치의학박사학위논문

Comparison of the marginal accuracy and internal fit of Co-Cr alloy crown-copings fabricated by casting, CAD/CAM milled, and 3-D printing laser-sintered techniques

주조, CAD/CAM milled 및 3-D printing 을 활용한 laser sintered 기법을 이용한 코발트-크롬 크라운-코핑의 변연 정확도 및 내부 적합도 비교

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ABSTRACT

Comparison of the marginal accuracy and internal fit of Co-Cr alloy crown-copings fabricated by casting, CAD/CAM milled, and 3-D printing laser-sintered techniques

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Purpose The purpose of the present study was to compare marginal accuracy and internal fit of Co-Cr alloy crown-copings fabricated by casting, CAD/CAM milled, and 3-D laser sintered techniques and to investigate the degree of precision of manufacturing methods.

Materials and methods Thirty six Co-Cr alloy crown-copings were fabricated from a standard titanium implant abutment (TS system, Osstem, Seoul, Korea) for fit evaluation and divided into three groups according to the manufacturing methods; twelve copings for casting (n=12), twelve copings for milled technology (n=12), and twelve copings for laser sintered technology (n=12). Fit evaluation was performed using three different techniques; weighting the silicone material simulated a cement material, investigating the two-dimensional vertical marginal discrepancy, and measuring the internal gap widths in the cemented and sectioned specimens. One-way ANOVA followed by Scheffe's and Bonferroni's test were performed to determine the significant differences between the groups, and the level of significance was set at p = 0.05 and calculations were handled by the statistics software package (SPSS 19.0, IBM Co, NY, USA). The Pearson's correlation analysis was used to assess the existence of the interrelation between the methods used for fit evaluation in this study.

Results Significantly low mean weight of silicone material (*p<.001*) were observed for the casting coping group, compared to the CAD/CAM milled and 3-D laser sintered groups. Mean two-dimensional vertical marginal gap widths were 38.229 ± 6.186 μm in the casting group, 51.479 ± 6.986 μm in the CAD/CAM milled group, and 72.458 ± 12.440 μm in the laser sintered group, respectively. Significant differences were found among the all three groups as noted by the multiple comparison tests (*p<.003*). The mean average internal gap values was 61.528 ± 11.445 μm in the casting group, 64.278 ± 9.145 μm in the CAD/CAM milled group, and 95.806 ± 7.944 μm in the laser sintered group, respectively. The 3-D laser sintered group showed the highest average internal gap value which was significantly different from those of the casting and the CAD/CAM milled copings (*p< .0001*).

Conclusion The different manufacturing methods influence the marginal accuracy and the internal fit of Co-Cr alloy crown-copings. The vertical marginal gap and the average internal gap of the casting group revealed the significantly smallest gap followed by the CAD/CAM milled and the laser sintered group. However, the Co-Cr alloy crown-copings fabricated with casting, CAD/CAM milled, and 3-D laser sintered technology in this in vitro study demonstrated acceptable range of marginal discrepancy and the internal gap widths referring to the literatures.

Keywords: Co-Cr alloys, CAD/CAM dental, dental laser sintering, marginal discrepancy, internal fit

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INTRODUCTION

Cobalt-chromium (Co-Cr) alloys have been widely used in dentistry for removable partial dentures, metal frames, and porcelain-fused-to-metal crowns,[1] mainly because alloys are strong, resistant to corrosion, and relatively inexpensive compared to gold alloys and some all-ceramic materials.[1-5] Base metal alloys may be preferable over noble alloys for implant-retained structures[1, 6] due to their higher fracture strength, elastic modulus, hardness, and low cost.[7] The fabrication process for alloys, including casting, cutting, and plastic works, are usually difficult because of their high melting point (1349-1449℃), hardness, and limited ductility[8]. Conventionally casted implant superstructures are often associated with marginal and fitting discrepancies. These faults can be attributed to the expansion and contraction of the impression materials, gypsum, wax, investment, and alloy.[9] Casting has been the most common method to fabricate dental alloy for many decades,[1] but errors accumulated in the series of laboratory steps are inevitable. The casting technique, veneering method, and technical experience can also limit the accuracy of the lost-wax casting technique. Simplification of procedure can reduce these errors along with costs that are related to expensive devices.

In recent years, there have been attempts to use the conventional casting in combination with the Computer-aided design/computer-assisted manufacture (CAD/CAM) technology, as milling the fabricated wax pattern followed by scanning instead of the conventional investing and casting procedures (WAX/CAM).[10] Also, the castable pattern resin was designed using three-dimensional system (ProJet® 3510 MP, 3D Systems, South Carolina, USA)and milled for the fabrication of the copings in place of the conventional manual wax-up procedures for maintaining the standardized design.[11]

Computer-aided design/computer-assisted manufacture (CAD/CAM) technique was also introduced in dentistry more than 20 years ago.[12] The pioneers of CAD/CAM system tried to designing an optimal crowns considering functional movement using an optical impression of the abutment in the mouth, and controlled milling machine.[13] Recently, the introduction and increased use of CAD/CAM technology in dentistry have replaced error-prone manual laboratory steps with aligned industrial manufacturing processes.[14] One major advantage of using milling technology is that some disadvantages of casting, such as several clinical appointments needed in including impression taking procedure, casting-induced flaws and porosities which can degrade the quality of the reconstructions, can be avoided. Therefore, it can be both time-saving and cost-effective compared to conventional casting technology.

There are numerous CAD/CAM systems for the scanning and the corresponding milling procedures used in different dental applications. The Procera® system (Nobel Biocare AB, Göteborg, Sweden), introduced in 1991, was developed for manufacturing individualized dental restorations with networked CAD/CAM systems. CEREC® system (Sirona Dental System LLC, Bensheim, Germany) also introduced for in-office chair side use with compact machine set.[15] The 3Shape D 800 (3Shape A/S, Copenhagen, Denmark) which was used in this study, is one of the widely used and authorized three dimensional systems for dental applications, since it has been introduced in 1980s. Also, Pro 50® system (Cynonad Inc, Montreal, Canada), DCS Dental® (DCS Dental AG, Allschwil, Switzerland), Everest® (Kavo Dental GmbH, Biberach, Germany), Cercon smart ceramics® system (DeguDent GmbH, Hanau, Germany), and LAVA® system (3M ESPE Dental AG, St. Paul, MN, USA) etc. have been introduced and mainly utilized for diverse dental applications.[13] Nevertheless, accurate digitization of free form dental objects and industrial manufacture of restorations remain challenging and require continuous quality assessments.[14, 16, 17]

Laser sintering is a type of additive manufacturing and a relatively new method compared to both casting and CAD/CAM milling technique. This is also called as the three-dimensional (3-D) printing or rapid prototyping (RP). Additive manufacturing can fabricate 3-D objects in a single stage, directly from their computer-aided design (CAD), for which X-ray CT and MR images are available.[8] Different from CAD/CAM-based cutting technology, additive manufacturing technology creates products layer by layer on the basis of sliced data from the 3-D design.[8] A laser scans metal powders according to the sliced data to obtain a layer of products. The powders for the next layer are covered on the melted layer, and the laser is again scanned according to the next sliced data. This sequence continues until the near-net-shape of the products is formed automatically.[8] In addition, free form shaping can be achieved without mold and limitations from cutting tools in the process. Therefore, this process is expected to be applied in the fabrication of dental devices with complex geometry. It involves several advantages over the casting and the CAD/CAM technique, and it also saves the raw materials and requires fewer tools to reduce costs.[18]

