Strength of CAD/CAM-Generated Esthetic Ceramic Molar Implant Crowns

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Purpose: *One-visit in-office CAD/CAM fabrication of esthetic ceramic crowns as a superstructure for posterior implants is quite new. The aim of the study was to evaluate the strength of esthetic ceramic CAD/CAM crowns with varied occlusal thickness and seated with adhesive and nonadhesive cements on titanium and zirconia abutments.* ***Materials and Methods:*** *Esthetic ceramic CAD/CAM-generated molar crowns (n = 15 per group) with occlusal thicknesses of 0.5 mm and 1.5 mm were seated on titanium (1) and zirconia (2) abutments: noncemented (a) and with nonadhesive cement (b) or 2 adhesive resin-based cements (c) and (d). In addition, 15 molar crowns with 5.5-mm occlusal thickness were seated on short zirconia abutments (3) using cements (c) and (d). All crowns had the identical occlusal morphology and were loaded with a crosshead speed of 0.5 mm/min until fracture. Load data were analyzed using 2-way ANOVA, the Scheffé test, and Weibull probability of failure analysis.* ***Results:*** *Fracture loads of 1.5-mm occlusal thickness crowns (a, b, c, d) were higher (P < .001) than those of 0.5-mm crowns (except for group 1d). Occlusal 5.5-mm crowns on short zirconia abutments had similar (2c) or less (2d) strength than the respective 1.5-mm crowns. Nonadhesive crowns (1b, 2b) were weaker (P < .001) than adhesive crowns (1c, 1d, 2c, 2d). Fracture loads of 0.5- and 1.5-mm crowns were significantly higher on titanium than on zirconia abutments with both cements. Adhesive cement d generally showed higher fracture loads than c on both titanium and zirconia.* ***Conclusion:*** *Esthetic ceramic CAD/CAM molar implant crowns gained high strength with adhesive cements on both titanium and zirconia implant abutments compared to nonadhesive cementation.* INT J ORAL MAXILLOFAC IMPLANTS 2008;23:609–617

Key words: *adhesive cementation, CAD/CAM esthetic ceramic, CAD/CAM implant crowns, fracture load, titanium abutments, zirconia abutments*

In-office computer-aided design and manufacture (CAD/CAM) offers the possibility of fabricating esthetic ceramic molar implant abutment crowns during a single visit.[1] Titanium has been a traditional material for posterior implant abutments because of its mechanical properties.[2,3] To overcome esthetic problems encountered even in the posterior area, high-strength ceramic abutments (Al_2O_3, ZrO_2) have been developed as an alternative.[4–6] Zirconia ceramics are able to fulfill the requirements of strength and biocompatibility needed for implant abutments.[7] YTZP-zirconium oxide (Yttrium-Tetragonal-Zirconia-Polycrystals) has a tetragonal metastabile crystal structure stabilized by the addition of 3 to 6 mol% yttrium oxide.[8] Its flexural strength is at least 900 MPa.[9,10] Kelly[11] categorizes CAD/CAM machinable ceramic as particle-filled, glass-matrix esthetic ceramic. Its flexural strength after CAD/CAM machining is between 103 and 127 MPa, depending on the brand.[12]

All-ceramic crowns have been used increasingly as a superstructure for dental implants in recent years.[13,14] Unilateral bite forces in the posterior area vary[15–17] between 216 N and 847 N, but a maximum of 1031 N has been reported.[18] Cyclic loading under wet conditions may reduce the initial strength of

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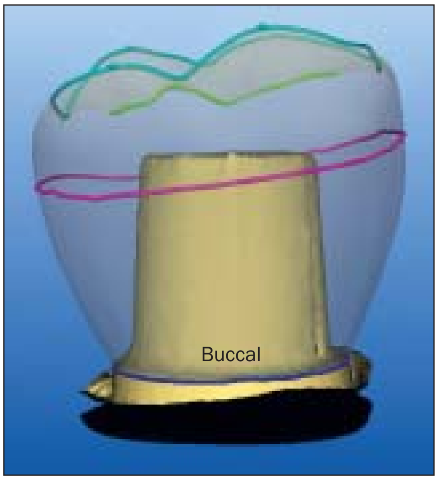
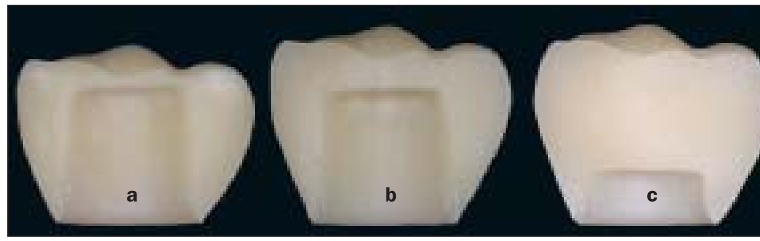


Fig 1 *(left)* Construction lines of the sample crown as designed on a standard abutment. The sample shown is identical in form to the titanium (Gingihue) and zirconia (ZiReal) abutments used in this study. The "edit" mode of the CAD design software (Cerec R 1500, German version) is shown. "Buccal" indicates buccal aspect of the crown.

