A comparison of failure load for zirconia-ceremics restorations with different zirconia/veneer thickness and cooling rate

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A comparison of failure load for zirconia-ceremics restorations with different zirconia/veneer thickness and cooling rate

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2014년 12월

탕 우 룽 드림

Contents

Figure index

Table index

Abstract

A comparison of failure load for zirconia-ceremics restorations with different zirconia/veneer thickness and cooling rate

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Objectives: The purpose of the current study was to evaluate the influence of different zirconia coping thicknesses and cooling rates on the failure load of zirconia crowns.

Methods: Forty identical abutment models were milled out of polymethylmethacrylate, and zirconia copings of two thicknesses (0.5 mm or 1.5 mm; n = 20 each) were fabricated using a dental computer-aided design and computer-aided manufacturing system. Zirconia crowns were completed by veneering feldspathic ceramics under different cooling rates (conventional or slow, n = 20 for each cooling rate), resulting four zirconia crown groups (n = 10 per group). Each crown was cemented on the abutment and 300,000 cycles of a 50-N load was applied on the crowns in conjunction with 1263 thermocyclings. After fatigue loading, a static load was applied on each crown until failure using a universal testing machine. The mean failure loads were statistically evaluated with one-way and two-way analysis of variance tests ($p = 0.05$).

Results: No cohesive or adhesive failure was observed after fatigue loading. The greatest mean failure load occurred in zirconia crowns that had 1.5-mm thick coping and had undergone slow cooling ($p < 0.001$). Furthermore, six of 10 crowns with the 1.5-mm thick coping in the slow cooling group showed coping fractures. However, no coping fractures occurred in the other groups.

Conclusions: Coping thickness and the cooling rate had a significant influence on the mean failure loads of the zirconia crowns. Under conventional cooling conditions, the mean failure load was not influenced by the coping thickness; however, under slow cooling conditions, the mean failure load was significantly influenced by the coping thickness.

Clinical significance: A thicker coping design or slow cooling after the final firing of the veneer ceramic would be beneficial in reducing the incidence of chipping failure in zirconia crowns. A thicker coping design with slow cooling is therefore recommended to minimize chipping failures.

Key words: zirconia, chipping failure, cooling rate, coping thickness, failure load

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I. Introduction

Because of its high strength, dental zirconia has been successfully used as a framework material for long span posterior fixed dental prostheses and anterior single tooth restorations. Previous studies report no fractures in the zirconia framework during 3-5 years of clinical service [1-3]. In addition to its excellent strength, zirconia, compared to titanium, shows a favorable peri-implant soft tissue color match [4]; therefore, dental zirconia is also preferred as a abutment material for anterior implant restorations.

Despite these advantages, dental zirconia has a major drawback. Clinical studies show that the chipping rate of the veneering ceramic is higher in zirconia ceramics than in metal ceramics [5-7]. Monolithic zirconia restorations, which are fabricated from more translucent zirconia blocks, have been clinically used recently to overcome chipping problems [8,9]. Monolithic zirconia can be characterized using special coloring liquids before the sintering process to get esthetic results. However, there are limitations in obtaining excellent anterior esthetics with a coloring technique; therefore, layering ceramics on a zirconia framework remains the preferred method to fabricate anterior restorations.

Experimental studies have suggested the following causes of failure: (1) damage to the ceramic surface after occlusal adjustments [10]; (2) mismatched coefficient of thermal expansion between the veneer ceramic and the zirconia coping [11]; (3) relationship between the coping thickness and the coefficient of thermal expansion [12]; (4) inadequate zirconia framework design [13,14]; and (5) poor adhesion between the ceramic and the zirconia coping [15,16].

