In vitro assessment of three types of zirconia implant abutments under static load

Jae Seon Kim, DDS,[a] Ariel J. Raigrodski, DMD, MS,[b] Brian D. Flinn, PhD,[c] Jeffrey E. Rubenstein, DMD, MS,[d] Kwok-Hung Chung, DDS, PhD,[e] and Lloyd A. Mancl, PhD[f]

Georgia Regents University College of Dental Medicine, Augusta, Ga; School of Dentistry, University of Washington, Seattle, Wash

Statement of problem. Although various zirconia abutments have been introduced, insufficient data exist regarding the maximum load capacity of internal tri-channel connection zirconia implant abutments with various implant-abutment interfaces.

Purpose. The purpose of this in vitro study was to compare the maximum load capacity of 3 different types of internal tri-channel connection zirconia abutments and to assess their mode of failure.

Material and methods. The study investigated 3 groups (n=20) of zirconia implant abutments with different implant-abutment interfaces. Group AllZr consisted entirely of zirconia (Aadva CAD/CAM Zirconia Abutment), group FrZr of a titanium insert friction-fitted to the zirconia abutment component (NobelProcera Abutment Zirconia), and group BondZr of a titanium insert bonded to the zirconia abutment component (Lava Zirconia abutment). All the abutments were thermal cycled for 20 000 cycles between 5°C and 55°C. Sixty test implants made of titanium (Dummy NobelReplace) were embedded in autopolymerizing acrylic resin, and 60 zirconia copings (Lava Zirconia) with a uniform thickness of 2.0 mm were fabricated and bonded to the abutments. A universal testing machine was used to statically load all the specimens at a crosshead speed of 1 mm/min. The maximum load was recorded and used as the failure load. The fractured specimens were collected and representative specimens were studied with a stereomicroscope and scanning electron microscope (SEM). One-way ANOVA and post hoc comparisons with the Tukey HSD tests were used for statistical analysis (α=.05).

Results. The mean (SD) maximum load capacity was 484.6 (56.6) N for NobelProcera, 503.9 (46.3) N for Aadva, and 729.2 (35.9) N for Lava abutments. The maximum load capacity of Lava abutments was significantly higher than that of Aadva or NobelProcera (P< 05). No significant difference between Aadva and NobelProcera abutments was noted. The mode of failure among the Aadva, NobelProcera, and Lava abutments was different.

Conclusions. With standard diameter internal tri-channel connection implants, the maximum load capacity of the Lava abutment was significantly higher than that of the Aadva or NobelProcera abutment. No significant difference in maximum load capacity was noted between Aadva and NobelProcera abutments. However, the fracture behavior of all 3 abutments was different. (J Prosthet Dent 2013;109:255-263)

Presented at the Graduate Student Research Competition of the Pacific Coast Society for Prosthodontics, Pasadena, Calif, June 2011.

[a]Assistant Professor, Department of Oral Rehabilitation, Georgia Regents University College of Dental Medicine.
[b]Professor and Director of Graduate Prosthodontics, Department of Restorative Dentistry, School of Dentistry, University of Washington.
[c]Research Associate Professor, Materials Science and Engineering, University of Washington.
[d]Professor, Graduate Prosthodontics, Department of Restorative Dentistry, School of Dentistry, University of Washington.
[e]Professor, Department of Restorative Dentistry, School of Dentistry, University of Washington.
[f]Research Associate Professor, Department of Oral Health Sciences, University of Washington.

CLINICAL IMPLICATIONS

For standard diameter internal tri-channel connection implants, zirconia abutments with bonded titanium inserts may provide increased maximum load capacity than pure zirconia abutments or zirconia abutments with titanium inserts that are friction fitted.

