Influence of firing cycles on the margin distortion of 3 all-ceramic crown systems

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Statement of problem. Although all-ceramic restorations are widely used, there is a lack of information about how the fit is affected by fabrication procedures. The adequacy of the fit of all-ceramic restorations has been questioned.

Purpose. This study examined the effect of porcelain and glaze firing cycles on the fit of 3 types of all-ceramic crowns.

Material and methods. Ten standardized all-ceramic crowns were fabricated on a metal die from each of 3 systems: conventional In-Ceram, copy-milled In-Ceram, and copy-milled feldspathic crowns. Copings of the conventional and copy-milled In-Ceram crowns and nonglazed copy-milled feldspathic crowns served as the control. A device was used to apply a uniform load on specimens during measurement and to reposition the specimens on the measurement device after each manufacturing process. The specimens were not cemented and were measured on the metal die using a profile projector. Measurements were recorded at 18 points selected along horizontal and vertical planes. The crown systems were compared by use of the Student t test and 1-way analysis of variance (ANOVA). Data of measurements repeated at identical locations were analyzed with a multivariate repeated-measures ANOVA. The Bonferroni post hoc test was used for multiple comparisons (α=.05).

Results. The conventional In-Ceram (57 $\pm$ 24 μm) and copy-milled In-Ceram (57 $\pm$ 32 μm) crowns demonstrated nearly identical marginal discrepancy values, followed by the copy-milled feldspathic crowns with a mean of 17 $\pm$ 12 μm in the vertical plane. The copy-milled In-Ceram crowns had a mean horizontal discrepancy value of -12 ± 4 μm, followed by the copy-milled feldspathic crowns with a mean of -4 ± 5 μm and the conventional In-Ceram crowns with a mean of -6 ± 4 μm. Statistical analyses demonstrated no significant differences in the marginal discrepancy values among the 3 all-ceramic crown systems, except for the horizontal discrepancy values between the conventional and copy-milled In-Ceram crowns after the porcelain firing cycle. Results indicated that the addition of porcelain to the copings caused a significant change ($P<.05$) in the marginal fit of the crowns, except for the fit in the horizontal plane of the conventional In-Ceram crowns. However, no significant changes occurred in the fit of the 3 all-ceramic crowns after the glaze firing cycle. There were significant differences in the marginal discrepancy values among the measurement locations ($P<.05$), and the discrepancy value at each location was independent of the mean of the entire crown.

Conclusions. Within the limitations of this study, it was concluded that the 3 all-ceramic crown systems demonstrated a comparable and acceptable marginal fit. The porcelain firing cycle affected the marginal fit of the all-ceramic crowns. However, the glaze firing cycle had no significant effect on fit. The conventional and copy-milled In-Ceram crowns demonstrated medial deformations at the labial and palatal surfaces that might result in occlusal displacement of the crown. (J Prosthet Dent 2005;93:346-55.)

CLINICAL IMPLICATIONS

The results of this in vitro study suggest that the 3 all-ceramic crown systems may be recommended to obtain a favorable marginal fit. The addition of porcelain to the copings of all-ceramic systems may cause a negative effect on the fit of the crowns. The copy-milled feldspathic crowns demonstrate the least marginal discrepancy because the internal and external surfaces of the crowns are completely formed by a copy-milled technique, and milled crowns are subjected to the glaze firing process only. Clinically, the occlusal displacement of the crowns may result from a nonuniform deformation in the horizontal plane of the ceramic substructure.

All-ceramic restorations that permit light transmission are the material of choice when translucency is required to achieve an esthetic match with the adjacent dentition.[1] However, these crowns can be distorted during the manufacturing process and cause misfit.[2]

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Distortion creates a potential space between the restoration and preparation. As this space increases, more luting material is exposed to the oral environment. Because of the solubility of most dental cements, bacterial plaque can easily accumulate in this defective area, which, in turn, can result in gingival inflammation, caries, and pulpal lesions.[3-8] In addition, variations in fit can create stress concentrations, which may reduce the strength of the restoration.[2,9]

Several authors have attempted to determine what constitutes clinically acceptable marginal openings that are not visible to the naked eye and are undetectable with a sharp explorer. Christensen[10] evaluated the fit of subgingival and supragingival margins of gold inlays with a group of dentists and stated that the least acceptable marginal discrepancy in visually accessible surfaces was 39 μm, according to the linear regression prediction formula. In an in-vivo study, Lofstrom and Barakat[11] used a scanning electron microscope to measure the supragingival margins of the crowns that were considered clinically well fitting by several dentists and reported marginal discrepancy values in a range of 7 to 65 μm.

The fit of all-ceramic restorations was investigated by several authors,[12-23] and the mean marginal discrepancy range was reported as 19 to 160 μm. The results indicated large variations of marginal discrepancy within a single-crown system.[21] This may result from the number of measurements that were necessary for determination of the discrepancy values[16,18,24,25] and may explain the confusion concerning the clinically acceptable gap size for such restorations.[25-27] The fit of the crown is generally evaluated with the gap between the prepared tooth and the intaglio surface of the restoration.[2,28] The linear distance from the cavosurface finish line of the preparation to the margin of the restoration is defined as the absolute marginal discrepancy.[16,21] However, it is impossible to describe a marginal gap by a single definition.[25]