Fig 2 *(below)* CAD/CAM-generated esthetic ceramic sample crowns. Sample a has an occlusal thickness of 0.5 mm while b has an occlusal thickness of 1.0; however, they are identical in shape. An occlusal thickness of 5.5 mm was used on the shortened abutment. The occlusal shape was identical for samples a to c.



ceramic by 50% through fatigue,[19,20] which raises the demands for adequate strength of esthetic ceramic abutments. In vitro studies have shown that adhesive cementation of esthetic ceramic CAD/CAM-generated crowns on conventional tooth preparations reinforces them against occlusal loading and fracture.[21–24] A survival rate of 94.6% up to 7 years has been reported for CAD/CAM-generated esthetic ceramic molar crowns adhesively cemented to natural tooth preparations.[25] CAD/CAM-generated esthetic ceramic crowns are now being used clinically on implants.[1,26,27]

Molar implant abutments have a perfectly circular diameter of a maximum of 7.5 mm at the shoulder, forming a small crown basis compared to the large rectangular gingival cross-section of a natural molar (approximately 10 × 10 mm).[28] Bulging lateral walls compensate for the geometric difference between the abutment and natural crown basis outlines to restore the natural anatomy of a molar crown (Figs 1 and 2). The lateral wall design of a molar implant crown therefore differs from the wall design of a conventional molar crown preparation.[29] Consequently, fracture load data for esthetic ceramic crowns on tooth preparations may not exactly apply to implant abutment crowns apart from the different physical properties of the abutments. Data on the fracture strength of CAD/CAM-generated esthetic ceramic molar crowns on implants are not yet available. It was hypothesized that the fracture load of this type of crown might be affected by the occlusal crown thickness, the abutment material, mode of cementation, type of adhesive cement, and height of the abutment.

The objective of the study was to evaluate the fracture load of esthetic ceramic CAD/CAM-generated molar crowns on titanium and zirconia implant abutments.

MATERIALS AND METHODS

Materials and instruments used in this study are listed in Table 1. Identically shaped titanium (Gingihue) and zirconia (ZiReal) abutments (Biomet/3i, Palm Beach Gardens, FL) were used. Both abutment types had a platform diameter of 5 mm, an abutment width of 7.5 mm, a height of 10.5 mm, and a circular shoulder width of 0.8 mm and were used in their original form for the design of crowns with 0.5 mm and 1.5 mm occlusal wall thickness (Figs 1 and 2). Additionally, occlusally thick (5.5 mm) crowns were evaluated on shortened zirconia abutments (Fig 2c). For this purpose the zirconia abutments were occlusally shortened by 4 mm to the residual height of 2.5 mm above the shoulder using a diamond microsaw (Leica SP 1600, Leica Microsystems, Glattbrugg, Switzerland). The abutments were mounted on titanium implants (Table 1). As shown in Fig 3, the implants were embedded into the center borehole (10 mm depth, 5 mm diameter) at the upper side of polymethylmethacrylate blocks (35 × 35 × 20 mm; Angst & Pfister, Zurich, Switzerland) using self-cure polymethylmethacrylate (Paladur; Heraeus Kulzer, Dormagen, Germany) with additional heat (10 minutes; 55°C) and pressure polymerization (2 bars).

For the CAD design of the crowns, the abutments were scanned using a 3D mouth camera (Cerec serial no. 01014; Sirona, Bensheim, Germany). For scanning the occlusal screw access, the opening of the abutment was filled with wax (Surgident Periphery Wax; Heraeus Kulzer), and the abutment was sprayed with titanium dioxide reflective spray (Scan'spray; Dentaco, Bad Homburg, Germany) to create the white-opaque surface necessary for optical 3D scanning. A maxillary first molar crown was designed using a dental CAD unit (Cerec 3, serial no. 01394, model no. 58 11 000 D 3344, Sirona) and the tooth library mode

