดสอบสถิติด้วยการทดสอบความแปรปรวนแบบสองทาง (two-way ANOVA) และ Tukey HSD ลักษณะของความล้มเหลวหลังจากการทดสอบได้รับการประเมินโดยใช้กล้องจุลทรรศน์อิเล็กตรอน
ผลการทดลอง: จากผลของ ANOVA พบว่าการนำวัสดุบางกลุ่มไปผ่านการให้แรงซ้ำเป็นเวลานานมีผลต่อความต้านทานการแตกหักอย่างมีนัยสำคัญในกลุ่มของลิเทียมไดซิลิเกต และกลุ่มที่มีผลึกดูไลต์เสริมแก้ว

คำสำคัญ: ความต้านทานการแตกหัก, ครอบฟันเซรามิกล้วน, ลิเทียม ไดซิลิเกต