Accumulated residual stresses during the cooling process of the veneering ceramics have recently been focused on as a major cause of veneer chipping [17-20]. In contrast to metal ceramics, slow cooling is recommended for zirconia ceramics because fast cooling after the final sintering of the porcelain introduces greater residual tensile stress in the veneering porcelain [21,22], and increased tensile residual stress is vulnerable to crack propagation. Previous research shows that the amount and type of residual stresses (i.e., compressive or tensile stress) is also influenced by the thickness of the zirconia coping and the veneering porcelain [23,24]. Therefore, the cooling rate and the zirconia/veneer thickness ratio should be considered to minimize chipping. To date, little information is available concerning the interaction between the cooling ratio and the coping thickness on the failure load of zirconia ceramic restorations. The purpose of the current study was to evaluate the impact of different zirconia coping thicknesses and cooling rates on the failure loads of zirconia crowns. The null hypothesis tested was that neither the zirconia coping thickness nor the cooling rate influences the amount of failure load of zirconia crowns.

II. Materials and methods

1. Fabrication of the abutment model

A simplified configuration of a prepared tooth model was designed. Forty tooth models were fabricated from polymethylmethacrylate (Arystal 100; Plavex Ltd., Geumwang, Korea) using a dental computer-aided design and computer-aided manufacturing (CAD/CAM) system (Chameleon, Neobiotech, Seoul, Korea).

2. Fabrication of the zirconia crowns

Tooth models were randomly divided into two groups (N = 20 teeth per group). Each tooth model was digitally scanned using a dental scanner (D700; 3Shape, Copenhagen, Denmark). Using dental CAD software (Model Builder; 3Shape), two different coping configurations were designed: 0.5-mm thick zirconia coping and 1.5-mm-thick zirconia coping (Figs. 1A and 1B). Forty zirconia copings were milled from presintered zirconia blocks (NaturZ; D-max, Seoul, Korea) using a milling machine (Zmatch; DentAim, Seoul, Korea). They were then sintered at 1450℃ for 7 h using a special furnace (Zmatch sintering furnace; DentAim). The zirconia coping was randomly chosen and veneered with feldspathic porcelain (e.max Ceram, A2 shade; Ivoclar Vivadent, Schaan, Liechtenstein), and then sintered to form a simple contour of zirconia ceramic restoration. A mold was fabricated by indexing the restoration with a heavy viscosity silicone impression material (Aquasil Heavy Putty; Dentsply International, York, PA, USA) to form a mold for the veneering ceramic build up. Additional 39 zirconia ceramic crowns were fabricated using the mold. To check the dimension of the veneering porcelain, the final dimension of each crown was measured using a digital caliper (Series 500; Mitutoyo America Corporation, Plymouth, MI, USA).

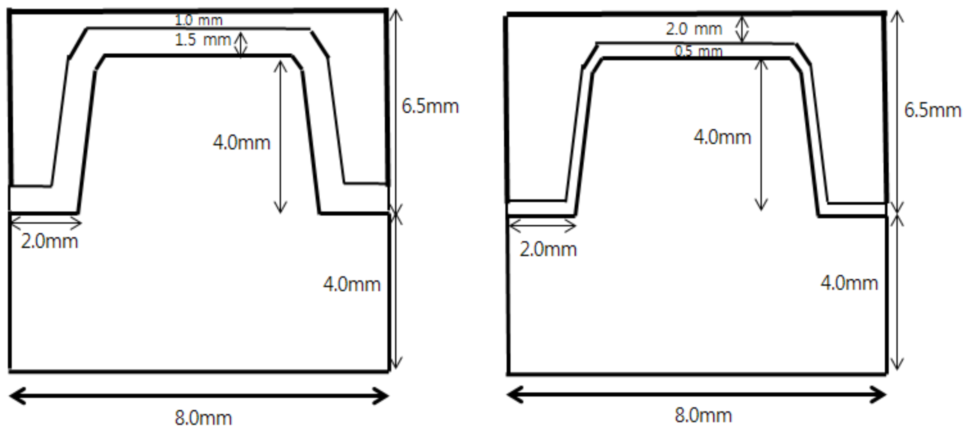

Figure 1. The dimensions of specimens with (left) the thick (1.5-mm) coping and (right) the thin (0.5-mm) coping.