The initial use of implant abutments was to act as an intermediate element between the prosthesis and the implant platform for screw-retained multiunit implant prostheses.[1,2] Recently, their role has expanded to supporting and managing the soft tissue emergence and submergence profiles[3-5] and to providing base shades at the cervical aspect of single tooth and multiunit implant prostheses.[6] Such demands, along with the advent of computer-assisted design/computer-assisted manufacturing (CAD/CAM) technology, have led to the development of various custom abutment fabrication techniques using titanium and zirconia.[7]

Commercially pure titanium has been widely used as an abutment material in implant therapy because of its well-documented biocompatibility[8,9] and mechanical properties.[10] Even though these materials have demonstrated predictable outcomes in long-term clinical studies,[11,12] titanium abutments may cause an unnatural bluish appearance at the soft tissue junction in patients with relatively thin tissues that can result in a compromised esthetic outcome[13,14]; however, numerous materials can be used to overcome this shortcoming, including cast gold alloys and gold-colored titanium abutments. These materials may improve the gingival hue,[15] but the overall translucency of the restoration may remain limited because of the opaque nature of metal. Ceramic materials such as alumina have been used as implant abutment materials to assist in achieving optimal esthetics,[16,17] but studies have shown the relatively low fracture resistance of the material.[18,19] As a result, zirconia implant abutments have gained popularity because of their improved fracture resistance over alumina and superior optical properties over titanium. Several in vitro studies have shown that the fracture resistance of zirconia implant abutments exceeds the maximal reported incisal forces (90 to 370 N).[20-24] Although most clinical failures result from fatigue loading, static loading tests may model situations such as a person occluding into a hard object or receiving trauma to the implant-abutment complex. Depending on its thickness, zirconia allows a certain degree of light transmission,[25] which enables the dental laboratory technician to fabricate restorations to satisfy patients with high esthetic expectations.

Regardless of the clinical success reported for zirconia abutments in anterior and premolar regions,[4,26,27] fracture of the abutments has been reported.[28] Consequently, some may question the validity of using such a material in the oral environment. However, not all zirconia abutments behave in the same manner.[29]

As compared to titanium abutments, which are monolithic, zirconia abutments can be fabricated in various ways. They can be made entirely of zirconia, of zirconia with a friction fitted metal component which connects to the implant, or of zirconia with a bonded metal component which connects to the implant. These multiple connections may affect the overall durability of the abutment/implant complex.[30] Studies have been published regarding the load capacity of zirconia abutments with different implant-abutment connections in various implant systems and implant diameters.[31,32] However, the authors identified no study that compared zirconia abutments with different implant-abutment interfaces in a standardized dimension on a single implant diameter. Such a study is needed to minimize variables and to focus on the effect of the connection type on the maximum load capacity. In addition, the mode of failure for the abutments and its residual effect on the implant platform need to be studied.

Brodbeck[33] reported the damaging effect of zirconia on the implant's external hexagon. Klotz et al[34] reported the wear of zirconia and titanium implant abutments under cyclic loading and showed more titanium transfer on the zirconia abutment than on the titanium abutment with a conical connection implant. Such potential damage to the implant at the abutment implant interface may result in clinical failure.

The purpose of this in vitro study was to compare the maximum load capacity of standard diameter, internal, and tri-channel connection zirconia abutments with 3 different implant-abutment interfaces and to assess the mode of failure of these abutments. The null hypothesis was that no difference in the maximum load capacity and mode of failure among the 3 types of zirconia abutments exists under static load.

MATERIAL AND METHODS

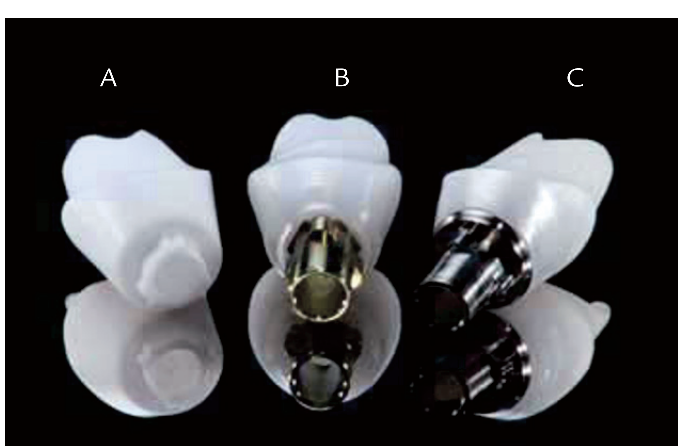
Sixty zirconia implant abutments from 3 different manufacturers were used (n=20). The different groups of abutments, abutment composition, abutment and implant platform interface, and manufacturers are presented in Table I. Group AllZr consisted entirely of zirconia (Aadva CAD/CAM Zirconia Abutment; GC Advanced