The commercial laser sintering systems, EOSINT M270 (EOS GmbH – Electro Optical Systems, Krailling, Germany),[5, 11, 18] PM 100 Dental System (PHENIX Systems, Clermont-Ferrand, France),[2, 15, 19] and BEGO MEDIFACTURING System (BEGO Medical, Bremen, Germany)[20, 21], are recently reported in literatures. PM 100 Dental System (PHENIX Systems, Clermont-Ferrand, France) is the first rapid manufacturing system using laser sintering of cobalt-chromium powders that is commercially available to dental laboratories for fabrication of prostheses.[2] EOSINT M270 (EOS GmbH – Electro Optical Systems, Krailling, Germany) system also has been widely used in fabricating the cobalt-chrome fixed dental prostheses including the metal frames of removable partial dentures, and is the first system utilized for laser sintering fabrication technique of base metal restorations in Korea.

Both casting and CAD/CAM techniques have been widely used for a long time to manufacture dental prostheses and many studies have been reported. The mechanical properties and microstructures, which are a dominant factor for influencing mechanical properties, of laser sintered Co-Cr alloy were also reported.[8, 20] And there was a study about comparison of mechanical properties and microstructural characteristics of the fractured surfaces for Co-Cr alloys manufactured by three different methods – casting, CAD/CAM milled, and 3-D laser sintered technique.[22] It reported that the different manufacturing methods influence the mechanical properties and microstructural characteristics of the fractured surfaces for Co-Cr alloys as well.[22] The casting specimens showed highest Vickers hardness, and the CAD/CAM milled specimens revealed highest tensile strength value.[22] However all alloys represent adequate mechanical properties satisfying the ISO standards of dental alloy.[22] Akova et al.[2] demonstrated that the bond strength of a laser sintered Co-Cr alloy to porcelain was not significantly different from that of casting Co-Cr alloy.

Precise marginal and internal fit is one of the most important criteria for clinical success of dental restorations. Smaller marginal gaps produce less gingival irritation[23, 24] and cement washout,[25, 26] improving the clinical outcome and longevity of the restoration. Subgingival marginal discrepancies in implant-supported restorations are related with changes in the ecologic environment that may contribute to the occurrence of peri-implantitis or of bone loss at the marginal portion of the implant.[27] There has been substantial disagreement about the acceptable marginal gap for dental restorations. McLean and von Fraunhofer[28] stated that a gap of 120 μm should be considered the maximum marginal gap in their 5-year examination of 1,000 restorations, and that marginal discrepancies of less than 80 μm are difficult to detect under clinical conditions. And the other studies reported the acceptable marginal gap values were in the range of 50 to 128 μm.[29-31] Bindl and Mormann[32] evaluated both the marginal gap and internal gap width of different all-ceramic CAD/CAM crown copings on chamfer preparations, and reported results varying from 17 to 43 μm for marginal gap width and from 81 to 136 μm for internal gap width.

The marginal and internal fit of metal-ceramic crowns fabricated by laser sintering technique is comparable to conventional production procedures.[21] The few published studies on the fit of Co-Cr alloy copings using laser sintered technology have demonstrated marginal discrepancies of 74 to 99 μm, with internal gap ranging from 250 to 350 μm on single crowns,[21] and a mean internal gap of 63 μm.[15] Furthermore, in a recent study on cement-retained implant supported cast Co-Cr frameworks, the mean vertical misfit was 78 μm.[33] However there has been little information on the marginal and internal gap of Co-Cr alloy copings for single implant restoration, except representing average gap values. And no clinical data on the marginal and internal fit of Co-Cr alloy restorations produced by laser sintered method is available yet.[21] Therefore, investigation about the direct comparison of marginal and internal fit for Co-Cr copings fabricated by different manufacturing methods is needed. The purpose of the present study was to compare marginal accuracy and internal fit of Co-Cr alloy single crown-copings fabricated by casting, CAD/CAM milled, and 3-D laser sintered techniques. The null hypothesis is that the fabrication methods have no effect on the marginal accuracy and internal fit of Co-Cr alloy crown-copings.

MATERIAL AND METHODS

A. Material and preparation of specimens

A standard titanium implant abutment (Transfer type abutment, TS system, Osstem, Seoul, Korea), representing a mandibular first premolar with a beveled shoulder finish line, 6 - degree taper angle, diameter of 5.0 mm, hex, gingival height of 5.0 mm, and vertical height of 5.5 mm was used to produce the superstructures. Figure 1 shows the cross-sectioned image and sizes of the abutment used in this study and the schematic diagram of fabricated Co-Cr crown-coping. The thickness of coping was designed to be 0.5 mm, and the cement gap was set at 30 ㎛. The implant abutment was screwed onto a titanium implant replica (Lab analogue, Osstem, Seoul, Korea) using the recommended torque (25 Ncm). Thirty six cobalt-chromium (Co-Cr) alloy copings were fabricated and divided into three groups according to the manufacturing methods; twelve copings for casting (n=12), twelve copings for CAD/CAM milled technology (n=12), and twelve copings for laser sintered technology (n=12). Figure 2 shows the workflow of the fabrication stages of the specimen according to the three different manufacturing methods.

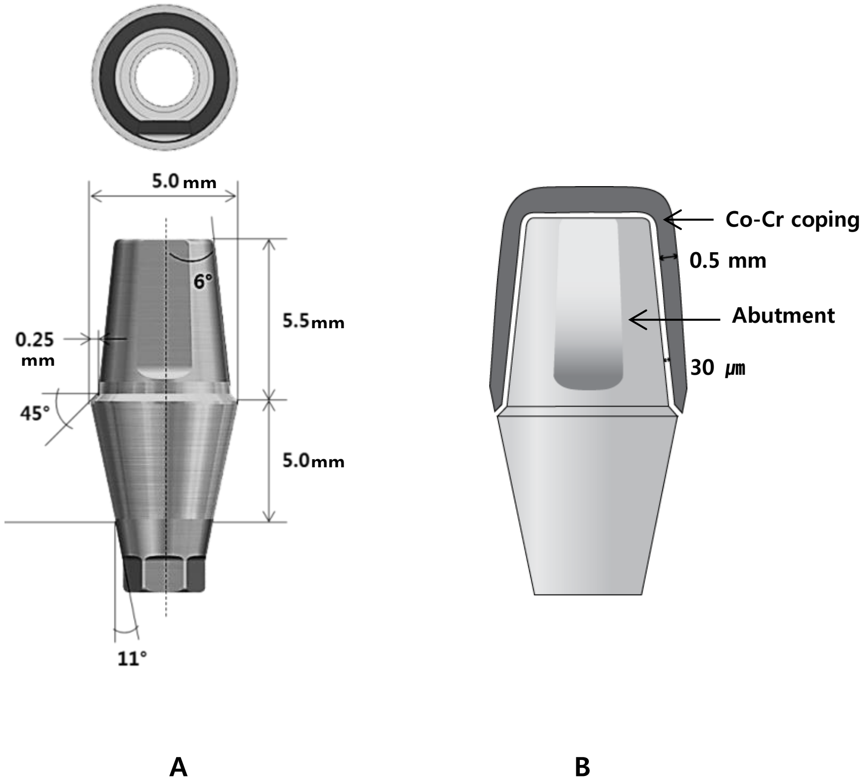

Figure 1. **A.** The cross-sectioned image and sizes of the abutment used in this study. **B.** Schematic diagram of fabricated Co-Cr crown-coping. The thickness of coping was designed to be 0.5 mm, and the cement gap was set at 30 ㎛.

