Three-Dimensional Accuracy of CAD/CAM Titanium and Ceramic Superstructures for Implant Abutments Using Spiral Scan Microtomography

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Purpose: To introduce a new three-dimensional (3D) method of evaluating the fit of implant superstructures made using computer-aided design/computer-assisted manufacture (CAD/CAM) technology and conventional casting and to determine which biomaterial would produce optimal fit for the long-term clinical longevity of dental implant restorations. ***Materials and Methods:*** Five groups of materials were used to make 50 copings (n = 10) using CAD/CAM technology for titanium, partially sintered zirconia, fully sintered zirconia, and leucite-reinforced glass-ceramic materials and a conventional casting technique for the nickel-chromium group. The vertical marginal gap was measured at 16 equidistant points using a traveling microscope and compared with the 3D spatial gap values obtained by using spiral scan microtomography. Multivariate analysis of variance and Tukey post hoc tests were used for statistical analysis. ***Results:*** The vertical marginal gap width ranged from 13.21 to 75.26 μm for the CAD/CAM groups and 64.89 to 115.27 μm for the conventionally casted group. The spatial gap ranged from 0.22 to 0.67 mm^3 for CAD/CAM groups and 0.75 to 0.89 mm^3 for the conventionally casted group. The highest accuracy of fit was observed in the titanium group, followed by the leucite-reinforced glass-ceramic, partially sintered zirconia, fully sintered zirconia, and nickel-chromium groups. ***Conclusion:*** When used in combination with the CAD/CAM technique, titanium produces the most accurate implant superstructure. Spiral scan microtomography can be used to measure the accuracy of fit of dental implant superstructures and restorations as it provides a 3D measurement with less chance of errors compared with conventional methods of measurement. *Int J Prosthodont 2013;26:451–457. doi: 10.11607/ijp.3302*

The passive fit of implant superstructures is an important factor that determines the long-term success of dental implant restorations.[1–3] A lack of passive fit can cause unequal stress distribution,[3] which can increase the risk of mechanical failures, such as framework distortion,[2] cement failure, ceramic debonding,[3] loosening of the abutment/prosthetic screws, and fracture of components in the system, or biologic failures, including adverse tissue reactions, such as pain, tenderness, marginal bone loss, and even loss of osseointegration.[4–7]

Conventionally casted implant superstructures are often associated with marginal and fitting discrepancies.[8] These faults can be attributed to the expansion and contraction of the impression materials, gypsum, wax, investment, and alloy.[9] The casting technique, veneering method, and technical experience[3,10,11] can also limit the accuracy of the lost-wax casting technique. These problems were overcome when Francois Duret introduced the computer-aided design/computer-assisted manufacture (CAD/CAM) technique in 1971.[12]

Several materials ranging from metal alloys to ceramics have been proposed for the fabrication of implant superstructures. Titanium has been used as an alternative to high gold and other metal-ceramic alloys since the early 1990s.[13] All-ceramic restorations are esthetic alternatives to metal-ceramic restorations and are successfully used to restore anterior and posterior teeth.[14] As with metal-ceramic restorations, all-ceramic restorations rely on a high-strength ceramic substructure (core) material to provide resistance to cyclic fatigue loading.[15] The high-strength ceramic core materials include leucite-reinforced glass-ceramics[16,17] and yttrium-stabilized tetragonal zirconia polycrystal (Y-TZP).[15] The leucite-reinforced glass-ceramics have leucite (potassium aluminum

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Fig 1 Implant abutment and superstructure.