The other important subject related to the measurement of the fit is the SD of the mean. The SD is a degree of variability and is reported as approximately 20 μm in many studies.[2,7,8,12-17] Increased SDs may result from a nonuniform distortion of the substructure during porcelain firing cycles,[13] asymmetric contours of the crown margin,[13,29] damage to the crown margin during the manufacturing process,[16] and incomplete seating of the restoration on the die.[30]

The methods for measurement of the marginal fit include the following: (1) cross-sectional view, (2) direct view of the crown on a die, (3) impression replica technique, and (4) clinical examination.[31] The cross-section technique has been used to measure the marginal fit of cemented inlays,[10,32] metal-ceramic crowns,[13,14,33,34] and all-ceramic crowns.[2,12-14,16,19,35] The direct view is a nondestructive technique and is often used to measure the distortion during the manufacturing process of the restorations.[1,33,36-41]

The all-ceramic crown systems tested are based on different technologies. These systems require specialized equipment, techniques, and manufacturing processes. Copy-milled In-Ceram substructures are milled using the Celay system (Mikrona AG; Spreitenbach, Switzerland), which is a machinable ceramic technique using sintered aluminium oxide blanks (Vita Celay Alumina Blanks; Vita Zahnfabrik, Bad Säckingen, Germany). Substructures are subsequently glass-infiltrated and veneered with porcelain (Vitadur Alpha; Vita Zahnfabrik). Conventional In-Ceram substructures are manually fabricated with aluminous porcelain (In-Ceram Alumina; Vita Zahnfabrik) and sintered. Sintered substructures are subsequently glass-infiltrated and veneered with the porcelain. Copy-milled feldspathic crowns are milled as complete crowns by using the Celay system (Mikrona AG) from feldspathic porcelain blocks (Vitablocs; Vita Zahnfabrik). Nevertheless, there is a lack of information as to how the fit is affected by various firing procedures that are used for the all-ceramic crown systems. The aim of this study was to evaluate the vertical and horizontal discrepancies of the 3 all-ceramic crown systems after the porcelain and glaze firing cycles.

MATERIAL AND METHODS

Thirty crowns, 10 crowns from each of 3 all-ceramic crown systems (conventional In-Ceram, copy-milled In-Ceram, and copy-milled feldspathic crowns) were evaluated. Except for fabrication of the conventional In-Ceram copings, the fabrication and measurement of specimens were performed on a metal die.

An Ivorine maxillary right central incisor (Columbia Dentoform Corp, Long Island, NY) was prepared for a complete-coverage crown with the aid of a surveyor (Paraflex; Bego, Bremen, Germany). The preparation had a 90-degree shoulder with a rounded axiogingival internal line angle. The shoulder width was 1.2 mm for the labial and palatal surfaces and 1 mm for the mesial and distal surfaces. The height of the preparation was 7 mm, with a convergence angle of 6 degrees. A silicone (Reprosil; Dentsply Caulk, Milford, Del) impression was made of the prepared tooth to create a mold, and an autopolymerizing acrylic resin (GC Pattern Resin; GC Corp, Tokyo, Japan) was poured into the impression to form a pattern that was used to create the metal die. The acrylic pattern was invested, subjected to the burnout process, and cast with a base metal alloy (Wiron 99; Bego, Bremen, Germany). After the metal die was trimmed and polished, an identifiable reference ring was attached to the die at an area approximately 1 mm apical to the finish line of the preparation.

The conventional and copy-milled In-Ceram copings were fabricated according to the manufacturers'

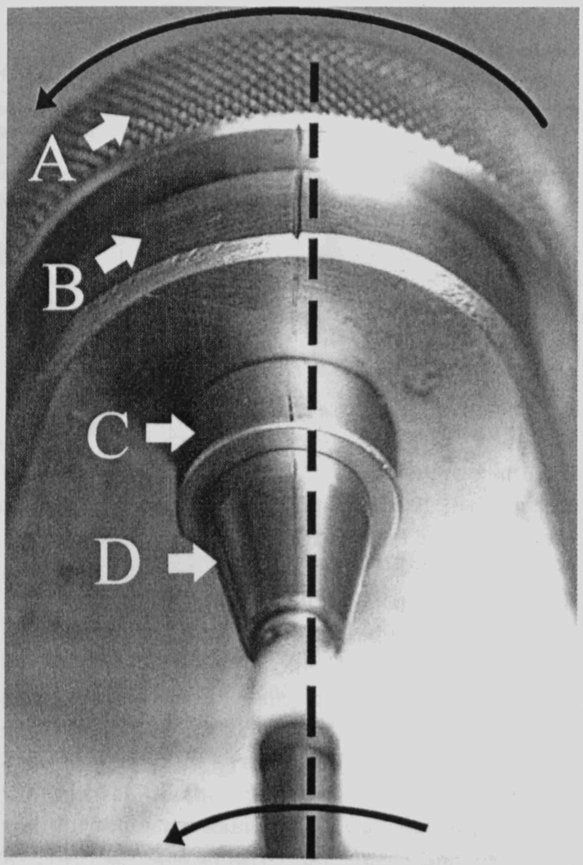

Fig. 1. *Dotted line* shows reference indentations used as starting point for measuring specimens. *Black arrows* indicate rotation direction of horizontal rod of device and crown and die assembly. *(A,D)*, rotation units; *(B, C)*, fixed units (*white arrows*).