Each group was divided into two subgroups, based on the last firing (i.e., the slow cooling and fast cooling groups; N = 10 crowns per subgroup). Two different firing cycles were used for the last firing. For the fast cooling cycle, the zirconia crowns were tempered from 900℃ to room temperature by opening the furnace door. The crowns were then removed from the mesh tray as soon as the muffle had fully descended. For the slow cooling cycle, the furnace temperature was cooled from 900℃ to 500℃ at a cooling rate of 2℃ per minute. The furnace door was then opened. Table 1 shows the ceramic firing procedures for all groups. Each zirconia ceramic crown was cemented onto its tooth model using a self-cure resin cement (Multilink Automix; Ivoclar Vivadent). The crown was then stored in distilled water before undergoing artificial aging.

3. Artificial aging

The specimens were embedded in a self-curing acrylic resin (Jet Tooth Shade, Lang Dental Manufacturing Co., Wheeling, IL, USA) at 1 mm apical from the crown margin. The specimens were submitted to a fatigue load of 300,000 cycles using a chewing simulator with sliding movement (CS-4.8; SD Mechatronik, Feldkirchen-Westerham, Germany), which simulates 1 year of clinical function. The chewing simulator applied mechanical loading (50 N, 1.6 Hz) and thermal aging between 5℃ and 55℃. After the completion of the chewing simulation, the specimens were carefully inspected using binocular magnifying (4×) glasses (Eye

Mag Pro; Zeiss, Jena, Germany). This was to determine whether any chipping or fracture of the veneering ceramics or copings had occurred.

4. Failure load measurement

Each specimen that did not show any fracture or chipping after undergoing artificial aging was subjected to a fracture test by a universal loading device (Z 250/SN 5S; Zwick GmbH and Co., Ulm, Germany). Each test was performed at a cross-head speed of 0.5 mm/min. The load was applied 2 mm from the center of the occlusal surface parallel to the long axis of the crown-tooth (Fig. 2). The loading stylus had 4-mm diameter stainless steel ball. The maximum failure load was recorded in newtons (N).

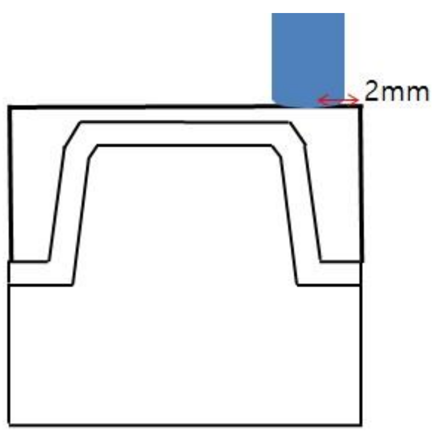

Figure 2. The static load receiving area.

5. Statistical analysis

Statistical analysis was performed using a software package (IBM SPSS Statistics 20; IBM, USA). The Kolmogorov−Smirnov test was performed to check the normality of the data of each group. Based on the results of the normality test, two-way ANOVA was performed to analyze the significance of the failure load between the groups (α = 5%).

III. Results

After undergoing chewing simulation, none of the specimens had cohesive or adhesive failure of the ceramic veneer. Therefore, all 40 specimens received a static load until failure. One specimen with 1.5-mm thick coping in the slow cooling group did not fail until it was exposed to 8000 N, which was the maximum force of the loading device. The amount of failure was therefore regarded as 8000 N for the specimen. Table 1 lists the mean and standard deviation of the different cooling rates and coping thicknesses. Table 2 presents the results of two-way ANOVA, which was used to check the effect of different cooling rates, coping thicknesses, and the interaction between the different cooling rates and coping thicknesses.