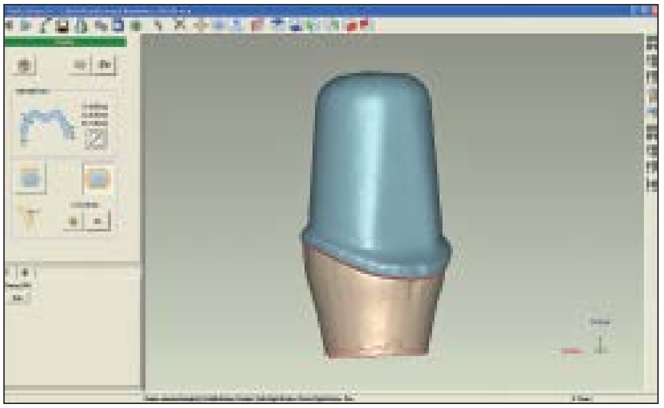

Fig 2 CAD software module interface.

silicate, SiO_2-Al_2O_3-K_2O or $KAlSi_2O_6$) crystals incorporated into their structure, giving them improved toughness and strength,[16] whereas the high strength and fracture toughness[18] of Y-TZP ceramics render them capable of withstanding the rigorous CAD/CAM milling process.

The absolute value of the vertical marginal gap deemed to be clinically acceptable has been debated in the literature, with proposed values ranging from 10 to 160 μm, although values close to 100 μm appear to be within the range of clinical acceptance.[19–22] The methods commonly used to measure marginal accuracy involve the direct visualization or sectioning of samples, followed by the visualization of the marginal interface at multiple sites via microscopy.[23] The number of measurement sites to be used has been a matter of debate, with authors suggesting up to 100[24,25] measurements per restoration. These measurements can be a source of human error and can cause variability. In recent years, microtomography has gained popularity in dental research.[26] Microtomography allows for the nondestructive, three-dimensional (3D) evaluation of materials with quantitative analysis[26] and has been used in multiple studies to evaluate marginal leakage,[27] endodontic anatomy,[28] and remineralization[29]; however, its application in determining the accuracy of implant superstructures has not been reported.

Therefore, the purpose of this study was to introduce a new 3D method of measuring the accuracy of implant superstructures and to determine which biomaterial and technique would produce the most accurate implant superstructure for the long-term success of dental implant restorations. The null hypothesis was that there would be no difference in the marginal accuracy of implant superstructures fabricated using different biomaterials and techniques.

Materials and Methods

A standard titanium implant abutment (TiDesign 4.5/5.0, 3 mm, Astra Tech), representing a mandibular first premolar with a chamfer finish line, 6-degree taper angle, diameter of 5.5 mm, and vertical height of 10 mm, was used to produce the superstructures. Four reference marks were made on the buccal, mesial, lingual, and distal surfaces of the implant abutment to aid in the marginal gap measurements. The implant abutment was screwed onto a titanium implant replica (implant replica 4.5/5.0, Astra Tech) using the recommended torque (25 Ncm) and placed vertically with the aid of a paralleling device (F3 Ergo, Degudent) in a cylindric silicone mold filled with unpolymerized polymethyl methacrylate (PMMA) acylic resin (Lucitone 199 Repair Material, Dentsply) (Fig 1).

Four types of materials (group A, B, C, and D) were used to fabricate the implant abutment superstructures using CAD/CAM technology. Group E consisted of conventionally casted base-metal alloy superstructures. Each of the five groups consisted of 10 implant abutment superstructures. Table 1 represents the different groups and their compositions.

CAD/CAM Fabrication Technique

The PMMA-mounted implant abutment (Fig 1) was coated with Optispray (CEREC, Sirona) to obtain a nonreflective surface and scanned using an optical scanner (Everest Scan Pro 4102, KaVo) to record the external surface of the implant abutment. The superstructure was designed using the CAD software module (Everest Scan Control 6.1.2.8, KaVo) (Fig 2). The preparation margin was determined, and the superstructures were designed to be 1 mm thick. The cement gap (die spacer) was set at 50 μm starting at

Table 1 Materials Used for Implant Abutment Coping Fabrication

Group	Material	Manufacturer	Composition
A	ZS blank (16)	KaVo Everest	Partially sintered, yttrium-stabilized zirconium oxide (shrinkage, 20.71%)
B	ZH blank (12)	KaVo Everest	Fully sintered, pressed, yttrium-stabilized zirconium oxide
C	G blank (10)	KaVo Everest	Leucite-reinforced glass-ceramic
D	T blank (12)	KaVo Everest	Medical pure titanium (grade 2)
E	I-Bond 02	Interdent	Ni = 64.3%; Cr = 24.2%; Mo = 10%; Si = 1%; Nb, Fe, Co, Cb < 1%