directions. For the fabrication of the conventional In-Ceram copings, the metal die was duplicated with the silicone impression material (Reprosil; Dentsply Caulk) to produce the plaster (In-Ceram Alumina Special Plaster; Vita Zahnfabrik) dies. The slip casting material (In-Ceram Alumina Powder; Vita Zahnfabrik) was applied to the die and then sintered in a furnace (Inceramat; Vita Zahnfabrik) for 2 hours at 1120°C. All axial surfaces of sintered copings were verified with a caliper (Iwanson decimal caliper 2550-2; ASA Dental, Bozzano, Italy) and adjusted to a thickness of 0.6 to 0.7 mm with a fine-grained diamond rotary cutting instrument (30 μm, 7862M-029; Brasseler USA, Savannah, Ga). Copings thinner than 0.6 mm were excluded from the study and replaced with new copings. A special glass powder (In-Ceram Alumina Glass Powder; Vita Zahnfabrik) was mixed with distilled water and brushed onto the sintered copings. Glass-coated copings were then placed on a platinum foil and fired for 4 hours in the furnace (Inceramat; Vita Zahnfabrik) at 1100°C. Excess glass was removed from all copings with a coarse-grained diamond rotary cutting instrument (100 μm, 6934B; Brasseler USA) and airborne-particle abraded with 50-μm alumina particles at 2-bar pressure. The thickness of the copings were verified with the caliper (Iwanson), and adjusted to a thickness of 0.6 mm with the fine-grained diamond rotary cutting instrument (7862M-029; Brasseler USA). Glass-infiltrated copings were mounted on a specimen-positioning device (SPD), and measurements were made between the reference points.

The SPD was used to secure the specimens at the same position on the die, applying a uniform load to each specimen-die assembly during measurement.[7,13,18,40,42] The device consisted of fixed and rotation units on a rectangular base. The metal die was attached precisely in a horizontal rod that was a rotation unit so that it could be stable during the measurements. The midlabial point of the stabilized die was selected as a first measurement point and served as a fixed reference point. To position the specimens at the first measurement point of the marginal fit, the horizontal rod of the device was rotated to the right until indentations on the rotation units coincided with those on the fixed units (Fig. 1). The completed copings or crowns were seated on the metal die and then rotated to each successive measurement position. These positions were previously marked on the SPD at 20-degree intervals to ensure a total of 18 recording points on the margin of each specimen.

For the fabrication of the copy-milled In-Ceram copings, prototype resin composite copings were directly fabricated on the metal die by using a light-polymerizing resin composite (Celay Tech; ESPE, Seefeld, Germany). The thickness of the composite copings was adjusted to 0.7 mm with the fine-grained diamond rotary cutting instrument (7862M-029; Brasseler USA) at slow speed, similar to the conventional In-Ceram copings, and then mounted in the scanning unit (Serien Nr: CL1.00990) of the Celay system (Mikrona AG). The structures were scanned and simultaneously milled from sintered aluminium-oxide blanks (AC-12 Vita Celay Alumina Blank; Vita Zahnfabrik). The copings were fired for glass infiltration in the furnace (Inceramat; Vita Zahnfabrik) at 1100°C for 40 minutes. The excess glass was removed from all copings with the coarse-grained diamond rotary cutting instrument (Brasseler USA) and airborne-particle abraded with 50-μm alumina particles at 2-bar pressure. The thickness was adjusted as previously described. The glass-infiltrated copings were mounted on the SPD, and measurements were made.

The thickness of all copings was 0.6 mm, except for the incisal edge, where the core material was 1.0 mm thick. The copings that exhibited an obvious misfit to the naked eye were excluded because of the difficulty of standardization that would have resulted from internal grinding. Instead, new copings were fabricated. A metal former was fabricated in

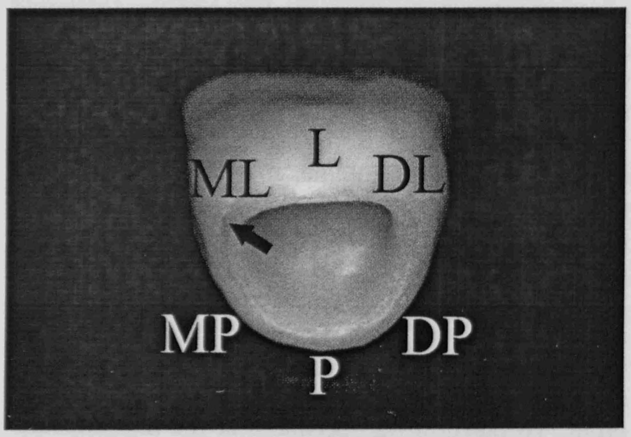

Fig. 2. Locations in which measurements were evaluated. *(L),* Labial; *(ML),* mesiolabial; *(MP),* mesiopalatal; *(P),* palatal; *(DP),* distopalatal; *(DL),* distolabial. Porcelain was not applied approximately 0.5 to 1 mm from coping margin to prevent contamination of margin and intaglio surface (*arrow*).

which the die was inserted to form the mesial, distal, labial, and palatal surfaces. After the glass infiltration, the copings were veneered with the porcelain (Vitadur Alpha; Vita Zahnfabrik) to establish a complete crown form. After condensation of the porcelain, the labial and palatal surfaces were trimmed to meet the contour of the device with a scalpel. The porcelain firing cycle for the conventional and copy-milled In-Ceram specimens was made in 2 stages: initial dentin layer (1 minute at 960°C) and second dentin layer (1 minute at 950°C). The specimens were fired in a newly recalibrated furnace (Vacumat 40; Vita Zahnfabrik). At no time was any grinding done on the porcelain after initial coping measurements were recorded. The crowns were remounted on the SPD and remeasured. For precision of measurement, the porcelain was not applied to an area approximately 0.5 to 1 mm wide at the coping margin (Fig. 2). The specimens were glazed in air at 940°C for 1 minute and remeasured. The rate of increase in temperature for each step was constant as the same furnace was used throughout.