Technologies Inc, Alsip, Ill), group FrZr of a titanium insert that is friction-fitted to the zirconia abutment component (NobelProcera Abutment Zirconia; Nobel Biocare, Yorba Linda, Calif), and group BondZr of a titanium insert that is bonded to the zirconia abutment component (Lava Zirconia abutment; 3M ESPE, St Paul, Minn) as shown in Figures 1 and 2.

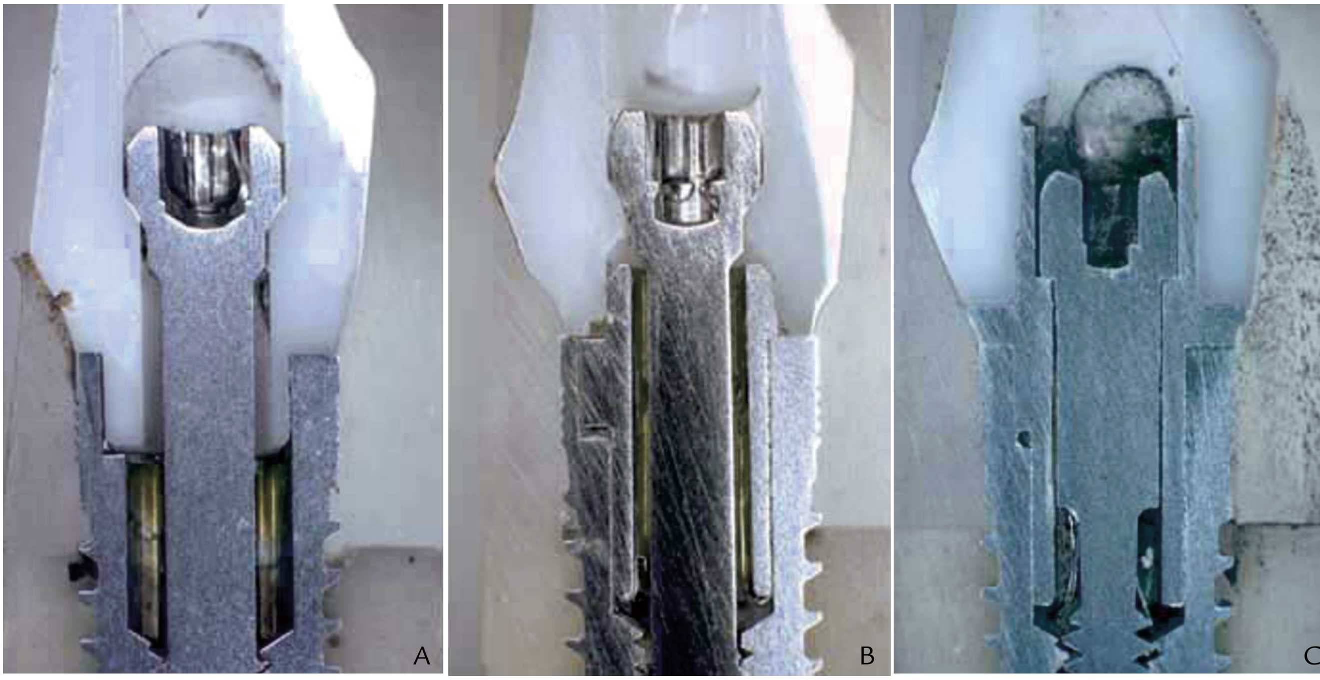
A single abutment for a maxillary left central incisor was fabricated with a CAD/CAM system (Aadva CAD/CAM Zirconia Abutment; GC Advanced Technologies Inc) from a prototype cast, designated as the prototype abutment, and scanned with 2 other scanners (NobelProcera Scanner; Nobel Biocare and 3M ESPE Lava Scan ST Dental Scanner; 3M ESPE). Zirconia abutments were obtained from GC Advanced Technologies Inc, Nobel Biocare, and 3M ESPE. In this manner, all the abutments were fabricated such that their dimensions were identical, with a 0.5 mm deep circumferential chamfer and 8 mm of incisogingival height on the buccal surface and 6.5 mm on the lingual. The axial wall thicknesses were 1.0 mm at the mid-facial and mid-palatal surfaces and 1.3 mm at the mid-mesial and mid-distal as shown in Figure 3. The identical dimensions of the abutments were confirmed with a digital caliper (Mitutoyo 500-196-20; Mitutoyo America Corp, Aurora, Ill). The Lava abutments required bonding to the titanium inserts. The manufacturer recommended a bonded surface area of at least 33 mm^2. Calculations indicated that the titanium insert for a NobelReplace Regular Platform implant needed at least 2.7 mm of axial wall height. The titanium inserts (Engaging Ti Base; Attachments Intl Inc, Burlingame, Calif) were reduced to 3 mm in height to meet the manufacturer's specifications. The surfaces of the titanium inserts and the intaglio surface of the zirconia abutment were tribochemically treated (Rocatec; 3M ESPE) according to the manufacturer's instructions. The titanium inserts and the zirconia abutments were bonded with dual-polymerizing composite resin cement (RelyX Unicem Self-adhesive Universal Resin Cement; 3M ESPE) according to the manufacturer's instructions. Excess cement was removed under ×10 magnification. For the Procera abutments, the zirconia sprue attached to the coronal portion of the abutment was removed with a diamond rotary cutting instrument (KS 4; Brasseler USA, Savannah, Ga) and copious water with a custom device (Pattern Resin LS, GC Advanced Technologies Inc) fabricated from the prototype abutment to standardize the dimensions. After 24 hours of storage in water at room temperature, all 60 zirconia implant abutments were thermal cycled (v2.1a; Proto-tech, Portland, Ore) for 20 000 cycles between 5 and