Table 2 Conventional Burnout Temperature Rate

Temperature	Rate of heating	Holding time
Room temperature to 270°C	7°C per min	40 min
270°C to 580°C	7°C per min	30 min
580°C to 900°C	9°C per min	30 min

1 mm from the internal margin. The completed CAD design was transmitted as CAM data to the engine (Everest engine 4140, KaVo), which milled the implant abutment superstructures from blanks (Table 1). The milled partially sintered zirconia blank superstructures were sintered over a period of 591 minutes at 1,450°C (ZS sintering program, Everest Therm 4180, KaVo) using a sintering oven (Everest Therm 4180, KaVo) to achieve shrinkage (20.71%), full density, and the final dimensions.

Fig 3 Vertical marginal gap measurements.

Casting Fabrication Technique

The PMMA-mounted implant abutment was duplicated using polyvinyl siloxane (Aquasil Light Viscosity and Exaflex putty) and poured into type IV die stone (Silky Rock, WhipMix). A single layer of die hardener (Yeti Dental), followed by two layers of die spacer (Blue 10 MY, Yeti Dental), was applied to the die. A polyvinyl siloxane mold was fabricated around a G-blank (leucite-reinforced glass-ceramic) superstructure, which had been seated on the stone die. Molten wax (GEO Classic beige opaque, Renfert) was poured into the mold, and the die was inserted. Upon sufficient cooling of the wax, the mold and the die/superstructure combination were removed. The thickness of the superstructures was verified using a wax gauge (Caliper Standard, Renfert), and the margins were adapted and finished using ×10 magnification (OPMI Pico, Carl Zeiss Surgical). Wax sprues were placed, and all 10 superstructures were invested together in a phosphate-bonded investment (Intervest K+B Speed, Interdent) following the manufacturer's instructions. The conventional burnout technique was followed (Table 2) per the manufacturer's recommendations, and the mold was cast in a nickel-chromium based alloy (I-Bond 02, Interdent) using a centrifugal casting machine (Megapuls Compact, Dentaurum). The castings were devested and sandblasted with 50-μm aluminum oxide. Figure 1 represents the different superstructures manufactured using different materials and techniques.

The two-dimensional vertical marginal gap at the superstructure-abutment junction was measured at 16 equidistant points using a traveling microscope at ×120 magnification (Titan Tool Supply) (Fig 3).

For the 3D spatial gap measurement, each superstructure was placed on the implant abutment and was scanned using spiral scan microtomography (SkyScan 1173), operating at 130 kV with a spatial resolution of 5 μm to obtain microcomputed tomography (CT) image slices, followed by 3D image reconstruction (NRecon, version 1.6.4.8, Skyscan). The upper and lower level of measurement was defined (A to B), and the 3D gap between the superstructure and abutment was measured in terms of volume using the proprietary software (CTAnalyzer, version 1.11.10.0, Skyscan) that used a volume-rendering algorithm to calculate the volume of air and, therefore, the space between the superstructure and abutment (Fig 4).

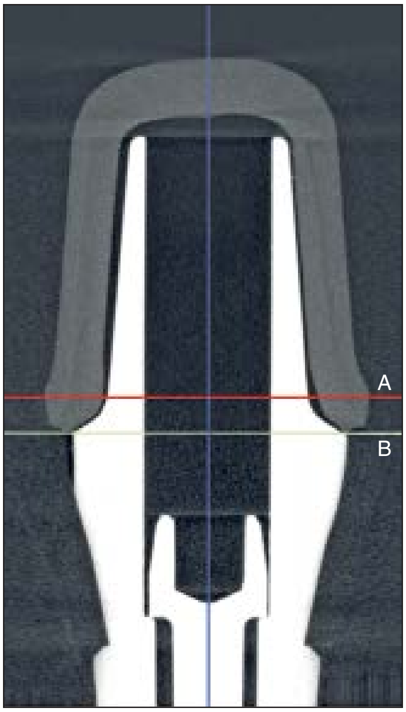

Fig 4 Spatial marginal gap measurements.