The prototype complete crowns of the copy-milled feldspathic system were made directly on the metal die and the metal former assembly by using light-polymerizing resin composite (Celay-Tech; ESPE) and mounted in the scanning unit of the Celay system (Mikrona AG). The crowns were milled from feldspathic ceramic blocks (Vitablocs; Vita Zahnfabrik), mounted on the SPD, and measured. The crowns were then glazed for 1 minute at 930°C, in air, and remeasured. The fabrication of all specimens was performed by a single dental technician.

Measurements of the marginal fit were performed in the vertical and horizontal planes. The specimens were viewed under ×20 magnification with a profile projector (Somet SPS 200U; Tovarny Strojirenske Techniky, Prague, Czechoslovakia). The profile projector is an

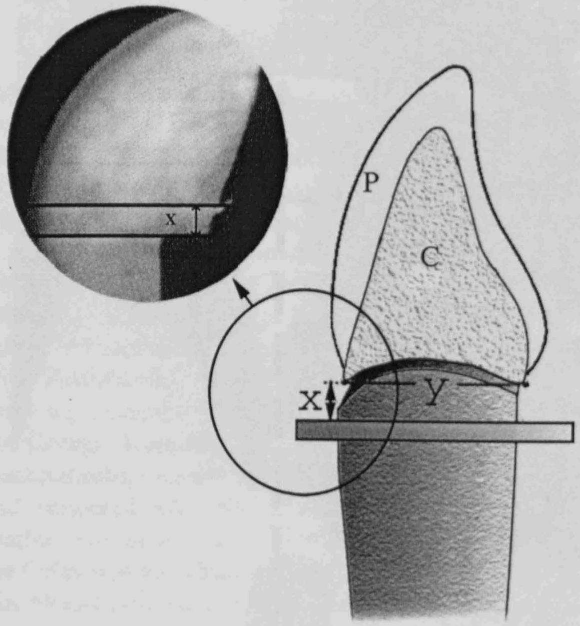

Fig. 3. Drawing shows sites in which measurements were made on die and crown. *(X),* Distance between outermost point of coping margin and reference ring on die; *(Y),* distance between outermost points of coping margin; *(C),* coping; *(P),* porcelain.

inspection and measurement device that enlarges and projects the image of the specimen onto a screen and has a measurement stage that is adjustable in the vertical (x), horizontal (y), and focusing (z) planes. In the present study, the device was used to measure the distances between the reference points during the fabrication of the coping and all successive stages at the 18 points in the x and y planes.

For measurement on the vertical plane, the measurement device was focused on the outermost point of the coping margin and the reference mark on the die. The table of the device was moved along the x-axis until the long axis of the horizontal rod of the SPD coincided with the y-axis of the screen. After the outermost margin of the coping was fixed at the center of the screen, the table was moved along the y-axis until the reference ring was seen at the center of the screen; namely, vertical measurements were made along the long axis of the die between the margin of the coping and the reference mark on the die (X). For horizontal measurement, the outermost point of the coping was fixed at the center of the screen, and the table was moved along the x-axis until another margin of the coping was seen at the center of the screen; in other words, horizontal measurements were made along the x-axis of the screen between the outermost margins of the coping (Y) (Fig. 3). The distances (X and Y) were recorded using an electronic digital counter (POSITIP D 8225; Heidenhain, Traunreut, Germany) with a precision of 0.001 mm.

Table I. Statistical comparison, using Student *t* test, of marginal discrepancy values between conventional and copy-milled In-Ceram groups after porcelain firing cycle

Measurement plane	Comparison	*df*	t	*P*
Vertical	Conventional copy-milled In-Ceram	18	−0.315	.760
Horizontal		18	−3.302	.007*

df, Degrees of freedom.
*Statistically significant.

Table II. Statistical evaluation, using 1-way ANOVA of marginal discrepancy values among 3 all-ceramic groups after glaze firing cycle

Measurement plane	Source	Sum of squares	*df*	Mean square	F	*P*
Vertical	Between groups	0.012	2	0.006	1.098	.350
	Within groups	0.126	27	0.005		
	Total	0.137	29			
Horizontal	Between groups	0.001	2	0.000	2.564	.096
	Within groups	0.003	27	0.000		
	Total	0.004	29			

df, Degrees of freedom.

After each fabrication step, measurements were made at the 18 sites for each specimen. The specimen was removed and replaced on the measurement unit, and another 18 measurements were made at the same sites. This procedure was repeated to attain a total of 3 measurements at each reference point. Fifteen specimens, 5 of the conventional In-Ceram, 5 of the copy-milled In-Ceram, and 5 of the copy-milled feldspathic crowns, were selected, mounted onto the measurement unit, and then measured at a single reference point 3 times, removing and remounting the specimens between the measurements to determine the reliability of placement and removal of the specimens onto the metal die. Readings were reproducible within ±4.3 μm for the conventional In-Ceram, ±3.2 μm for copy-milled In-Ceram, and ±4.9 μm for the copy-milled feldspathic crowns.