Table 1 Restorative Materials and Burs Used

Material/instrument	Manufacturer
CAD/CAM block ceramic, Vitablocs Mark II, size I14, lot 7535 and 7542	Vita Zahnfabrik, Bad Säckingen, Germany
Titanium (1) abutment, Gingihue, IWPP574G	Biomet/3i, Palm Beach Gardens, FL
Zirconoxide (2) abutment, ZiReal, IWCAP574	Biomet/3i
Self-cure polymethylmethacrylate, Paladur	Heraeus Kulzer, Dormagen, Germany
Surgident Periphery Wax, no. 92189	Heraeus Kulzer
Resin-based posterior composite Tetric A3 lot E53622	Ivoclar Vivadent, Schaan, Liechtenstein
Fermit light-cure provisional filling material	Ivoclar Vivadent
Optical scanning surface agent Dentaco Scan'spray, lot 865773	Dentaco, Bad Homburg, Germany
Glass ionomer cement (b) Ketac Cem, lot 216105	3M ESPE, Seefeld, Germany
Metal Primer, lot H20614	Ivoclar Vivadent
4.9% hydrofluoric acid gel, Ceramics Etch	Vita
Silane agent, Monobond, lot H08177	Ivoclar Vivadent
Resin-based cement (c), Multilink, lot H00866 G15780	Ivoclar Vivadent
Protection gel, Air Block Liquid Strip	Ivoclar Vivadent
Resin-based cement (d). Panavia 21 21 TC lot Nr. 0032A	Kuraray, Osaka, Japan
Alloy Primer Lot 190BA	Kuraray
ED Primer liquid A Lot 0209A	Kuraray
ED Primer liquid B Lot 0134C	Kuraray
Oxyguard II	Kuraray
Cerec cylinder 1.6 mm diamond bur, D 64 µm; no. 54 66 193	Sirona, Bensheim, Germany
Cerec conical 1.6 mm, diamond bur, D 64 µm; no. 58 55 734	Sirona

of the 3D software (R 1500, Sirona). The occlusal surface was designed in such a way that the load transfer steel ball (width 12 mm) in the testing machine rested on even point contacts at the internal slopes of the mesiobuccal, distobuccal, and lingual cusps (Fig 3), as applied in earlier studies.[22,24] To enable this, a "bite registration" of the lower hemisphere of the load transfer steel ball was formed in the axial center position right above the screw access opening of the abutment using light cured composite (60 seconds; Tetric; Ivoclar Vivadent Schaan, Liechtenstein). The "bite registration" surface was covered with Scan'spray (Dentaco), and a 3D optical scan was taken in the "antagonist" mode of the design software. The virtual antagonist registration and the free-form tools of the 3D software were employed to establish even contacts between the sample crowns and the load transfer steel ball when loaded (Fig 3).

The occlusal crown thickness at the level of the central main fissure was set to 1.5 mm for the first set of crown data and was reduced to 0.5 mm with the "position tool" for the second crown dataset. The occlusal morphology was kept unchanged (Figs 1 and 2). The crown with 5.5-mm occlusal thickness was designed using the "correlation" mode by taking an "occlusion" optical 3D scan from a machined 1.5-mm crown and a "preparation" optical 3D scan of the reduced zirconia abutment.[29]

The machining of all crowns was done using 2 CAM units (Cerec 3 no. 01307 and 01428, Sirona) equipped with standard cylinder and conical burs, both with a diameter of 1.6 mm and D 64 µm diamond coating. New burs were used for each new crown series (n = 15). The crown material was

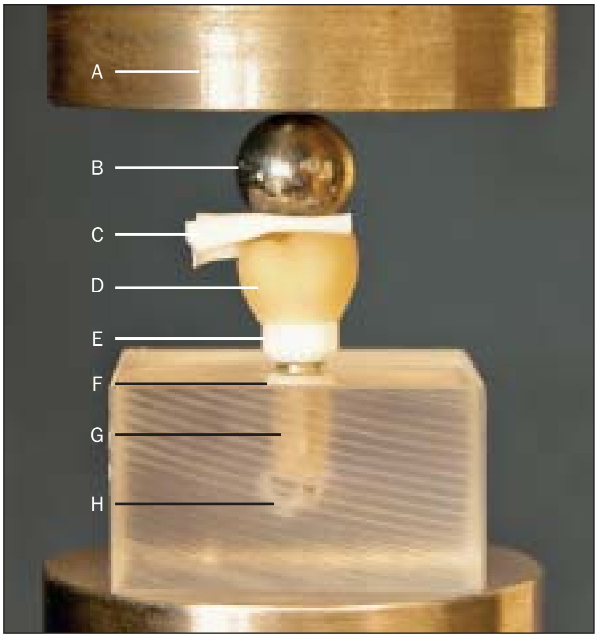


Fig 3 Loading until fracture: *(A)* loading stamp, *(B)* steel ball, *(C)* Teflon foil, *(D)* sample crown, *(E)* abutment, *(F)* fixture, *(G)* implant, *(H)* polymethyl methacrylate supporting block.

esthetic ceramic (Vitablocs Mark II; Vita Zahnfabrik, Bad Säckingen, Germany).