Table 3 Vertical and Spatial Marginal Gap Measurements for Each Material

Group (material)	Sample (n)	Vertical marginal gap (μm)		Spatial marginal gap (mm^3)	
		Mean (SD)	Range	Mean (SD)	Range
A (ZS blank)	10	58.60 (4.40)	52.17 to 68.12	0.56 (0.03)	0.51 to 0.62
B (ZH blank)	10	67.71 (5.36)	56.82 to 75.26	0.59 (0.05)	0.47 to 0.67
C (G blank)	10	54.75 (9.39)	45.78 to 68.36	0.50 (0.03)	0.45 to 0.57
D (T blank)	10	18.32 (3.42)	13.21 to 24.81	0.33 (0.05)	0.22 to 0.39
E (Ni-Cr)	10	91.50 (14.72)	64.89 to 115.27	0.82 (0.04)	0.75 to 0.89

SD = standard deviation.

Table 4 Vertical and Spatial Marginal Gap Measurements for Each Technique

Technique	Vertical marginal gap (μm)		Spatial marginal gap (mm^3)	
	Mean (SD)	Range	Mean (SD)	Range
CAD/CAM	49.84 (19.91)	13.21 to 75.26	0.50 (0.10)	0.22 to 0.67
Casting	91.50 (14.72)	64.89 to 115.27	0.82 (0.04)	0.75 to 0.89

SD = standard deviation.

Statistical analysis was performed using SPSS software, version 19 (IBM). In addition to the calculation of the means and standard deviations, multivariate analysis of variance (MANOVA) was performed, followed by the Tukey honestly significant difference (HSD) post-hoc analysis test, to determine the significant differences among the groups.

Results

The results indicated that the vertical and spatial marginal gaps differed significantly among the five groups of materials and the two manufacturing techniques tested.

The statistical results indicated that the T (titanium) blank (group D) had the highest accuracy followed by the G (leucite-reinforced glass-ceramic) blank (group C), the ZS (partially sintered) blank (group A), the ZH (fully sintered) blank (group B), and nickel-chromium based alloy (Ni-Cr) (group E) (Table 3).

The superstructures manufactured by the CAD/CAM technique were more accurate compared with the conventionally casted group (Table 4).

Tukey post-hoc comparisons of the five groups revealed significant differences ($P < .05$) in accuracy between titanium (group D), zirconium (groups A and B), glass-ceramic (group C), and nickel-chromium (group E) (Table 5).

Nonstatistically significant differences in accuracy were observed between partially and fully sintered zirconium groups (groups A and B), and between partially sintered zirconium (group A) and glass-ceramic (group C) (Table 5). The 3D gap values comparing the different manufacturing techniques and biomaterials are presented in Figs 5 and 6, respectively.

Discussion

The statistical data obtained in this study support the rejection of the null hypothesis.

The mean gap widths of the CAD/CAM-fabricated superstructures (groups A, B, C, and D) obtained were smaller than those of the casted group (group E) and slightly smaller than the ranges reported in previous studies.[25,30–33] This finding can be attributed to advancements in scanning technology, restoration-designing software with improved margin detection, and precision milling technology.[33,34] However, it is important to note that the measurements obtained were specific to the KaVo Everest hardware/software combination.[35]

For CAD/CAM titanium crowns, Witkowski et al[13] reported an initial vertical discrepancy of 18.16 to 82.26 μm, and Tan et al[35] reported a discrepancy of 79.43 ± 25.46 μm. In this study, the vertical gap widths of the CAD/CAM titanium superstructures were in the range of 12.61 to 22.69 μm, and the spatial gap was in the range of 0.22 to 0.39 mm^3, making these the most accurate among the five groups of material tested. The vertical gap values obtained were within the range of clinical acceptance, ie, 10 to 160 μm.[19–22] This finding is consistent with the findings of previous studies related to CAD/CAM titanium restorations.[13,35–37] The high accuracy of the titanium superstructures can be attributed to their comparatively lower modulus of elasticity (91 GPa) and flexural strength (322 to 461 MPa), which helps in reducing wear on the milling instruments and places less demand on the milling unit and, consequently, produces more precision in fit.