Vertical and horizontal measurements of the conventional and copy-milled In-Ceram specimens were made during 3 stages: (1) after the glass infiltration of the copings, (2) after the second porcelain firing, and (3) after the glaze firing cycles. The glass infiltrated copings of each group served as the control, and the changes in the marginal fit of the coping after the porcelain and glaze firing cycles were calculated at the 18 points for each coping. Vertical and horizontal measurements of the copy-milled feldspathic crowns were made during 2 stages: (1) after the milling of the complete crowns and (2) after the glaze firing cycle. The milled crowns served as the control for that group, and the changes in fit after the glaze firing cycle were calculated at the 18 points for each specimen.

In the present study, any existing openings between the margin of the coping and the finish line of preparation were not measured; in other words, the initial seating discrepancy of the coping was eliminated. Measurements were made between the margin of the coping and the reference mark on the die as the discrepancy values obtained after the firing cycles (porcelain and glaze firing) were considered.[36] The measurement values after the fabrication of the coping or the milling of the crown were subtracted from those at the successive stages. Therefore, it is important to note that the marginal discrepancy values represent differences after the porcelain and glaze firing cycles, with negative values representing apical displacements in the vertical plane and medial displacements in the horizontal plane of the coping margin. The grand mean of the 18 discrepancy values was determined as the marginal discrepancy for that crown. The mean values and SDs of the marginal fit were rounded to the nearest 1 μm.

Using this technique, 3240 (20 specimens × 18 points × 3 times × 3 manufacturing processes) vertical and 3240 horizontal measurements for the conventional and copy-milled In-Ceram specimens, and 1080 (10 specimens × 18 points × 3 times × 2 manufacturing processes) vertical and 1080 horizontal measurements for the copy-milled feldspathic specimens were made. Measurements were made by a single investigator.

The 18 points selected along the vertical and the horizontal planes for all specimens were evenly divided into the following 6 locations, with 3 points for each location: the labial (L), mesiolabial (ML), mesiopalatal (MP), palatal (P), distopalatal (DP), and distolabial (DL) surfaces (Fig. 2). The mean of the marginal discrepancies was recorded in each group for each manufacturing process. The marginal discrepancy values of the 10 specimens in each group were averaged for a marginal discrepancy value of the group.

The Student *t* test was used to determine the significant differences between the conventional and copy-milled In-Ceram crowns after the porcelain firing cycle. One-way analysis of variance (ANOVA) was used to evaluate the marginal discrepancies among the 3 all-ceramic crown systems after the glaze firing cycle. Data of measurements repeated at identical locations after the manufacturing processes were analyzed with a multivariate repeated-measures ANOVA. If a significant result was obtained, the Bonferroni post hoc test was used for multiple comparisons. All tests were estimated at 95% level of confidence (α=.05).

RESULTS

The occlusal and lateral displacements of the marginal area were regarded as positive values, while the apical and medial displacements were regarded as

Table III. Results of multivariate repeated measures ANOVA and Bonferroni post hoc test for mean marginal discrepancies between manufacturing processes at all locations

	Comparison	Conventional In-Ceram		Copy-milled In-Ceram		Copy-milled feldspathic	
Plane	Manufacturing processes	Mean	P	Mean	P	Mean	P
Vertical	P - C	49.75	.001	55.38	.011	–	–
	G - P	7.366	.797	1.69	.500	16.67	.886
	Total discrepancy	57 (24)		57 (32)		17 (12)	
Horizontal	P - C	−4.28	.090	−9.531	.003	–	–
	G - P	−1.50	.917	−2.234	.092	−3.53	.103
	Total discrepancy	−6 (4)		−12 (4)		−4 (5)	

SDs shown in parentheses.
C, Fabrication of coping; *P,* porcelain firing; *G,* glaze firing.

Table IV. One-way ANOVA results of marginal discrepancy values among measurement locations

Plane	Source	df	F	P
Vertical	Conventional In-Ceram	5	32.869	.001
	Copy-milled In-Ceram	5	15.31	.005
Horizontal	Conventional In-Ceram	5	45.53	.000
	Copy-milled In-Ceram	5	12.29	.007

df, Degrees of freedom.

the negative values. The conventional In-Ceram crowns had a mean vertical discrepancy of 57 ± 24 μm and a horizontal discrepancy of −6 ± 4 μm. The copy-milled In-Ceram crowns had a mean vertical discrepancy of 57 ± 32 μm and a horizontal discrepancy of −12 ± 4 μm. The copy-milled feldspathic crowns had a mean vertical discrepancy of 17 ± 12 μm and a horizontal discrepancy of −4 ± 5 μm. The 3 all-ceramic crown systems demonstrated comparable marginal discrepancy values. The results of the Student *t* test for the conventional and copy-milled In-Ceram groups after the porcelain firing cycle are presented in Table I. No significant differences were found in the vertical discrepancy values between the 2 groups (P=.760). However, there were significant differences in the horizontal discrepancy values (P=.007). ANOVA results of the 3 all-ceramic groups are presented in Table II. No significant differences were found in the marginal discrepancies among the groups in the vertical (P=.350) and horizontal (P=.096) planes after the glaze firing cycle.