Before cementation of the crowns, both titanium (1) and zirconia (2) abutments were air-abraded using alumina powder (110 µm grain size) from a distance of 5 mm at 2 bar pressure, and the screw access openings of the abutments were closed with provisional light curing resin (Fermit; Ivoclar Vivadent) and light cured (60 seconds) in all groups. Fifteen crowns each with 0.5-mm and 1.5-mm occlusal thickness were fabricated and placed uncemented (a) as controls on the titanium (1) and zirconia (2) abutments to be loaded until fracture. After this, 15 crowns each with 0.5-mm and 1.5-mm occlusal thickness were cemented nonadhesively (b) using glass ionomer cement (Ketac Cem; 3M ESPE, Seefeld, Germany) on titanium (1) and zirconia (2) abutments; these served as additional control groups. For cementation, the crowns were filled with Ketac Cem, placed on the abutments, and held in position while a constant finger pressure was exerted for 3 minutes. Excess material was removed after 10 minutes using an explorer (EXD 5, Hu-Friedy, Chicago, IL). The samples were stored dry at 21°C room temperature for 24 to 48 hours before load testing.

For adhesive cementation, the abutments were air-abraded as described. Before using adhesive cement c (Multilink, Ivoclar Vivadent), both titanium (1) and zirconia (2) abutments were conditioned using a primer containing methacryl phosphate with methacrylate and phosphoric esters as the reactive components (Multilink Metal Primer, Ivoclar Vivadent). The primer was thinly brushed on using microbrushes (Ivoclar Vivadent) and the abutment was blown dry after 180 seconds. The internal surface of the crowns was etched 60 seconds with 4.9% hydrofluoric acid gel (Ceramics Etch, Vita). The gel was sprayed off thoroughly (30 seconds) with water, and the internal surface was blown dry using oil-free compressed (2 bars) air. Silane solution (Monobond S, Ivoclar Vivadent) was brushed on the internal surfaces, allowed to react for 60 seconds, and blown dry. Fifteen crowns each with 0.5-mm and 1.5-mm occlusal thickness were cemented adhesively on titanium (1) and zirconia (2) abutments using resin-based cement c. Equal parts of the 2-paste material were mixed (30 seconds) using a plastic spatula to form a homogenous mass, which was applied to the internal surface. The crowns were seated on the abutment and held in position, exerting constant finger pressure for 3 minutes. Gross excess material was removed using an explorer (EXD 5, Hu-Friedy), and the cementation interface was covered with oxygen protective gel (Air Block Liquid Strip, Ivoclar Vivadent). The samples were stored dry at 21°C between 24 and 48 hours.

Before using adhesive cement d (Panavia 21 TC; Kuraray, Osaka, Japan) to seat another 15 crowns each with 0.5 mm and 1.5 mm occlusal thickness on titanium (1) and zirconia (2) abutments (sandblasted as described), the titanium abutments were first conditioned with a primer containing 10-nethacryloyloxydecyl dihydrogen phosphate (MDP) and 6- (4-vinylbenzyl-n-propyl) amino-1, 3, 5-triazine-2, 4-dithione (VBATDT); (Alloy Primer, Kuraray). The prepared solution was thinly brushed on. Thereafter, 1 drop of methacryl phosphate primer (ED Primer A and B, Kuraray) was mixed, and the solution was applied to the titanium abutment surface and gently air dried after 60 seconds. Equal parts of the 2-paste adhesive cement d were mixed (30 seconds) using a plastic spatula to form a homogenous mass, which was applied to the internal surface, the crown seated as described, the margins were covered with oxygen protective gel (Oxyguard II, Kuraray), and curing was allowed for 10 minutes. All other working steps were the same as with Multilink. Furthermore, 15 crowns with 5.5-mm occlusal thickness were cemented adhesively on shortened zirconia abutments (3) using adhesive cements c and d, with the same working steps as described above.

All abutment crown samples were mounted into a universal testing machine (RM 50, Schenck-Trebel, 8606 Nänikon, Switzerland). A Teflon foil (0.2-mm thickness, no. 540, Angst & Pfister, Zurich, Switzerland) was placed in between the crown and the steel ball as a stress breaker (Fig 3). In each loading series (n = 15), 3 samples each were loaded on the same block-implant-abutment unit (ie, crown loading was distributed on 5 block-implant-abutment units). Loading was done with a crosshead speed of 0.5 mm/min until fracture. The load force (N) was recorded on a digital display and at fracture the maximum load force (N) was displayed and entered into Excel (Microsoft Office Mac 04, Redmond, WA) tables.