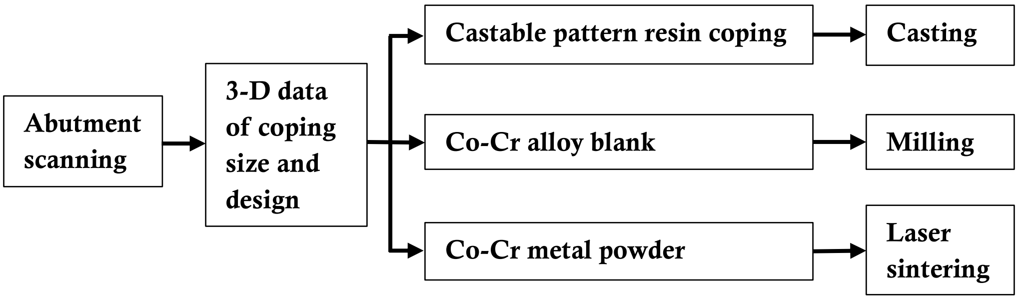

Figure 2. Workflow of the specimen preparation according to the fabrication methods

For the fabrication of the casting crown-copings, the data of coping size and design was captured using software (3Shape D800, 3Shape A/S, Copenhagen, Denmark). The coping was designed to be 0.5 mm thick, and the cement gap was set at 30 ㎛ starting at 1 mm from the margin according to the manufacturer's recommendation (Fig 1). Then the copings were fabricated with castable pattern resin using three-dimensional system (ProJet® 3510 MP, 3D Systems, South Carolina, USA). These copings were invested in a phosphate-bonded investment material (UNI VEST NON-PRECIOUS, SHOFU Inc. Kyoto, Japan) with metal ring, and casted with the Co-Cr-based metal alloy (JEWOOS02, JEWOO M-Tech, Seoul, Korea). The composition of this Co-Cr-based alloy is provided in Table 1. Casting is usually carried out with induction heating in combination with the centrifugal casting (Casting machine, Seki Dental Co., Seoul, Korea) according to the manufacturer's instructions. Cooling procedure, deflasking and blasting with 250 ㎛ aluminum oxide at a pressure of 3 bar and 20 mm distance between nozzle and specimen surface with an angle of 45° were all carried out according to the manufacturer's instructions. The casting sprues and the casting beads on the inside of the copings were removed using a handpiece (KaVo K9, KaVo Dental GmbH) with a separating disc (0.6 mm, No. 43135, Orbis Dental, Offenbach, Germany), and with rotating instruments (No. H71EF, Brasseler GmbH dn Co, Lemgo, Germany). The thickness of copings was confirmed with a thickness gauge (Iwanson crown wax caliper, Surgidental instruments, New York, USA) and the margin and the internal casting beads were examined with a stereomicroscope (Wild M1B, Leica Geosystems AG, Heerbrugg, Switzerland) at ×14 magnification. No additional internal adjustment of the copings was performed except the elimination of casting nodules with rotating instruments.

The 3Shape CAD data of coping was also sent to a communicating 5-axis milling machine (DNM-500, SMT Solution Co., Seoul, Korea) for the fabrication of the CAD/CAM milled copings from the Co-Cr alloy blanks (Starbond CoS, S&S Scheftner GmbH, Mainz, Germany) according to the manufacturer's recommendation. The composition of this alloy blank is also showed in Table 1. The copings were milled by the machine to the wall thickness as defined by the computer. The size of the smallest milling bur was 0.8 mm. No treatment after fabrication was performed.

The laser sintered specimens were prepared from Co-Cr powder (particle size of 15 ㎛) using direct metal laser sintering (DMLS) technology. The EOS CobaltChrome SP2® granule (Biomain AB, Helsingborg, Sweden) was used and its composition is provided in Table 1. The same 3Shape CAD data of coping was sent to the production center (E-Master Dental Hub, Seoul, Korea) where the laser sintering was to be performed using the direct metal laser sintering system (EOSINT M270, EOS GmbH – Electro Optical Systems, Krailling, Germany). The laser sintering procedure followed the recommendations of the manufacturer (EOS GmbH – Electro Optical Systems, Krailling, Germany). The copings were fabricated under a laser power of 200 W and scan spacing from 0.1 to 0.2mm. The laser scan speed and layer thickness were fixed at 7.0 m/sec and 30 ㎛, respectively. All copings were sandblasted with 250 ㎛ aluminum oxide at a pressure of 3 bar before the heat treatment. The heat treatment was performed in a furnace (LAB24 SF-25, Dongseo Science Co. Ltd, Seoul, Korea) at 800 ℃ during 5 hours for releasing residual internal stress.

Table 1. Chemical composition of the casting, milled, and laser sintered Co-Cr alloys for as a percentage according to the manufacturer's instructions (wt %). All alloys are for fabrication of crowns.

Alloys	Co	Cr	Mo	W	Si	Fe	Mn
Casting	63	28	5.5			etc. max. 3.5	
CAD/CAM milled	59	25	3.5	9.5	1.0	max. 1.5	
Laser sintered	63.8	24.7	5.1	5.4	1.0	max. 0.50	max. 0.10

B. Fit evaluations and statistical analysis

Thirty six copings were divided into three groups according to the manufacturing methods, and all copings of each group (n=12) were distinguished by assigned numbers. Each coping was adapted on the abutment intermediated with silicone pressure indicator material (Fit Checker Ⅱ, GC Corporation, Tokyo, Japan). After mixing equal amounts of base and catalyst, the silicone material was placed inside each coping, simulating the clinical application of a luting agent. Copings were then seated on the abutment using finger pressure.[34] Following the removal of excess unpolymerized silicone material at the margin, finger pressure was applied again for one minute. After polymerization of the silicone material, copings were removed from the abutment, and the silicone was weighed using an analytical balance (OHAUS PA214 Pioneer™, OHAUS Co., Parsippany, USA). All measurements were performed by the same operator. The order of measurements within three groups was randomized using a random number generator (Microsoft Office Excel 2010, Microsoft Co., Redmond, USA). The results from the three groups (n=12) were analyzed initially using one-way analysis of variance (ANOVA), and subsequent multiple comparisons between groups were performed using the Scheffe's and Bonferroni's test. In all tests, the level of significance was set at $p = 0.05$ and calculations were handled by the statistics software package (SPSS 19.0, IBM Co, NY, USA).