For CAD/CAM ceramic crowns, gaps of 17 to 118 μm have been reported by various authors.[25,30,31,33,38–40] Similar results were obtained in the present study. However, a higher accuracy was achieved with the soft, partially sintered Y-TZP ceramics (ZS blank, group A) compared with the hot isostatic pressed (HIP) Y-TZP blocks (ZH blank, group B) (Table 3). This finding can be attributed to the ease of machining and the precisely controlled sintering cycle in a specially designed sintering oven, which aided in achieving a consistently accurate fit. The lesser accuracy of hard HIP-TZP ceramics can be attributed to their extreme hardness and higher flexural strength (> 1,200 MPa), which can cause greater wear of the milling burs and a reduction in the efficiency of the milling unit, consequently leading to lesser accuracy of fit. This effect was further evident in the breakage of the milling bur (no. ZH-3, KaVo Everest) three times during the milling of the ZH blank (group B) superstructures. The post hoc comparison of groups A and B showed no statistical significance, indicating that either form of Y-TZP ceramic produces clinically acceptable restorations. The comparable mechanical properties and the relative ease and speed of soft Y-TZP blank milling may explain why more operators choose this method to fabricate zirconia restorations, whereas only a small number prefer the hard HIP Y-TZP blanks.[41]

Glass-ceramics have superior stability, biocompatibility, esthetics, and chemical inertness, making them a viable alternative restorative material.[16,17,42] Leucite-reinforced glass-ceramics were originally designed for CAD/CAM restorations because of their high durability and ability to be milled accurately.[16,17,43] These ceramics are reinforced by the incorporation of leucite crystals into their structures, giving them improved toughness and strength.[16,42,44] In the present study, the leucite-reinforced glass-ceramic superstructures (group C) showed higher accuracy compared with the zirconia superstructures (groups A and B) (Table 3). This finding might be due to the comparatively lesser flexural strength (≥ 125 MPa) and fracture toughness[45] of leucite-reinforced ceramic materials, which makes milling easier on the instruments, less time-consuming, more efficient, and, therefore, more accurate.

Table 5 Statistical Comparisons with Regard to Mean Vertical Marginal Gap Width (Tukey HSD)

Comparison	Vertical marginal gap *P* value	Spatial marginal gap *P* value
ZS blank vs ZH blank	.138	.623
ZS blank vs G blank	.851	.055
ZS blank vs T blank	.000*	.000*
ZS blank vs Ni-Cr	.000*	.000*
ZH blank vs G blank	.012*	.001*
ZH blank vs T blank	.000*	.000*
ZH blank vs Ni-Cr	.000*	.000*
G blank vs T blank	.000*	.000*
G blank vs Ni-Cr	.000*	.000*
T blank vs Ni-Cr	.000*	.000*

*Statistically significant ($P < .05$).

The conventionally casted Ni-Cr superstructures were less accurate when compared with the CAD/CAM superstructures (Table 4). This finding can be attributed to the expansion and contraction associated with the impression materials, gypsum, wax, investment, and alloys involved in the lost-wax casting process.[9] The variability in die spacer application, wax pattern distortion during removal, and the spruing process are other factors that may affect the accuracy of superstructures fabricated using the lost-wax process.

The fitting surfaces of the superstructures were not refined because the amount of refinement is difficult to quantify or standardize. The implant abutment used in this study had a chamfer margin; this type of margin was preferred, as it is associated with higher marginal accuracy compared with the shoulder and knife-edge margin configurations.[46]

Data from the literature report a wide disparity in the vertical marginal gap measurements of full-coverage dental restorations. This can be attributed to variations in measurement techniques[23] and the numbers of measurement sites.[24] The present study introduces a 3D quantitative method of measuring accuracy of implant superstructures by calculating the difference in material densities and estimating the intervening air space volume. With this technique, multiple measuring sites are avoided, which are a matter of debate and are prone to human error.