Statistical Analysis

All fracture load data were entered into the StatView Program 4.5 (Brain Power, Calabasas, CA) and are presented as box-plot diagrams. For statistical analysis, 2-way analysis of variance (ANOVA) and the 1-way ANOVA Scheffé test were used. Additionally, ANOVA of the fracture load values of the adhesively placed crowns only was used to analyze the variables occlusal thickness, type of adhesive, and type of abutment. Weibull probability plots for failure of esthetic ceramic CAD/CAM-generated crowns with 1.5-mm occlusal thickness placed with adhesive cements c and d on titanium and zirconia implant abutments were calculated using Minitab 14 Software (Minitab, State College, PA).[30]

Table 2 Titanium Versus Zirconia Abutments: Mean Fracture Load (n = 15) of Esthetic Ceramic CAD/CAM-Generated Crowns Seated with Adhesive and Nonadhesive Cements

Cement/occlusal thickness	Titanium (1) Mean	Titanium (1) SD	Zirconia (2) Mean	Zirconia (2) SD	*P**
Ketac (b)					
0.5 mm	1,517	156	1,634	211	.090
1.5 mm	2,,072	290	1,921	337	.200
Multilink (c)					
0.5 mm	1,838	115	1,615	284	.009
1.5 mm	2,625	441	2,217	208	.003
Panavia (d)					
0.5 mm	2,928	590	1,851	183	< .001
1.5 mm	2,836	420	2,517	209	.014

*Scheffé test.

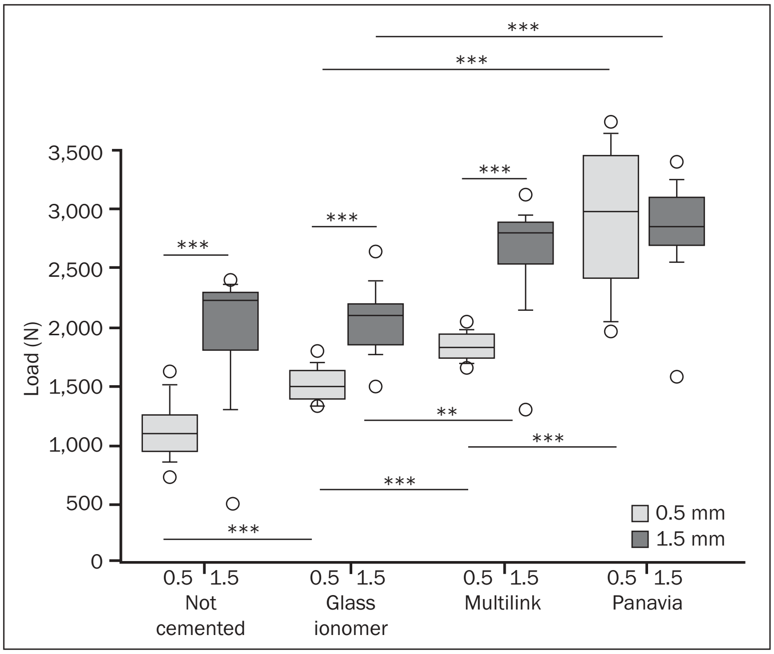


Fig 4 Fracture loads (n = 15) of esthetic ceramic CAD/CAM crowns on titanium abutments with 0.5- and 1.5-mm occlusal thickness on titanium abutments. **$P < .01$; ***$P < .001$; Scheffé tests.

RESULTS

Fracture load (N) data are presented in Table 2 and in Figures 4 to 6. The occlusal crown thickness influenced fracture load data. Occlusal thickness of 1.5 mm generally showed significantly ($P < .001$) higher fracture load (N) than 0.5 mm occlusal thickness, except those seated with adhesive cement d on titanium abutments (Fig 4).

Two-way ANOVA revealed interaction between abutment material and mode of cementation. The abutment material influenced fracture load in that values on titanium were generally higher ($P < .05$ to .001) than on zirconia abutments for both adhesive cements (Table 2).

Mode of cementation influenced fracture load data. Adhesive cementation generally resulted in higher fracture loads than nonadhesive cementation. On titanium abutments (1), crowns with 0.5- and 1.5-mm occlusal thickness showed significant ($P < .001$) increase of strength between nonadhesive 1b and adhesive 1c as well as 1d cementation (Fig 4). On zirconia abutments (2), crowns with 1.5-mm occlusal thickness showed strengthening by adhesive 2d ($P < .001$) versus nonadhesive 2b cementation (Fig 5).