The two-dimensional vertical marginal discrepancy was assessed by measuring the distance parallel to the abutment axis between the margins of the copings and their respective abutments at the four predetermined equidistant points using a stereoscopic zoom microscope (SZM-45T2, Sunny Optical Technology Co., Zhejiang, China) at x40 magnification (Fig. 3). For these measurements, the copings were sequentially placed on the master abutment and immobilized by customized clamp with predetermined screw stop and frame. The abutments were fitted in a special support in order to situate the vertical gap perpendicularly to the optic axis of the stereomicroscope, thus guaranteeing repeatable projection angles. The four equidistant points were marked on the submarginal surface of the abutment before coping adaptation procedure. A digital photograph was made of four points of the abutment per coping using a digital SLR camera (Nikon D50, Nikon Inc., NY, USA) attached to the stereomicroscope with a millimeter ruler. This millimeter ruler, at the same magnification, was used as a standardized reference in calibration of the measurement software (Image J 1.44p, National Institute of Mental Health, Maryland, USA). The camera reproduced a x40 magnification on a high-resolution computer monitor, so that an image of the marginal discrepancy could be examined using software (Image J 1.44p, National Institute of Mental Health, Maryland, USA). The software determined the mean separation between the margin of the coping and the abutment line in micrometers. To ensure that the software was correctly calibrated for the data collection, a measurement of a known distance (0.5 mm) was preceded at every measurement using the image of the millimeter ruler. The entire procedure was carried out by one trained investigator. Mean vertical marginal gap for all four points of the thirty six copings was recorded and all values of determined vertical marginal gaps were exported to a spreadsheet (Microsoft Office Excel 2010, Microsoft Co., Redmond, USA) for statistical analysis. Evaluation of the mean vertical marginal gaps (calculated by four points per coping, twelve copings per group, total one hundred and forty four measurements) was performed according to the literatures[35, 36] as well as by considering the averaged maximum marginal gap within one group. One-way ANOVA was used to determine if the manufacturing methods influenced the vertical marginal gap. The Scheffe's and Bonferroni's test were performed to determine the significant differences between groups.

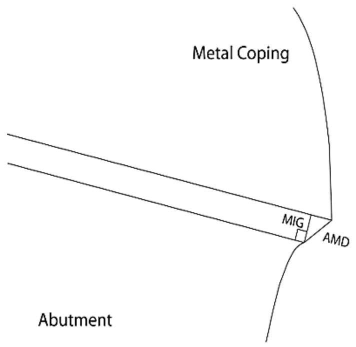

Figure 3. Schematic sectioned view of reference points for evaluation the marginal fit in this study, Marginal internal gap (MIG); the perpendicular measurement from the internal surface of the coping to the axial wall of the abutment at the end of the margin, Absolute marginal discrepancy (AMD); the angular combination of the marginal gap and the extension error which is measured from the margin of the coping to the cavosurface angle of the abutment. In this study, the absolute marginal discrepancy (AMD) can be measured as the two-dimensional vertical marginal gap using this method.

After vertical marginal gap measurement, each coping was luted to the abutment which was screwed onto a titanium implant replica (Lab analog, Osstem, Seoul, Korea) with the recommended torque (25 Ncm), using resin modified glass ionomer cement (FujiCEM™ 2, GC Corporation, Tokyo, Japan). Then firm finger pressure was applied for five minutes until the hydraulic pressure was relieved and the excess cement was removed after polymerization. All specimens were embedded with self-curing acrylic resin (Ortho-Jet™, Lang Dental Manufacturing Co. Inc., IL, USA) in the center of prefabricated plastic mold. Each block was sectioned longitudinally in the labiolingual direction using electronically controlled diamond saw (KDMT-285, Kyungdo Precision Co. Ltd, Seoul, Korea). Sectioned surfaces of each specimen were polished with a series of silicon carbide (SiC) abrasive papers (160, 320, and 800 grit) to remove the metal particles that were adhered on the surfaces using a grinder-polisher machine (KDMT-300, Kyungdo Precision Co. Ltd, Seoul, Korea). Then sectioned surfaces were ultrasonically cleaned in water (WiseClean®WUC, DAIHAN Co., Seoul, Korea) for five minutes to remove the surface contaminants. The order of experiments within the three groups was randomized using a random number generator, as previously described, for each of the cementation, sectioning, and polishing procedures to eliminate any bias that might affect the results. After initially obtaining photographs of each cross-sectioned specimen with a stereomicroscope (SZM-45T2, Sunny Optical Technology Co., Zhejiang, China) at x40 magnification, three digital images were made of each specimen using the digital SLR camera (Nikon D50, Nikon Inc., NY, USA) attached to the stereomicroscope. The image of a millimeter ruler was made at the same magnification and used as a reference for calibration at each imaging session. Photographs were made with a digital camera (Nikon D50, Nikon Inc., NY, USA) and transferred to the imaging data program (Image J 1.44p, National Institute of Mental Health, Maryland, USA). The measurements of internal gap in this study were divided into three different areas of interest for better comparisons according to the terminology reported by Holmes et al.[37] The internal gap width was measured at six standardized points: two marginal points, two axial points, and two occlusal points which are shown in Figure 4. Measurement location of the marginal point was the center of beveled shoulder-area, and the measurement location of axial point was the center of axial wall, starting the end-point of margin and continuing until the transition point with occlusal area. Measurement location of occlusal area included the center of the occlusal surface of the coping both sides of the access hole. Each point was measured three times by a single investigator and the mean value was determined. The mean of the six measurements on each specimen was considered to represent the internal gap width, and the mean of the three measurement areas (marginal, axial, and occlusal points) on each specimen was calculated and compared in three groups either. The results for the three groups (n=12) were also compared using one-way ANOVA and the Scheffe's and Bonferroni's test (p=.05) were performed to determine the significant differences between groups.

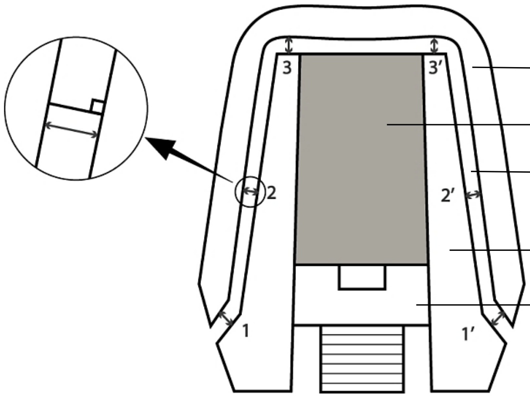

Figure 4. Schematic view of six standardized measurement points for internal gap: two marginal points (1, 1'), two axial points (2, 2'), and two occlusal points (3, 3'). Measurement location of the marginal gaps (1, 1') was the center of chamfer-area, and the measurement location of axial gaps (2, 2') was the center of axial wall, starting the end-point of margin and continuing until the transition point with occlusal area. Measurement location of occlusal gaps (3, 3') included the center of the occlusal surface of the coping both sides of the access hole. Small circle of the left side shows the internal gap measurements as the perpendicular distance between outer surface of the abutment and the inner surface of the coping.

Statistical comparisons of the weight of the silicone material, two-dimensional vertical marginal gap, and internal gap for the three groups of Co-Cr alloy copings were performed. One-way ANOVA was used to determine if the manufacturing methods influenced the silicone weight, the vertical marginal gap, and the internal gap value. The Scheffe's and Bonferroni's test were performed to determine the significant differences between groups, and the level of significance was set at p = 0.05 while calculations were handled by the statistics software package (SPSS 19.0, IBM Co, NY, USA). In addition, the Pearson's correlation analysis was used to assess the existence of the interrelation between the methods used in this study for fit evaluation.