Table 1. The means and standard deviations of the load failure for each group

Cooling	Thickness (mm)	Mean (Newtons)	Standard deviation (Newtons)	number
Conventional	0.5	2336.5	1378.0	10
	1.5	2724.9	1411.2	10
Slow	0.5	2089.7	663.4	10
	1.5	5737.4	1733.1	10

Table 2. Two-way analysis of variance for the failure loads

Source	Type III sum of squares	df	mean squares	F	significance
corrected model	86404244.201	3	28801414.734	15.708	.000
Intercept	415277200.842	1	415277200.842	226.494	.000
Cooling	19122395.514	1	19122395.514	10.429	.003
Thickness	40723784.862	1	40723784.862	22.211	.000
cooling*thickness	26558063.826	1	26558063.826	14.485	.001
Error	66006183.136	36	1833505.087		
Total	567687628.179	40			
Corrected Total	152410427.337	39			

The failure load is significantly influenced by the cooling rate ($p = 0.003$) and by the coping thickness ($p < 0.001$). The interaction between the cooling rate and the coping thickness also significantly influences the failure load ($p = 0.001$).

Table 3. The effect of coping thickness under the different cooling rates

cooling	thickness	thickness	Mean difference	Standard error	P value	95% confidence	
						Lower limit	Upper limit
conventional	0.5	1.5	-388.349	605.558	0.525	-1616.478	839.780
	1.5	0.5	388.349	605.558	0.525	839.780	1616.478
slow	0.5	1.5	-3647.678	605.558	0.001	-4875.807	-2419.549
	1.5	0.5	3647.678	605.558	0.001	2419.549	4875.807

Under conventional cooling conditions, the difference in the coping thickness did not influence the mean failure load of the zirconia crowns (p = 0.525). However, under slow cooling conditions, the coping thickness significantly influenced the mean failure load (p < 0.001).

Table 4. The effect of the cooling rate under different coping thicknesses

thickness	cooling	cooling	Mean difference	Standard error	P value	95% confidence	
						Lower limit	Upper limit
0.5	convnetional	slow	246.827	605.558	0.686	-981.302	1474.956
	slow	conventional	-246.827	605.558	0.686	-1474.956	981.302
1.5	conventional	slow	-3012.502	605.558	0.001	-4240.631	-1784.373
	slow	conventioanl	3012.502	605.558	0.001	1784.373	4240.631

With the thin coping, the difference in the cooling rate did not influence the mean failure load of the zirconia crowns ($p = 0.686$). However, with the thick coping, the cooling rate significantly influenced the mean failure load of the zirconia crowns ($p < 0.001$).