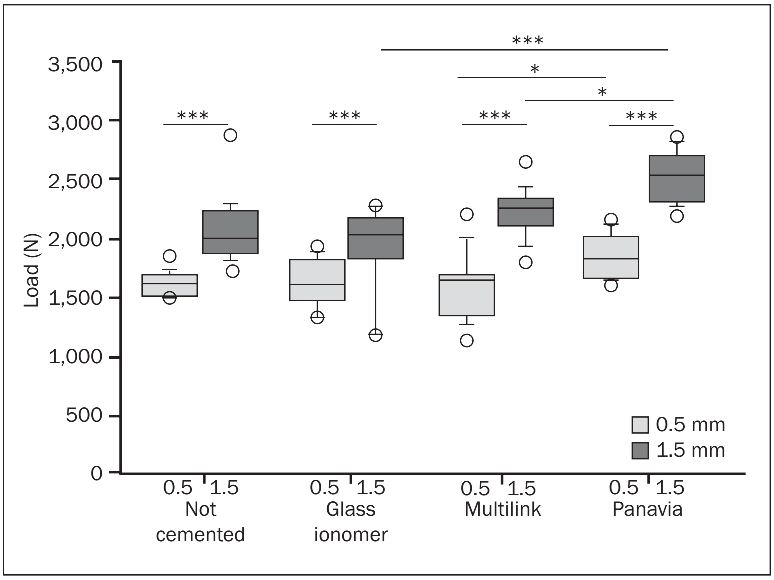


Fig 5 Fracture loads (n = 15) of esthetic ceramic CAD/CAM crowns with 0.5 and 1.5 mm occlusal thickness on zirconia abutments *$P < .05$, **$P < .01$, ***$P < .001$; Scheffé tests.

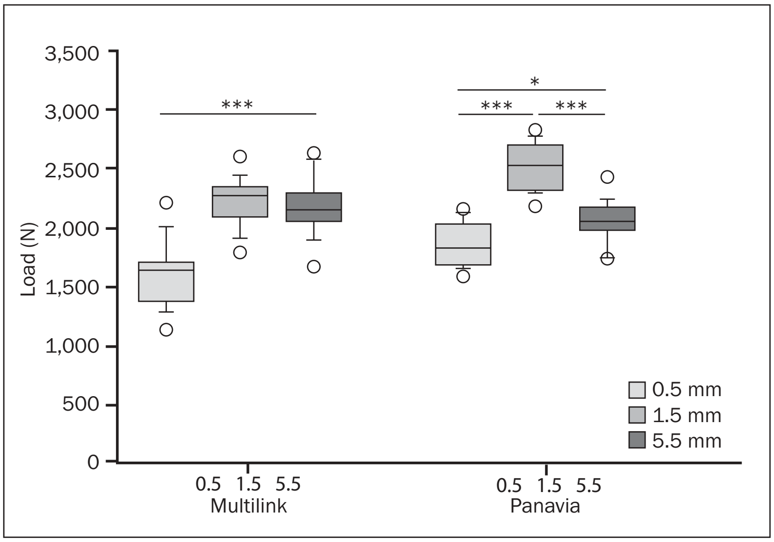


Fig 6 Fracture loads (n = 15) of esthetic ceramic CAD/CAM crowns with 0.5 and 1.5 mm occlusal thicknesses on standard zirconia abutments (2) and with 5.5 mm occlusal thickness on shortened (3) zirconia abutments. All crowns seated with adhesive cements c and d. *$P < .05$, ***$P < .001$; Scheffé tests.

Reduced height of the zirconia abutment (3) associated with increased thickness (5.5 mm) of adhesive crowns, resulting in the same (3c, $P > .05$) or decreased (3d, $P < .001$) fracture strength compared to crowns with 1.5-mm occlusal thickness (Fig 6).

The type of adhesive cement influenced fracture load data. On titanium abutments (1) crowns with 0.5 mm occlusal thickness, those cemented with adhesive cement d were significantly ($P < .001$) stronger than crowns cemented with adhesive c. However, the strength of the adhesively (c,d) cemented crowns was not significantly different (Fig 4). On zirconia abutments (2) crowns cemented with adhesive cement d with occlusal thicknesses of both 0.5 and 1.5 mm were significantly ($P < .05$) stronger than adhesive 2c cemented crowns (Fig 5). The Weibull probability of failure plots for crowns with 1.5-mm occlusal thickness show the range of dependability of the crowns seated with adhesive cements c and d on titanium (Fig 7) and zirconia (Fig 8) implant abutments.