RESULTS

The mean values and the standard deviations of the weight measurements for casting, CAD/CAM milled, and laser sintered specimens were summarized in Table 2. Weight of the silicone material are ranged from 0.005 g to 0.007 g in the casting coping group, from 0.006 g to 0.009 g in the CAD/CAM milled coping group, and from 0.006 g to 0.008 g in the laser sintered coping group. Significantly higher mean weights (p =.0006) of the silicone material were observed for the CAD/CAM milled coping group, compared to the casting coping group and no significant differences were found between other groups. The results from the multiple comparison tests are provided in Table 2.

Table 2. Means and standard deviations of the weight measurements for three groups (n=12) with result of Scheffe's & Bonferroni's test

Group	N	Mean (g)	SD (g)
Casting	12	0.006^{a*}	0.00097
CAD/CAM milled	12	0.007^{b}	0.001
Laser sintered	12	0.007^{ab}	0.00098

Different letters correspond to statistically differences for groups (p <.05) There were significant differences in the mean weight between the casting and the CAD/CAM milled groups and no significant differences were found between other groups.

The mean two-dimensional vertical marginal gap value was 38.229 ± 6.186 ㎛ in the casting group, 51.479 ± 6.986 ㎛ in the CAD/CAM milled group, and 72.458 ± 12.440 ㎛ in the laser sintered group, respectively. The laser sintered copings showed the highest mean value (72.458 ㎛) which is higher than the mean marginal gap of all alloy copings (54.056 ㎛) while the casting copings showed the lowest vertical marginal gap. Table 3 presents the means and standard deviations of the two-dimensional vertical marginal gaps for the three differently fabricated Co-Cr copings. Significant differences were found among all three groups for vertical marginal gaps as noted by the Scheffe's and Bonferroni's multiple comparison tests ($p<.003$).

Table 3. Means and standard deviations of two-dimensional vertical marginal gap (AMD) for the casting, CAD/CAM milled, and laser sintered copings.

Group	**N**	**Mean (㎛)**	**SD (㎛)**
Casting	12	38.229[a*]	6.186
CAD/CAM milled	12	51.479[b]	6.986
Laser sintered	12	72.458[c]	12.440

**** Mean values with different superscript letter indicate that values are significantly different between groups. The laser sintered copings showed the highest mean value while the casting copings showed the lowest vertical marginal gap. Significant differences were found among the all three groups (p<.003).***

Mean values and standard deviations for the internal gap width of three groups were showed in Table 4. The mean average internal gap value was 61.528 ± 11.445 ㎛ in the casting group, 64.278 ± 9.145 ㎛ in the CAD/CAM milled group, and 95.806 ± 7.944 ㎛ in the laser sintered group, respectively. The 3-D laser sintered group showed the highest average internal gap value which is significantly different from those of casting and CAD/CAM milled copings ($p < .0001$). There was no significant difference between the casting and the milled group ($p = .784$) as the result of the multiple comparison tests. The mean values and standard deviations for the marginal internal gap width measurements were 63.625 ± 11.886 ㎛, 52.167 ± 4.979 ㎛, and 81.125 ± 11.777 ㎛, respectively, for the casting copings, the CAD/CAM milled copings, and the laser sintered coping (Table 4). There were significant differences between all three groups as a result of the Dunnett T3 comparison test. On the other hand, the casting coping group showed the highest axial internal gap width (56.042 ± 8.966 ㎛) followed by the laser sintered group (53.833 ± 11.191 ㎛) and the milled group (38.292 ± 9.739 ㎛). The casting and the milled group ($p = .001$), the laser sintered and the milled group ($p = .002$) showed significant differences while the casting and the laser sintered group ($p = .865$) were not significantly different. Lastly, the laser sintered copings showed 152.458 ± 18.209 ㎛

for the mean occlusal internal gap width, which is the highest value while the casting group showed the lowest value (64.917 ± 22.002 ㎛). The differences between groups were significant in all coping groups ($p < .0001$). The results of the multiple comparison tests for internal gap width were summarized in Table 5. Figure 5 charts the mean internal gap widths of three groups according to the measurement regions and the two-dimensional vertical gap values of three groups as well.

Table 4. Means and standard deviations of internal gap for the casting, CAD/CAM milled, and laser sintered copings.

Group		**Marginal internal gap (㎛)**	**Axial internal gap (㎛)**	**Occlusal internal gap (㎛)**	**Average internal gap (㎛)**
Casting	Mean	63.625	56.042	64.917	61.528
	SD	11.886	8.966	22.002	11.445
CAD/CAM milled	Mean	52.167	38.292	102.375	64.278
	SD	4.979	9.739	25.765	9.145
Laser sintered	Mean	81.125	53.833	152.458	95.806
	SD	11.777	11.191	18.209	7.944

The average internal gap values were calculated by the mean values of the three measurement areas of each specimen in the group. The 3-D laser sintered group showed the highest average internal gap value which is significantly different from those of the casting and the CAD/CAM milled copings ($p< .0001$). There was no significant difference between the casting and the milled group ($p= .784$) ($n = 12$, total = 36).

Table 5. Multiple comparisons of internal gap values between three differently manufactured coping groups

Groups	Internal gap	Significance probability (p-value)
Casting - Laser sintered	Average	.000*
	Marginal	.004*
	Axial	.865
	Occlusal	.000*
Laser sintered - CAD/CAM milled	Average	.000*
	Marginal	.000*
	Axial	.002*
	Occlusal	.000*
Casting - CAD/CAM milled	Average	.784
	Marginal	.022*
	Axial	.001*
	Occlusal	.001*

***** *The mean difference is significant at the .05 level. The mean average internal gap value of the laser sintered group revealed significantly higher than the casting and the CAD/CAM milled groups. However, there was no significant difference between the casting and the milled group.*