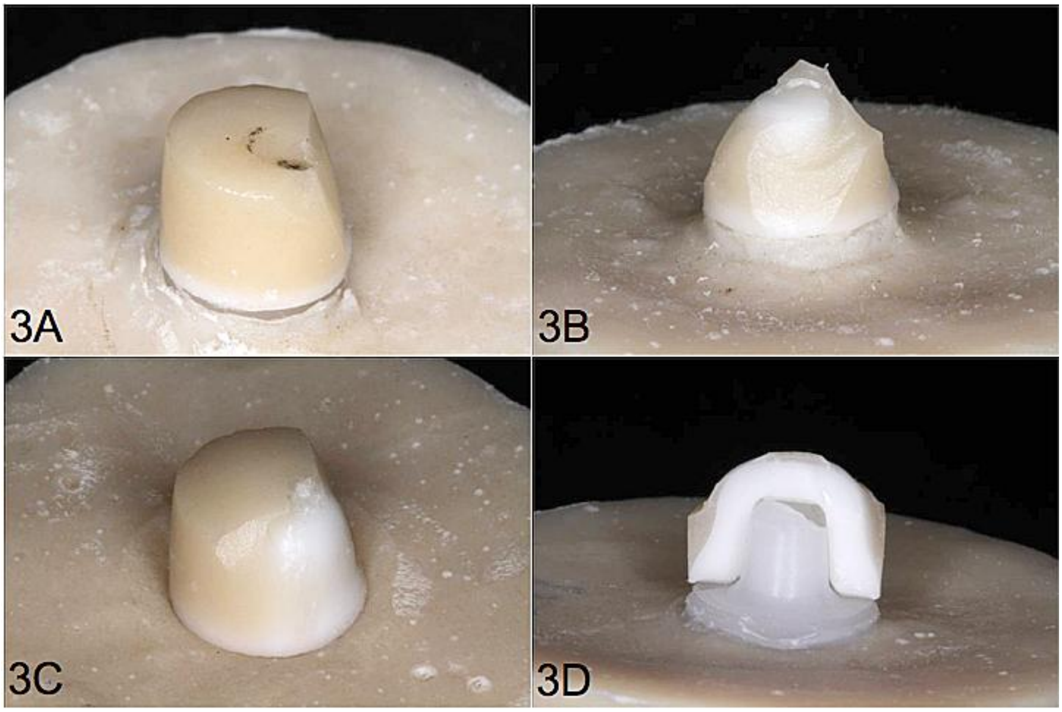

Figure 3. The fracture aspect of zirconia crowns from each group. (A) The 0.5-mm coping under the conventional cooling rate. (B) The 0.5-mm coping under slow cooling. (C) The 1.5-mm coping under conventional cooling. (D) The 1.5-mm coping under slow cooling.

Small edge chipping was observed without exposure of the zirconia coping, except for the margin area. Extended fracture of the veneer ceramic was present with a small area of exposed zirconia coping at the occlusal area. For specimens with the thin coping, the mean failure loads were not significantly different between the fast and slow cooling rates ($p = 0.686$). However, when the zirconia coping was 1.5 mm, the slow cooling group showed a significantly greater mean failure load, compared to the fast-cooled specimens (Fig. 3D).

IV. Discussion

In the current study, the mean failure loads were evaluated in zirconia crowns with different cooling rates and coping thicknesses. These are two main research topics in recent studies. The results of this study showed that a thicker coping and a slow cooling rate resulted in greater mean failure loads, compared to a thinner coping with a thicker veneer ceramic or conventional cooling after the final firing. Therefore, the null hypothesis was rejected.

It was only possible to design nonanatomic copings with a uniform thickness in the early stages of dental CAD/CAM services. Nonanatomic copings resulted in areas of unsupported veneering ceramics, which is considered the main cause of the high chipping rate [25]. Laboratory studies show that greater failure loads or a fewer number of chippings occur in zirconia crowns with anatomic or thicker coping designs [26-28]. Mathematical studies also show that modifying the coping design with a lingual and proximal collar significantly increases the reliability of zirconia crowns [29]. However, compared to thin coping or even-thickness zirconia coping designs, thick or anatomical coping designs are problematic. Tholey and coworkers [12] compared the temperature difference between the inner and outer surfaces of zirconia crowns with two different coping designs. They reported that the anatomical coping resulted in a greater temperature difference between the inner and outer surfaces of the zirconia crowns compared to crowns with an even coping thickness, and that a greater temperature difference resulted in high residual tempering stresses. Furthermore, clinical studies report a higher chipping rate and extended veneer fractures of zirconia ceramic restorations compared to metal ceramics—even with anatomical coping designs [7,30,31]. Therefore, the anatomical coping design is presumably insufficient to prevent veneer ceramic chipping in clinical practice.

In addition to the coping designs, recent studies emphasize the influence of the cooling rate until attaining the glass transition temperature of veneer ceramics after the final firing. Swain [17] report that the residual stress in veneer ceramic is closely associated with chipping failure, and that slow cooling decreases the amount of residual tensile stress in veneer ceramics [22,32]. During cooling, the surrounding temperature is transmitted through the coping material very fast because of the higher thermal diffusivity of an alloy or alumina. Therefore, the type and amount of residual stresses were determined by the thickness of the veneer ceramics, not by the thickness of the coping or the total thickness of the coping and veneer ceramics in metal ceramic and alumina ceramic teeth. In contrast to alloys or alumina, zirconia has a lower thermal diffusivity. It retains heat for a certain amount of time rather than transmitting the surrounding temperature to the veneering ceramics. The amount and type of residual stress are governed by the sum of the veneer ceramic and the coping thickness of the zirconia ceramics [17]. Slow cooling is also important in zirconia ceramics to compensate for the slow temperature transition through zirconia.