Mixed cohesive fracture of ceramic and cement as well as adhesive failure was seen after failure of crowns seated with adhesive cements c and d on both titanium and zirconia abutments (Fig 9).

DISCUSSION

Crown material and thickness have been identified as primary factors influencing the stress in the

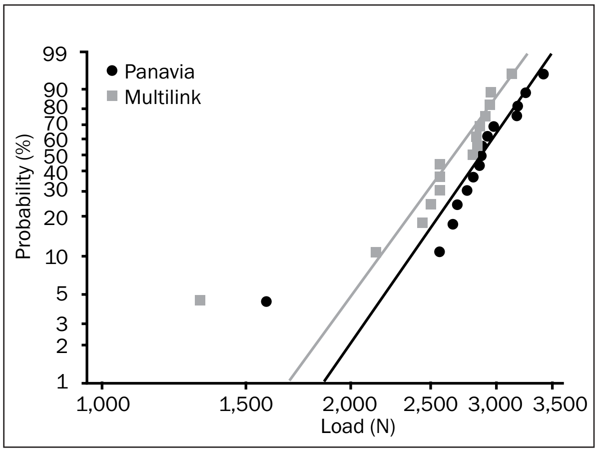


Fig 7 Probability plot for failure of esthetic ceramic CAD/CAM-generated crowns with 1.5-mm occlusal thickness placed with adhesive cements c (Multilink) and d (Panavia) on titanium implant abutments. The lowest value for Multilink was related to a sample crown showing a hairline crack before loading. The lowest value for Panavia was related to a chipping fracture. The steepness of the line is a measure for the dependability of the material.[30]

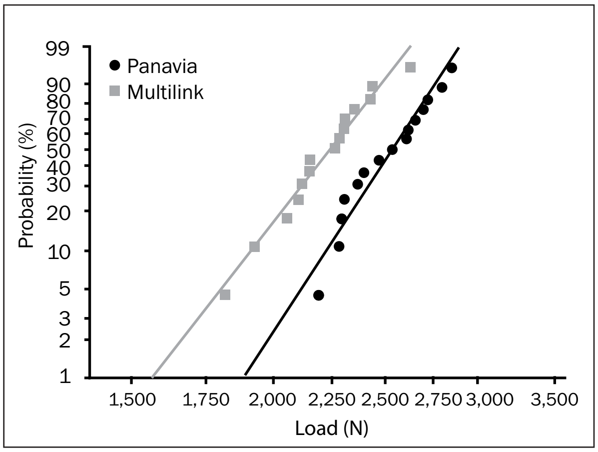


Fig 8 Probability plot for failure of esthetic ceramic CAD/CAM-generated crowns with 1.5-mm occlusal thickness placed with adhesive cements c (Multilink) and d (Panavia) on zirconia implant abutments. The steepness of the lines indicates the range of dependability. The steepness of the line is a measure for the dependability of the material.[30]

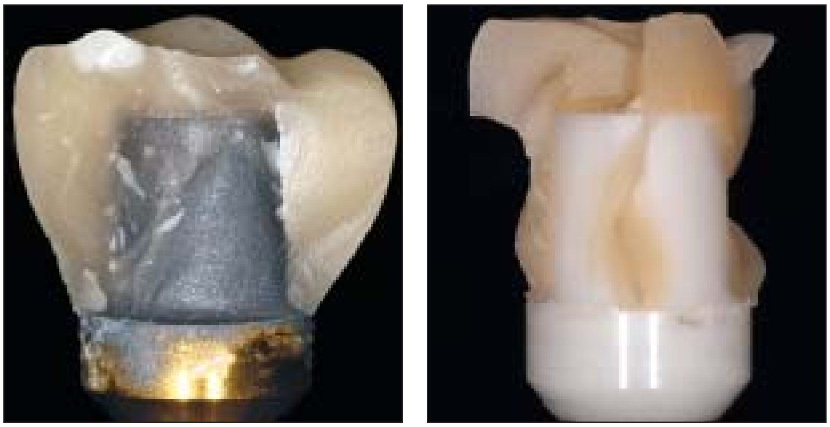


Fig 9 Esthetic ceramic CAD/CAM crowns with 1.5-mm occlusal thickness seated with adhesive cement d on titanium *(left)* and zirconia *(right)* abutments after loading until fracture. Remnants of cement and of ceramic adhere to both abutments, indicating mixed cohesive cement and ceramic fracture as well as adhesive failure.

crown-cement-tooth system among other variables.[31] In the present study, the fracture load of esthetic ceramic[11] CAD/CAM-generated implant crowns was influenced by the occlusal crown thickness, abutment material, mode of cementation, type of luting agent, and height of the abutment, confirming the hypothesis.