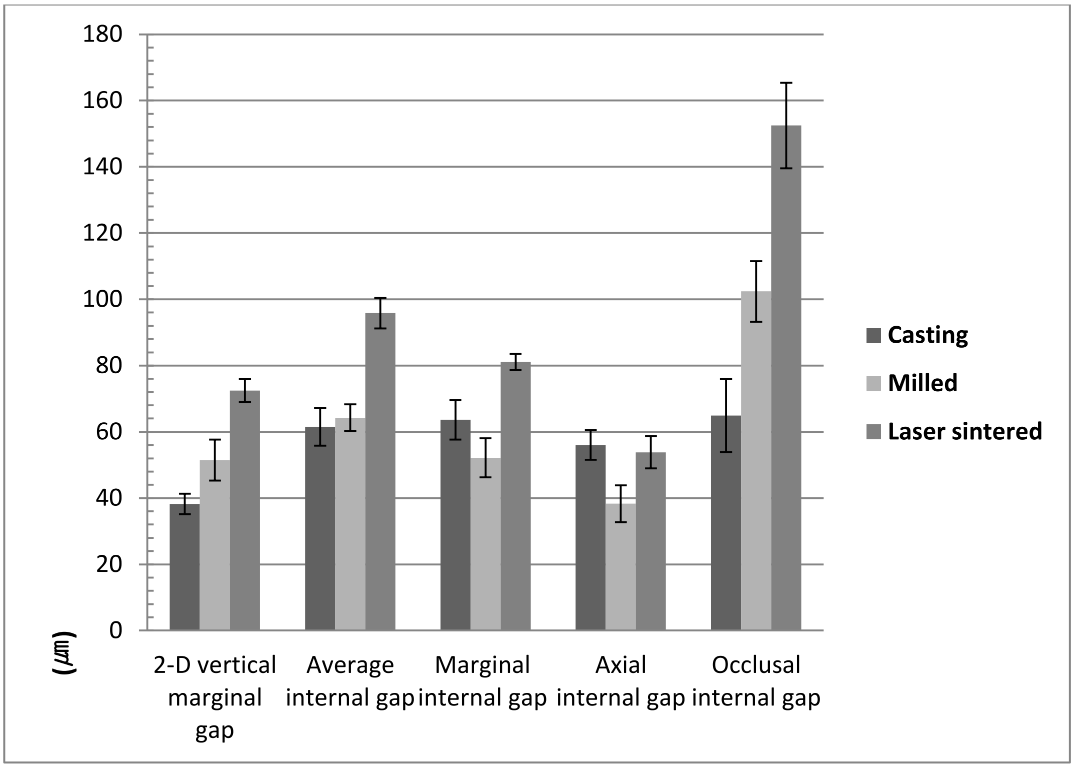

Figure 5. Comparisons of mean two-dimensional vertical marginal gap and the internal gaps between groups fabricated by different methods. The laser sintered copings showed the highest vertical marginal gap which is higher than the mean marginal gap of all alloy copings while the casting copings showed the lowest. In average internal gap value, the 3-D laser sintered group showed the highest which is significantly different from those of the casting and the CAD/CAM milled copings. The occlusal internal gap value presented higher than marginal and axial internal gap values in all three groups.

The interrelation between the methods used in this study for fit evaluation was investigated using Pearson's correlation analysis. The correlation coefficient values represented that there are significant correlations between the vertical marginal gap values and the internal gap width variables ($p < .01$) except the weight of silicone material.

DISCUSSION

The marginal accuracy and internal fit of Co-Cr alloy crown-copings fabricated by casting, CAD/CAM milled, and 3-D laser sintered techniques were compared in this study. The null hypothesis was that the fabrication methods would have no effect on the marginal accuracy and internal fit of Co-Cr alloy copings. The data supports rejection of the null hypothesis as there were differences in the marginal and internal gap between the three differently fabricated coping groups. The amount of marginal and internal discrepancy was in the clinically acceptable range of around 100 ㎛.[28, 38, 39]

The 3Shape D 800 (3Shape A/S, Copenhagen, Denmark) was used in this study for scanning abutment and designing of the crown-copings, because this is one of the widely used and authorized three dimensional systems for dental applications for decades, since it has been introduced in 1980s.

One captured data was used for the fabrications of all crown-copings in three groups. Since the machining tolerance of stock abutments is reported approximately in the range of ±0.01 – 0.1 ㎛ according to the manufactures, the possible errors related to the adaptation between the different abutments and the copings could be disregarded. For the casting group, the castable pattern resin was milled for the fabrication of the copings in place of the conventional manual wax-up procedures. It was an attempt to maintain the standardized design and the uniform thickness of the crown-copings by eliminating the errors related to impression taking procedures, model fabrications, and manual works. And it was possible to compare the marginal accuracy and the internal fit of the copings focused on the different metal fabrication methods.

Optimal marginal adaptation is an important factor in the biologic and mechanical stabilization of the fixed prosthesis. In this study, the mean two dimensional vertical marginal gap width of three groups were in the range of 38.229 to 72.458 ㎛, and these were within the clinical acceptable range of 39 to 120 ㎛.[31, 40] The cast coping group showed significantly smaller vertical marginal gap value than the CAD/CAM milled and the 3-D laser sintered group, and this finding is consistent with the result of previous studies,[21, 41] compared marginal accuracy between differently manufactured restorations. This may be explained that the hard material, Co-Cr alloy block, of milled group is more difficult to cut precisely due to its hardness. More vibration and resistance of the milling axis could affect the accuracy of milling procedure resulting in under preparation compared to the milling of the soft material, castable pattern resin, used in casting specimen. And this might attribute to the smaller marginal gap values of the casting group than other studies.[29-32]

In this study, 3-D laser sintered group showed the largest average internal gaps compared to other two fabrication methods. There are significant differences in average internal gaps between the casting group and the 3-D laser sintered group ($p<.0001$), the CAD/CAM milled group and the 3-D laser sintered group ($p<.0001$). In contrast, it has been reported that the proper use of the 3-D laser sintered technology may result in predictable fabrication under the tested experimental conditions. Ortorp et al.[42] reported that the laser sintered Co-Cr showed lower discrepancies than the casting Co-Cr in the construction of conventional fixed restorations. Ucar et al[15] found no significant differences between laser-sintered and cast Co-Cr sectioned crowns for the internal gap width. However, it has to be noted that the complete seating of the crown-copings were not reported in the laser sintered group despite the largest internal gap value in this study. This can be explained by the possible internal interference of the copings which needed to be refined. Witkowski et al.[43] evaluated the quality of the accuracy of copings after milling by machine and after casting, before manual refinement. And further measurements of the marginal discrepancies were performed after refinement, and the required amount of adjustment time was analyzed. They concluded that the manual refinement improved the marginal accuracy significantly in all groups. Therefore, the minimal refinement procedures should be considered before the evaluation of the marginal accuracy and internal fit of the restorations in further studies.

The descriptive terminology defining the 'fit' varies considerably in previous studies. Moreover, the same term is used for different measurements, or different terms are used for the same measurement.[37] No general guidelines exist on how to perform gap measurements restorations in vitro or in vivo. An important approach to this problem was provided by Holmes et al.[37] who established several gap definitions according to the contour differences between the crown and tooth margin. According to their classification, the perpendicular measurement from the internal surface of the casting to the axial wall of the preparation is called internal gap, and the same measurement at the margin is called the marginal gap. The vertical marginal misfit measured parallel to the path of draw of the casting is called the vertical marginal discrepancy. The angular combination of the marginal gap and the extension error (overextension or underextension) is called the absolute marginal discrepancy. The absolute marginal discrepancy is measured from the margin of the casting to the cavosurface angle of the preparation.[37] However, in practice it is almost impossible to describe a certain gap by only one definition, due to morphologic diversities, rounded margins, or defects.[44] This is one of the main reasons for the large amount of variation commonly reported among investigators. In the present study, the marginal gap was defined as the vertical marginal discrepancy, and the perpendicular measurement from the internal surface of the coping to the axial wall of the preparation is called internal gap for reference to the terminology reported by Holmes et al.[37] The internal gaps were divided into three types according to the measuring points.