The mean of the differences between the fabrication of the coping and the porcelain firing measurements and between the porcelain and the glaze firing measurements are presented in Table III. The initial seating discrepancy or marginal misfit of the coping was not considered in the study. Thus, the mean values show only the marginal discrepancy after the firing cycles. Results indicated that the porcelain firing cycle caused a significant change (P<.05) in the marginal fit of the crowns, except for the fit in the horizontal plane (P>.05) of the conventional In-Ceram crowns. However, no significant changes occurred in the

Table V. Significance levels of measurements repeated at identical locations around coping margin after manufacturing processes (fabrication of coping, porcelain and glaze firing cycles).

			Vertical		Horizontal	
Crown type	Locations	df	F	P	F	P
Conventional In-Ceram	1	2	119.824	.000*	27.071	.001*
	2	2	39.918	.000*	0.482	.634
	3	2	4.648	.046*	1.418	.297
	4	2	0.663	.541	70.195	.001*
	5	2	32.08	.000*	6.341	.022*
	6	2	6.595	.020*	1.012	.406
Copy-milled In-Ceram	1	2	23.023	.000*	16.237	.002*
	2	2	21.33	.001*	3.357	.087
	3	2	3.92	.065	0.247	.788
	4	2	5.901	.027*	7.443	.015*
	5	2	27.223	.000*	1.016	.404
	6	2	5.425	.032*	0.552	.612

df, Degrees of freedom.
*Statistically significant.

marginal fit of the 3 all-ceramic crowns after the glaze firing cycle. In addition, ANOVA results indicated significant differences (P<.05) in the discrepancy values among the selected measurement locations around the margin (Table IV).

Vertical plane

The measurement values obtained after the porcelain firing cycle were significantly greater than those for the fabrication of the coping (P<.001 for conventional In-Ceram and P=.011 for copy-milled In-Ceram). However, there were no significant differences between the porcelain and the glaze firing cycles for all specimens (Table III).

Measurements repeated at the identical locations after the fabrication of the coping, porcelain firing, and glaze firing cycles revealed significant differences in the marginal fit at the L, ML, MP, DP, and DL surfaces for the conventional In-Ceram crowns. Similarly, the copy-milled In-Ceram crowns demonstrated significant differences at the L, ML, P, DP, and DL surfaces

(Table V). The results indicated that the manufacturing processes caused a significant increase in the distance between the margin of the coping and the reference mark on the die.

Horizontal plane

In the copy-milled In-Ceram crowns, the measurement values obtained after the porcelain firing cycle were significantly greater than those for the fabrication of the coping (P=.003). However, the conventional In-Ceram crowns demonstrated no significant differences in the marginal fit after the porcelain firing cycle (P=.090). There was no significant difference between the porcelain and the glaze firing cycles for all specimens (Table III).

Measurements repeated at the identical locations after each manufacturing process revealed significant differences in the marginal fit at the L, P, and DP surfaces for the conventional In-Ceram crowns. The copy-milled In-Ceram crowns demonstrated significant differences at the L and P surface locations (Table V). These findings indicated that the manufacturing processes caused a decrease in the distance between the margins of the coping labiopalatally.

DISCUSSION

In the present study, the stainless steel die was used as an abutment. Several investigators have used metal[18,37,39] or acrylic resin[7,12,17] dies to measure the marginal fit. The advantages of the metal die are standardized preparation and lack of wear of the die during the manufacturing processes and measurements. The margin design of the metal die included a 90-degree shoulder with a rounded axiogingival line angle. This design is recommended for the preparation of all-ceramic crowns rather than a chamfer preparation.[18] Shillingburg et al[36] found that the shoulder finish lines resist distortion.

Die-spacing techniques have specific differences for each system and can affect the fit of the crown. Weaver et al[15] confirmed that the amount of die relief appeared to be a significant factor for fit. Therefore, in the present study, the die spacer was not applied to the surface of the die for any of the restorations.

The marginal fit of each crown system was evaluated by comparing the measurement values obtained at different stages of the manufacturing process. During measurements in the vertical and horizontal planes, the reference points on the specimen were the outermost portions of the coping margin. If the outermost point of margin is contaminated with porcelain, the additional porcelain mass will cause a decrease in the distance between the margin and the reference mark on the die during vertical measurement. Similarly, lateral contaminations on the margin will cause an increase in the distance, as horizontal measurement was made between the outermost points of the crown margin. Consequently, faulty discrepancy values may be obtained after the firing cycles. Therefore, porcelain was not applied to an area of approximately 0.5 to 1 mm at the cervical area of the specimens, as porcelain contamination on the margin of the coping might influence the precision of measurement during the manufacturing process. In addition, this procedure prevented the incomplete seating caused by contamination of the intaglio surface.

Some conditions are necessary for measurement of the marginal fit on a nonsectioned specimen: (1) measurements of the marginal fit must be repeated to increase reliability, (2) the restoration and die must be repositioned in the identical locations, and (3) the measurement points must be precise and well defined. The SPD was used to apply a uniform load to the specimens during measurement and to precisely reposition the specimens on the x-y stages of the measurement device after each manufacturing process. Thus, the data recorded during each manufacturing process could be compared with those at successive stages. In addition, the fixed starting point for measurement and the 18 points equally spaced along the device's rotation axis were important to identify the discrepancy value at each location around the crown margin.[42]

The marginal fit of the nonsectioned specimens is generally examined with direct microscopic view of the interface. Measurements with an optical microscope may be faulty due to the limited depth of the field. Unless the 2 points to be measured are on the same plane, it is not possible to focus on both points at once.[34] The profile projector presents the view of both the die and the specimen in the same plane on the screen, thus permitting an accurate focus.