To simulate the situation of an osseointegrated implant, a model taken over from other studies was used; the implants were embedded into a block of polymethyl methacrylate because its modulus of elasticity is similar to that of spongy jawbone.[32,33] The occlusal thickness of the sample crowns was similar to that used in previous in vitro studies.[21,22,24] The occlusal thickness of 0.5 mm was chosen as a critical mark clearly below the required minimum of 1.0 to 1.5 mm.[29] The 5.5-mm bulk thickness was chosen because it may offer potential for a particular CAD/CAM implant crown construction.[34]

The mode of cementation, particularly the strengthening effect of adhesive cementation,[35] strongly influenced fracture load values of esthetic ceramic implant crowns in the present study. The relatively high fracture load of noncemented control crowns (a) was not further increased by nonadhesive cementation (b) in most groups. This may be attributed to the characteristic high initial strength of the implant crowns caused by their geometric circular internal shape and the increasingly thick lateral walls toward the occlusal surface. However, significant increases of strength were caused by adhesive cementation with both adhesive cements c and d. This is in concurrence with the strengthening effect of adhesive cementation as reported in other studies.[21–24,35,36] The high fracture load of group 1d was similar for 0.5-mm and 1.5-mm occlusal thickness crowns, indicating that the adhesion provided by cement d obviously compensated for the generally lower strength of occlusally thin (0.5 mm) crowns. In a previous study, the strength-increasing effect of adhesive cement also compensated for the limited material strength of esthetic ceramic crowns, leveling it with the strength of lithium disilicate crowns.[21]

Abutment material influenced fracture load values in that fracture load values on titanium abutments were significantly higher than on zirconia abutments throughout the study. Alumina air-abrading and the use of a methacrylate-phosphate primer are a prerequisite of bonding with resin-based cements to titanium.[37–39] The acid phosphoric esters bond chemically to the metal oxide layer,[37] and the methacrylate provides the chemical bond to resin-based cement. While studies confirm the adhesive effects of primers to titanium by chemical bond,[38–40] alumina air abrasion appears to exert a major influence on adhesion to titanium through micromechanical retention.[37,40] Similarly, a stable chemical bond to zirconia can be established by air abrasion of the zirconia and using an MDP-containing resin such as that contained in adhesive cement d.[41–44] The chemical bond of adhesive cement c to zirconia is provided by the acid phosphoric acrylates contained in the metal primer, which form a zirconia-phosphate chemical bond (manufacturer's information, Ivoclar Vivadent, 2004). Both chemical and micromechanical factors probably contributed to the differences between bond strength to the titanium and zirconia abutments in the present study.

The type of resin-based adhesive cement influenced the fracture strength in that adhesive cement d generally showed higher fracture load values than adhesive cement c on both titanium and zirconia abutments. The Weibull probability plots for failure reveal the difference, particularly for zirconia abutments. Since the details of the chemical composition of both adhesive cements are proprietary, the exact mechanisms and reasons for the different performance cannot be determined here. The dependability of adhesive cement d, particularly when used for the placement of zirconia ceramic restorations, is well established.[43] In vitro, adhesive cement d showed excellent results after thermocycling.[44] In vivo adhesive cement d has since proved itself very well for cementation of zirconia fixed partial dentures.[45]

Occlusal crown thickness (0.5 mm versus 1.5 mm) consistently influenced the fracture load of the implant abutment crown, which is in concurrence with fundamental materials knowledge.[31] However, increasing the thickness of the crown to the unusual 5.5 mm in combination with the shortening of the abutments of group 3 did not result in higher crown strength. The reduced supporting area of the shortened abutment and the increased probability of the inclusion of fracture-inducing flaws with higher thickness may have opposed the further increase of strength and limited strengthening by added thickness.[46]

Crowns loaded to fracture on both titanium and zirconia abutments showed a mixture of cohesive fracture of resin cement and ceramic as well as adhesive failure in the present study, which is similar to mixed modes of fracture at titanium interfaces as reported in another study.[40] This particular fracture mode together with the high fracture load values indicates strong adhesive effects at the abutment-cement and cement-crown interfaces for both abutments and both adhesive cements.

In conclusion, the present study confirmed the reinforcing effects of adhesive cements for esthetic ceramic CAD/CAM implant crowns on titanium and zirconia abutments. Although the strength of the esthetic ceramic is limited,[11] the high fracture load values obtained with adhesive cementation in the present study indicate that esthetic ceramic may fulfill the demands for adequate strength of implant crowns if seated with adhesive cements.

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