The most important finding of this study was that the mean failure load increased remarkably when zirconia crowns with the thick coping had been slowly cooled after the final firing cycles, compared to the failure load of zirconia crowns with a thick coping or crowns that underwent slow cooling. Even in the zirconia crowns that had the thick coping design, the mean failure load was not significantly increased if the crowns were conventionally cooled after the final firing. However, the mean failure load of the crowns with the thick coping was significantly increased when the crowns were slowly cooled until attaining the glass transition temperature of the veneer ceramic (Table 3; $p < 0.001$). These results are in agreement with the findings of the study by Tholey et al. [12]. As mentioned previously, the thicker coping produced higher residual tempering stress because of the greater temperature difference between the inner and outer surfaces of the zirconia crowns; however, a smaller temperature difference occurred when the crowns were cooled slowly, which decreased the residual stress [12].

Statistical analysis showed that slow cooling did not significantly increase the mean failure loads when the zirconia crowns had the thin coping ($p = 0.686$); however, slow cooling significantly increased the mean failure load when the coping was thick ($p < 0.001$). The thick coping likewise only effectively increased the mean failure load when the crowns were slowly cooled after the final firing.

This result was clinically confirmed by the study of Rinke and colleagues [33] who reported that the survival, success, and chipping rate of the zirconia crowns and metal ceramic crowns were comparable during 3 years of clinical service when the anatomical core design and extra-cooling time were applied, even though they only added 6 minutes to the conventional cooling rate.

Each group presented different fracture aspects. The force was applied 2 mm from the occlusal–axial angle. The thinner coping (i.e., 0.5 mm) in the conventional cooling group showed small edge chipping of the veneer ceramic. Extensive fracture of veneer ceramic or coping exposure was not observed in this group. The thin coping in the slow cooling group showed extensive fractures in the veneer ceramic. Most specimens showed zirconia coping exposure, but the exposed areas were very limited. The thick coping (i.e., 1.5 mm) in the conventional cooling group showed extensive veneer fractures with a large area of zirconia coping exposure. One specimen in this group had a small amount of zirconia coping fracturing at the cervical area (Fig. 3D). Six of 10 specimens in the thick coping and slow cooling rate group showed catastrophic zirconia coping fracture. The crowns were cut into two or three pieces and separated from the abutment; little distortion was observed at the cervical areas of abutment. The cervical area of abutment was presumably first distorted because of the high failure load, and then the unsupported zirconia copings were fractured.

The current study has some limitations. No chipping was introduced after 300,000 chewing cycles with 1263 thermal stimulations. Because of the lack of chipping after the chewing simulations, static loads were applied to each specimen until fracture and cone cracks were observed by scanning electron microscope (Fig. 4).

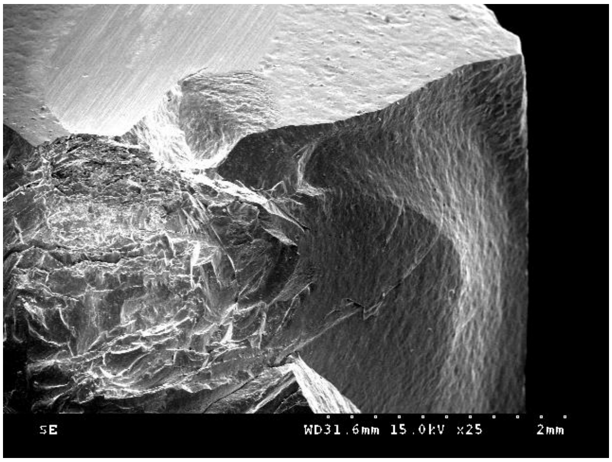

Figure 4. Cone crack was observed at the load receiving area.