Although there is no standard method available for measuring the marginal gap, some fit assessment protocols are described in the literatures. One is the measurements of the specimens by direct visualization under a microscope. This method is nondestructive and can provide several measuring points, however, it is difficult to obtain accurate measurements and the internal fit cannot be measured. Witkowski et al.[43] used this method in comparison of the marginal fit of the casting and CAD/CAM milled crown copings. Other method is the measurements of the embedded and sectioned specimens and Alghazzawi et al.[45] compared the marginal adaptation of two types of glass-infiltrated ceramic crown-copings by CAD/CAM technology. Although both techniques are well-established, most authors agree that these methodologies provide limited information,[46-48] and it is impossible to use these methods in vivo. The evaluation method by impression taking can be divided into the replica technique and the weight technique. The former, also called the cement analog technique, described initially by McLean and von Fraunhofer,[28] has been a reliable and valid noninvasive method to determine the adaptation of restorations to tooth structure. The latter is the weight measurements of cement analog layer, and Kokubo et al.[34] recently used a light-body silicone in place of luting cement to determine relative marginal gaps for ceramic crowns. This is a convenient and non-destructive method, and Nakamura et al.[49] and May et al.[50] used test-fit silicone paste for measurement of internal gaps as well. Besides, the clinical evaluation method using explorer and the scoring system, the Micro CT and 3D analysis can be used for evaluation of the restorations. Gonzalo et al.[47] concluded that the shortcomings of a technique must be considered when interpreting results. The authors highlighted the difficulty in repeating measurements from an identical angle, and the inability to detect internal discrepancies.[47] These conclusions were consistent with other investigations that concluded that horizontal, vertical, and absolute marginal discrepancy must be evaluated to obtain detailed information on the marginal quality of a restoration.[37, 48] Moreover, intrinsic errors in the measurement system like microscope, for instance, can affect measured values.[44] These issues have been addressed with the introduction of internal three-dimensional (3D) fit assessment methods,[14] and the computer-aided techniques that evaluate the marginal quality and fit of a restoration could provide more high accuracy and consistency of the data.[46] Among these methods, the direct visualization method was used in this study. The absolute marginal discrepancy has been considered as the best method to measure the marginal gap because the error at the margin is the largest,[37] which was investigated with direct visualization in this study as the two-dimensional vertical marginal gap. Also the inspection after sectioning, and the weight technique were used in this study.

To standardize the measurement, a standardized fabrication of the copings ensured a uniform thickness, and each specimen was sectioned at the same position to coincide with the reference indentations of the abutments. And the fitting surfaces of the copings were not refined because the amount of refinement is difficult to quantify or standardize. Taper angle of abutment was selected as 6°. In other in vitro studies[50, 51] of marginal adaptation, preparation angles varied between 6° and 15°. In this study, all groups had same taper angle which is not considered as a variable effecting marginal adaptation between groups. To standardize the manufacturing procedure, a single technician scanned and manipulated the entire fabrication process. The same operator performed the whole fit evaluation process including weight measurements, cementation procedures, sectioning processes, post-section treatments, and visual investigations. Measurement data were obtained by positioning the specimens under the microscope using a special clamp so that the marginal area of the abutment/coping junction was viewed from a directly perpendicular perspective like other investigators.[33] Moreover, misfit was assessed in equidistance points per image to reduce the operator bias, as previously reported.[33] The random assignment of the abutments to the experimental groups, control of the individual human factors can contribute to the validation of the findings.[33]

There were some limitations in this study. The copings were not veneered, but this may have presented another variable that could impact the marginal accuracy. Veneering can enlarge the gap size,[52] it can be considered this step unnecessary to accomplish the aim of the present investigations. The 3-D laser sintered group and the milled group showed significantly higher weight of the silicone material than the casting group (Table 2). However, the small mean value difference (less than 0.001 g) of the silicon weights suggests that the differences for the three groups shown in this study are not clinically significant. In the two-dimensional vertical marginal gap measurement procedure, the immobilization of the abutment and coping using customized clamp could be improved for quantifying the amount of force applied by the clamp screw. The load cell, for instance, can be attached on the clamp to standardize the force applied in adaptation of the crown-copings in further study.

Although there has been no consensus about the absolute number of the marginal measurements, and the measurement of the vertical marginal gap played a part of the entire evaluations in this study, four measurements of the equidistant points per specimen could be insufficient comparing to other studies.[53, 54] The differences in two-dimensional vertical marginal gap between the three groups were statistically significant in this study. Whether these differences are relevant to the clinical setting is questionable, because the mean marginal gap values and even the maximum ones of the three groups were below the recommended clinical limit of 120 ㎛.[28, 39, 55] A definitive value has not been identified for clinical acceptability because of the diverse clinical situations. As follows, the marginal discrepancy depends on the fabrication stage,[17] type of manufacturing systems, number of units in the substructure,[17] location of restoration, abutment preparation design, material stiffness,[47] presence of a luting cement,[32] and type and thickness of the luting cement.[32] Also the variation in reported mean marginal gap values can be explained by differences in study designs and measurement techniques, and the location and quantity of single measurements.[56] Copings were seated on the master abutments using finger pressure. Even though this method simulates the cementation of fixed restorations clinically,[34] it should be considered that the control of the finger pressure is difficult and this can be a limitation of this study. The internal gap of the restoration was measured as the perpendicular distance between outer surface of the abutment and the inner surface of the crown-coping in this study. The irregularities and roughness of these measuring surfaces could be a problem related to the consistency of the measurements. A certain standard could have been applied to define the internal gap as the actual distance between the outmost point of the coping and the outermost point of the abutment as the other study has suggested.[17]

The internal fit is evaluated by the gap between the intaglio surface of the restoration and the abutment. Variation in the internal fit can create stress concentrations, which may reduce the restoration strength.[45] The gap size is affected by the thickness of the dental cement layer influencing the seating of the restoration. Many factors affect film thickness, including preparation margin design, marginal configuration, surface roughness, cementation pressure, duration of cementation, powder/liquid ratio of the cement, types of cement, die spacers, and cementation techniques.[38]

It was found that the internal gap of copings in all three groups were greater than those of the designed cement space in this study. This is different from the findings of other studies which reported that the internal gaps of copings were almost the same as those of the designed cement space except the axial surface of copings were greater than the value set by the software (45 ㎛).[57] In this study, a recognized common feature in all three groups was a significantly greater occlusal internal gap values than the axial and marginal ones. This is in agreement with previous studies.[26, 41] It is assumed that this large discrepancy particularly in laser sintered and milled group could be attributed to the process errors related to the intrinsic setting of different tool path software programs used in manufacturing procedures. The vertical marginal gap and the internal gaps, except for the marginal internal gap, of the milled group appeared greater than the casting group in this study. This can be explained by the two possible factors related to the fit of restorations produced by CAD/CAM milling system; the skill of the technician and the accuracy of the scanning process.[17] Another source of errors is the wear of milling instruments during milling and changing the radius of the instruments during the milling procedure, which can reduce the milling precision.[57] A change of the milling instruments at regular intervals is highly recommended to control this factor.[58]

There are some studies about the comparisons of corrosion behavior, cytotoxicity, or bond strength to the veneering porcelain between different Co-Cr alloys commercially available. However, few studies compared the fit of restorations between different Co-Cr alloy brands. Therefore, the most popular and easily available Co-Cr alloy brands in Korea were used in this study for all groups and this could contribute to the clinical relevance of the study. Kim et al.[11] used a Co-Cr alloy powder (EOS CobaltChrome SP2 granule®, Biomain AB, Helsingborg, Sweden), with major components of cobalt-chromium-molybdenum-tungsten (Co-Cr-Mo-W) according to the EN ISO 2267;2006 standard,[59] which classifies metallic materials that are suitable for the fabrication of dental appliances and restorations. For this reason, this study used the same Co-Cr alloy powder in the laser sintered group, and Ortorp et al[42] used SP2 granule® Co-Cr powder in their study. There are some studies[15, 33] used ST2724G (SINT-TECH, Clermont-Ferrand, France) laser-sintered Co-Cr alloy in their comparison test. About the milled Co-Cr alloy group, the Starbond CoS (S&S Scheftner GmbH, Mainz, Germany) Co-Cr alloy blank was used in the current study. Although there is very few comparison study using milled Co-Cr alloys, LunaNEM Co-Cr alloy block (ACF GmbH, Germany)[33] and the prefabricated commercial Co-Cr dental alloy (CoCrMo-Legierung Typ 5, Eukamed Ceralloy CW, Germany)[19] were used. Further analysis would be needed comparing the fitness according to the different commercial brands of Co-Cr alloys in the same manufacturing methods.