The possible sites for measurement of the marginal discrepancy are reported in the literature.[28,32] In the present study, measurements of the vertical discrepancy were made between the outermost point of the crown margin and the reference mark on the die. This procedure eliminated measurement errors resulting from the worn or chipped finish line of a die.[36] In addition, if the distance between the margin and the preparation finish line is accepted as the standard for measurement of the marginal accuracy, the rounded cavosurface margin may cause difficulty while the gap is being measured. In addition, the specimens were not cemented on the dies in the present study. When the crown and preparation margins are covered with luting material, precise visualization of the reference point may be difficult.[21]

The number of measurement points per crown used in previous studies has varied considerably. Groten et al[25] suggested that, ideally, 50 points, or at least 20 to 25 measurements, should be made for each crown. Although measurement at 4 to 12 points may not be considered adequate for the comparison of different crown systems or the successive manufacturing processes, potential imprecision may be improved with a larger sample size.[25] In many studies, sample sizes range from 5 to 10 specimens for each test group.[12,16-18,22,31,39] Therefore, in the present study, 18 measurement points and 10 specimens for each crown system were used, so that the mean discrepancy value obtained from measurement points of each specimen could provide a reasonable representative quantity.[7]

The mean of the marginal discrepancies at all measurement locations reflects the magnitude of marginal discrepancy of the entire crown. However, the marginal discrepancy of each crown may vary greatly at different locations.[26] Because of high variation of the fit within 1 crown system, the mean values of all measurement locations can show a large local discrepancy and result in an increase in the SD. Although the SDs in such studies have been reported to be approximately 20 μm,[2,7,8,12-17,36,41] the mean values of the present study were accompanied by large SDs in a range of 4 μm to 32 μm. The fit of each location might have changed due to nonuniform distortion during the porcelain firing[13] and asymmetric form of the coping margin.[29] Holmes et al[16] found that the fit at various locations around the margin was not significantly different. In the present study, the results did not support that finding. After the firing cycles, the conventional and copy-milled In-Ceram crowns exhibited significant marginal discrepancies at 5 locations in the vertical plane. In the horizontal plane, the highest mean discrepancy values were obtained at 3 locations (L, ML, and P surfaces) for the conventional In-Ceram crowns and at 2 locations (L and P surfaces) for the copy-milled In-Ceram crowns.

With regard to longevity, the interface between the tooth structure and the restoration is of critical importance.[1-6,9] Several authors have investigated the marginal fit of all-ceramic and other crown systems. The results indicated that the all-ceramic crowns were comparable to the metal-ceramic[13-15,21] and gold alloy crowns.[16] In the present study, the initial measurement of each group served as the control, and the changes in the marginal fit of copings or milled crowns after the firing cycles were evaluated. The marginal discrepancy value for each crown system was compared with the clinically acceptable marginal openings and results of other studies.[12,17-20,23,35]

Although there are no accepted standards, Christensen[10] reported that the range of the clinically acceptable subgingival marginal opening was from 34 to 119 μm; however, the acceptable supragingival range was from 2 to 51 μm. McLean and Fraunhofer[27] stated that a marginal opening of 120 μm should be the limit of the clinical acceptability. Lofstrom and Barakat[11] evaluated the marginal opening of clinically well fitting crowns microscopically and reported marginal discrepancy values of 7 to 65 μm. When considering these criteria, the vertical discrepancy values of the copy-milled felspathic crowns (17 ± μm), conventional (57 ± 24 μm), and copy-milled In-Ceram (57 ± 32 μm) crowns obtained in the present study are within clinically acceptable ranges. In addition, these discrepancy values are in agreement with the findings of Beschnidt and Strub,[21] who found a median marginal discrepancy of 60 μm for the conventional In-Ceram crowns, as well as Weaver et al[15] and Holmes et al,[16] who found mean discrepancy values of 44 μm and 48 μm for Dicor crowns.

However, Pera et al[17] (26 μm), Rinke et al[18] (34 μm), and Shearar et al[19] (22 μm) found lower results for the marginal discrepancy. In the present study, the mean vertical discrepancy value of conventional In-Ceram crowns was smaller than the marginal discrepancy of 161 μm found by Sulaiman et al.[22] The differences between the present study and the results of other studies are possibly a result of the method of measurement,[15] type of microscope and magnification factor used for measurement, location[15] and number of measurements, type of die used for measurement, and measurement of cemented or noncemented crowns.[21]

There is no standardized method of measuring marginal fit.[31] The locations for measurement vary among studies,[16,18,24,25] and definition of fit may refer to different measurements.[18] Although the margins of the crown and die seem clinically sharp, these may appear rounded when viewed microscopically and cause difficulty in selecting a point where the marginal opening is to be measured.[25,31] The number of measurement points and the variation in their location may explain the differences among the results of the other studies.[10,16,27,31] The use of the steel die instead of the natural teeth may decrease the variation within each group, producing specimens of identical size and shape. In the cross-section technique, the identical measurement points in different studies may demonstrate different cement thicknesses, as a uniform cementation space between the intaglio surface of the crown and the die may not be provided.[19] In addition, cementation procedures may affect the marginal fit because of the differences in viscosity of luting agents and seating forces.[21]

Pera et al[17] used a stereomicroscope with ×100 magnification for the direct observation of the marginal fit and measured the marginal fit of cemented and noncemented crowns at 4 points on the dies. Rinke et al[18] evaluated measurements under ×180 magnification with a computer-aided stereomicroscope and measured the fit at 54 points on the margin of the conventional and copy-milled In-Ceram crowns. Shearer et al[19] used a reflex microscope with ×20 magnification. Examinations were made using cross-section and direct-observation methods with a cement analogue made from silicone impression material to evaluate marginal fit.