In most clinical situations, a subcritical crack is propagated by small and repeated occlusal forces, not by a single catastrophic force such as a static failure load. A chewing simulator is a very useful device for wear studies because it provides slide movement. However, it has limitations in fatigue studies. Instead of a chewing simulator, a cyclic loading device with varying force would be appropriate to reproduce the intraoral fatigue condition.

V. Conclusions

The results of this study suggest the followings: (1) the coping thickness and cooling rate significantly influences the mean failure load of zirconia crowns; (2) there is an interaction between the coping thickness and cooling rate on the mean failure load of zirconia crowns; and (3) there is a significantly greater mean failure load when the zirconia crowns have a thicker coping and are slowly cooled after the final firing.

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국문요약

냉각속도 와 지르코니아 두께에 따른 지르코니아 코핑- 전장 도재 수복물의 파절 강도 및 파절 경향에 대한 연구

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높은 강도와 심미성으로 인해 지르코니아 수복물의 사용이 점차로 증가하고 있는 추세이나 금속-도재관에 비해 높은 빈도로 나타나는 응집파절은 아직 해결되지 않은 문제로 남아있다. 응집파절의 원인으로는 여러가지 요소가 추정되고 있지만 최근에 발표된 실험연구에서 전장도재 소성 후의 냉각속도 차이와 지르코니아 코핑의 형태 차이가 응집파절에 영향을 미치는 주된 요소라고 발표되고 있다. 본 연구에서는 이 두가지 요소를 복합적으로 적용하여 제작한 지르코니아 수복물에 반복피로하중 후의 파절강도를 측정하여 냉각속도 차이와 코핑 두께의 차이가 파절강도의 크기에 미치는 영향을 평가하려하였다.

Polymethylmethacrylate 재질을 이용하여 동일한 형태의 지대치 모형 40 개를 제작 한 후 치과용 캐드캠 시스템을 이용하여 0.5mm 와 1.5mm 두께의

지르코니아 코핑을 각각 20 개씩 제작하였다. 코핑에 전장도재 축성 시 0.5mm 및 1.5mm 두께 군에서 각각 10 개는 최종 소성 후 냉각 속도를 conventional cooling 으로 나머지 10 개씩은 slow cooling 을 시행하여 총 4 개 실험군의 동일한 형태를 가지는 지르코니아 수복물 40 개를 제작한 후 레진시멘트를 이용하여 지대치 모형에 합착하였다. 지르코니아 수복물에 chewing simulator 를 이용해 50N 힘으로 30 만회 반복하중과 1263 회의 열순환을 부여 후, 파절되지 않은 시편은 universal loading device 를 이용해 단순 파절 강도를 측정하였다. 간 군의 파절강도의 결과는 0.05 유의 수준에서 1-way ANOVA 와 2-way ANOVA test 로 통계 처리하였다.
30 만회의 반복하중을 가한 후 파절이 나타난 시편은 없었다. 평균 파절강도는 1.5mm 두께의 코핑에 전장도재 축성 후 slow cooling 을 시행하여 제작한 군에서 다른 군들에 비해 유의성 있게 높았다($p < 0.001$). Conventional cooling 을 시행한 경우, 코핑 두께의 차이는 평균 파절 강도에 영향을 미치지 않았으나, slow cooling 을 시행한 군에서는 코핑 두께가 파절 강도에 유의한 영향을 미치는 것으로 나타났다.
본 연구결과에 기초할 때 임상에서 지르코니아 수복물 제작 시, 코핑의 두께를 증가시키고 전장도재는 최종 소성 후 slow cooling 을 하는 것이 추천되며, 본 연구결과를 뒷받침할 임상연구가 필요하리라 여겨진다.

핵심용어: 지르코니아, 응집 파절, 냉각 속도, 코핑 두께, 파절 강도