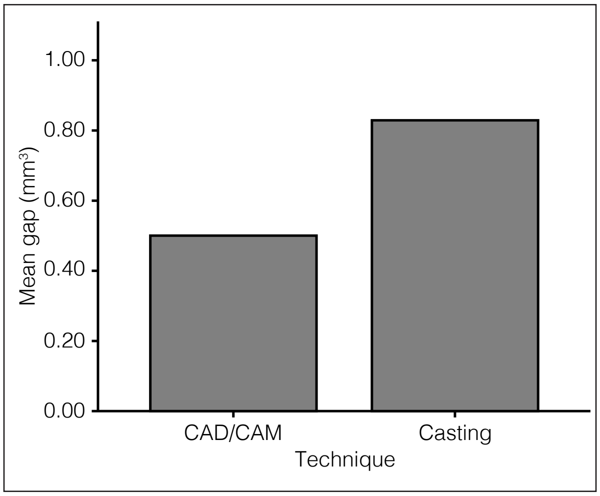

Fig 5 Spatial gap comparison between the different techniques used.

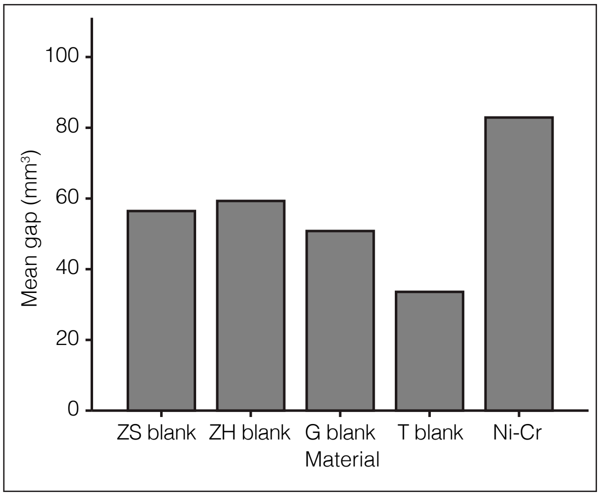

Fig 6 Spatial gap comparison between the different biomaterials used.

In this study, the two-dimensional accuracy was measured using a traveling microscope and statistically compared with a new 3D method using microtomography. The results obtained were statistically similar, suggesting that the 3D method can be a viable alternative to the conventional, multiple-site, two-dimensional measurement methods.

Limitations

The present study evaluated the accuracy of single-unit implant superstructures made with various CAD/CAM materials from a single manufacturer. Further studies are needed that compare the accuracy of multiple-unit implant superstructures made using the CAD/CAM dental biomaterials available from different manufactures. Investigations should be conducted that compare the efficiency of different CAD/CAM model scanners and restoration-designing software modules. The effects of veneering and cementation on marginal accuracy might also be included in future studies. Microtomography data provide opportunities for dramatic 3D visualization. However, spiral scan microtomography units can be expensive, need more time for high-resolution scanning and volumetric data analysis, and require specially trained and skilled operators.

Conclusions

Within the limitations of this study, the following conclusions were drawn. The CAD/CAM technique can produce implant superstructures with greater accuracy compared with the conventionally fabricated lost-wax casting technique. Among the various dental biomaterials, titanium can be used to produce implant superstructures with the greatest accuracy and passive fit, which is essential in the long-term clinical success of dental implant restorations. Soft, partially sintered zirconia is preferred over hard, fully sintered zirconia CAD/CAM superstructures due to their comparable accuracy, flexural strength, fracture toughness, and modulus of elasticity. Spiral scan microtomography can be a viable alternative and important research tool for determining the 3D accuracy of implant superstructures and dental restorations with less chances of error compared with conventional microscopic methods of measurement.

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