The conventional In-Ceram crowns can be produced with a clinically sufficient marginal accuracy.[18,21,23] In the present study, the conventional and copy-milled In-Ceram crowns demonstrated an identical marginal discrepancy and probability values in the vertical plane. The results indicate that the copy-milled crowns can be reproduced with a clinically sufficient marginal accuracy. However, these results do not agree with the findings of Rinke et al[18] and Beschnidt and Strub,[21] who found a significant difference between the 2 systems. In the present study, the copy-milled feldspathic crowns had a mean vertical marginal discrepancy of 17 μm between the milling of the crown and the glaze firing cycle. These results do not agree with the finding of Beschnidt and Strub,[21] who found a median marginal discrepancy of 99 μm for the copy-milled feldspathic crown.

To evaluate the accuracy of the fit of restorations, measurements must be made for both the vertical and horizontal planes. Horizontal measurements were made to evaluate the direction and quantity of the deformation during the firing cycles of the specimens. In the present study, the labial and palatal surfaces of the conventional and copy-milled In-Ceram specimens exhibited significantly larger marginal discrepancies than other surfaces. There was a tendency for the labiopalatal diameter to decrease with a concomitant increase in the mesiodistal diameter. The results are consistent with the finding of Sulaiman et al[22] that the conventional In-Ceram crowns demonstrated a significant medial shrinkage at the labiopalatal direction. An increase in marginal gap in the vertical plane can result from a medial displacement of the coping margin, which would produce tighter fit and incomplete seating. During the porcelain firing cycle, porcelain particles melt and fuse by filling up voids, and the contracting mass of fused porcelain exerts a compressive force on the coping during cooling.[7] If the coping margin begins to deform under the stress of the contracting porcelain, the stress is spread further around the circumference of the margin. Consequently, because the porcelain shrinks toward its greatest mass, the labiopalatal distance decreases, while the mesiodistal distance increases in the coping margin.[8]

Although measurements were made after the fabrication of the coping and the porcelain and glaze firing cycles, the marginal discrepancy values implied differences during the porcelain and glaze firing cycles. Cho et al[24] found that the marginal fit in each location was influenced by the manufacturing process. However, Shearer et al[19] found that addition of the porcelain to the conventional In-Ceram coping did not affect the fit. In the present study, the comparisons between the manufacturing processes demonstrated that the porcelain firing significantly altered the marginal fit of the crowns, except for the fit in the horizontal plane of the conventional In-Ceram crowns. This indicates that the copings are not completely stable during the porcelain firing cycle. The distortion that occurred during the porcelain firing cycle might be due to nonuniform porcelain mass. Because the firing shrinkage is a function of porcelain bulk, it is possible that the larger marginal discrepancy seen at the labial and palatal margins is related to the greater bulk of the porcelain at these surfaces.[22,33,40] The distortion of the copings during the porcelain firing affects the success of the restoration as it may cause an increase in the marginal opening.[38,41] The differences in the porcelain thickness may result in the differences in fit among the crowns within each group, as an extra bulk of the porcelain used during the manufacturing process may be the primary reason for variations in the marginal distortion.[8,33,36,40] Thus, the metal former was fabricated to create a uniform contour for each specimen in this study.

However, the 3 crown systems exhibited no significant marginal discrepancy values in the vertical and horizontal planes after the glaze firing. This suggested that the glaze firing cycle did not affect the accuracy of the fit. In addition, the 3 all-ceramic systems demonstrated comparable marginal discrepancy values, except for the horizontal discrepancy values between the conventional and copy-milled In-Ceram crowns after the porcelain firing cycle.

There were some limitations in this study. The crowns were not subjected to an artificial aging process. Thermal cycling and mechanical loading are generally used to simulate oral conditions. Hung et al[13] demonstrated a significant negative effect of thermal cycling on marginal fit of crowns. However, Beschnidt and Strub[21] demonstrated that there was no significant effect of an aging procedure on the marginal fit. Another limitation is that this study examined the 3-dimensional distortion of an anterior single crown and tooth preparation design. The use of fixed partial dentures rather than single crowns may result in different marginal discrepancy values due to varied geometric forms. In addition, the marginal accuracy may be influenced by the tooth preparation design.[24] Further investigation is necessary to evaluate the effect of different tooth preparation designs, fixed partial dentures, and the aging process on the margin distortion.

CONCLUSIONS

Within the limitations of this study, the following conclusions can be drawn:

1. There were no significant differences in the marginal discrepancy values among the 3 all-ceramic crown systems, except between the conventional and copy-milled In-Ceram crowns in the horizontal plane (P<.05).
2. The largest marginal discrepancy occurred during the porcelain firing cycle (P<.05).

3. There were significant differences in the marginal discrepancy values among the measurement locations, and the discrepancy value at each measurement location was independent of the mean of the entire crown.

4. The conventional and copy-milled In-Ceram crowns demonstrated medial deformations at the labial and palatal surfaces that might cause an occlusal displacement of crown.

5. The 3 all-ceramic crown systems tested produced crowns that were within a reported clinically acceptable range of 2 to 120 μm.

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