Laser sintered Co-Cr alloy copings have been introduced and become widespread in clinical use. However EOSINT M270 (EOS GmbH – Electro Optical Systems, Krailling, Germany) system, used in this study, is relatively new. Therefore further studies are needed to evaluate this system. The primary study[22] reported that the laser sintered Co-Cr alloys, compared with casting and CAD/CAM milling technology, display proper surface hardness, tensile strength, and homogenous microstructure that meet the demands of dental clinics. Thus from the viewpoints of the mechanical properties and structure, this newly introduced technique can be a promising candidate for dental application. Future research should include investigations of the biocompatibility of the laser-sintered Co-Cr alloy. The composition of the Co-Cr alloy for laser sintered has lower molybdenum content, compared to the composition of the casting Co-Cr alloy. Presumably, laser sintering of the former Co-Cr alloy is facilitated by the absence or diminished percentage of such refractory metals, which have much higher melting temperatures than conventional Co-Cr alloys. Future research in this area is recommended. This technology can be utilized more widely accompanied by the digitalization of dentistry and the development of direct oral scanning devices. In addition, the laser sintering technology has the advantage relating to the minimized human error in the manufacturing procedures that can keep consistent quality of restorations. And the manufacturing costs of restoration might be reduced through large-scale production at one time.[5] All misfit values in this study could be considered clinically acceptable, since marginal discrepancies of up to 150 ㎛ have been admitted for implant-cemented prostheses.[60] Nonetheless, long-term prospective clinical trials are required to quantify the misfit levels that could lead to biomechanical failures of the implant restorations.[33] Furthermore, investigations about the marginal accuracy and internal fit in different marginal configurations are recommended. In this study, the marginal adaptability of Co-Cr alloy copings fabricated by 3-D laser sintered technique was clinically acceptable but worse than that of copings fabricated by the casting and the milled technique. Continued research and investigations of the marginal accuracy and internal gap in multiple units of fixed dental prostheses or in porcelain firing besides single metal restorations are needed.

CONCLUSION

The following conclusions were drawn: the different manufacturing methods influence the marginal accuracy and the internal fit of Co-Cr alloy single tooth crown-copings. The weight of the silicone material, used to provide relative comparisons for the fit of copings to their dedicated abutment, was significantly low in the casting coping group, compared to the other two groups. However, significant difference was found only between the casting and the CAD/CAM milled group. The vertical marginal gap and the average internal gap of the casting group revealed the significantly smallest gap width followed by the CAD/CAM milled and the laser sintered group. However, the measured marginal discrepancy and the internal gap widths of the copings fabricated with all three manufacturing methods demonstrated a clinically acceptable range in this in vitro study. Also, it can be reported that restorations fabricated with 3-D laser sintered technology have a clinical fit within an acceptable range. This new fabrication system can compete with conventional systems for clinical fit, and can achieve relatively acceptable in-vitro marginal and internal fit with further improvements.

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요약 (국문 초록)

연구목적: 본 연구의 목적은 주조, CAD/CAM 기술을 이용한 밀링 방법 및 3-D printing laser sintered 방법으로 제작된 치과용 코발트-크롬 크라운-코핑의 변연 정확도 및 내부 적합도를 비교하고, 이를 통해 세 가지 제작 방법의 정밀도를 알아보고자 한다.

연구재료 및 방법: 기성 타이타늄 지대주 (TS system, Osstem, Seoul, Korea)로부터 적합도 검사를 위한 36개의 코발트-크롬 크라운 코핑을 제작하여 제작 방법에 따라 세 집단으로 나누었다; 주조 방식으로 12개, CAD/CAM 밀링 방법으로 12개, laser sintered 방법으로 12개의 코핑을 제작하였다. 다음의 세 가지 방법으로 적합도 검사를 시행하였다; 접착제의 역할을 하는 silicone material의 무게를 측정, 이차원적인 수직 변연 정확도를 조사, 그리고 접착 후 절단된 시편을 이용하여 내부 적합도를 측정하였다. 통계 프로 그램 (SPSS 19.0, IBM Co, NY, USA)을 통해 One-way ANOVA 및 Scheffe 및 Bonferroni 검정을 이용하여 세 그룹간 결과를 비교했으며, 통계적 유의 수준은 $p=0.05$ 로 설정하였다. 본 연구에서 적합도 평가에 사용된 방법들 간의 상관관계를 Pearson 상관 분석을 이용하여 분석하였다.

결과: 주조 방법으로 제작된 코핑 그룹에서 3-D laser sintered 및 CAD/CAM 밀링 방법으로 제작된 그룹과 비교했을 때 접착제 역할을 하는 silicone material의 무게가 통계적으로 유의하게 적게 관찰되었다 ($p<.001$).

이차원적인 vertical marginal gap 값은 주조 그룹에서 38.229 ± 6.186 ㎛, CAD/CAM 밀링 그룹에서 51.479 ± 6.986 ㎛, laser sintered 그룹에서 72.458 ± 12.440 ㎛로 나타났다. Multiple comparison test 결과 세 집단간에 모두 유의한 차이가 있었다 (*p<.003*). Average internal gap 측정값은 주조 방식으로 제작된 실험군에서 61.528 ± 11.445 ㎛, milled 그룹에서 64.278 ± 9.145 ㎛, 그리고 laser sintered 그룹에서 95.806 ± 7.944 ㎛로 나타났다. 3-D laser sintered 그룹에서 가장 높은 average internal gap 측정값을 나타냈으며, 이는 주조 및 CAD/CAM 밀링 그룹과 비교했을 때 통계적으로 유의한 차이를 보였다 (*p<.0001*).

결론: 서로 다른 제작 방법은 코발트-크롬 합금 크라운-코핑의 변연 정확도와 내부 적합도에 영향을 미친다. 주조 방식으로 제작된 코핑에서 유의하게 가장 작은 vertical marginal gap 및 internal gap 측정값을 나타냈으며, CAD/CAM 밀링 및 laser sintered 방법 순으로 크게 관찰되었다. 그러나, 본 in vitro 연구에서 사용된 주조 및 CAD/CAM 밀링, 그리고 3-D laser sintered 방법으로 제작된 코발트-크롬 합금 크라운-코핑은 모두 여러 문헌에서 보고된 적정 범위 내의 변연 정확성과 내부 적합도를 나타냈다.

주요어 : 코발트-크롬 합금, 치과용 CAD/CAM, 치과용 laser sintering,

변연 정확성, 내부 적합도

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