Table I. Materials evaluated

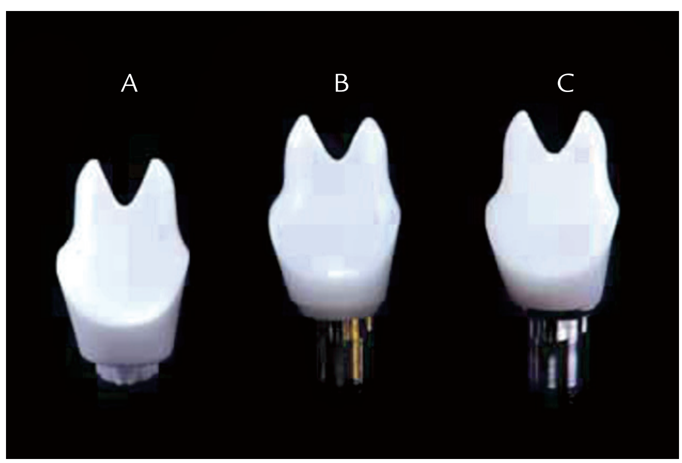
Material	Abutment Composition	Abutment/Implant Platform Interface	Manufacturer
Aadva CAD/CAM Zirconia Abutment	Zirconia	Zirconia/Titanium	GC Advanced Technologies Inc, Alsip, Ill
NobelProcera Abutment Zirconia	Zirconia + Ti insert (friction fit)	Zirconia/Titanium	Nobel Biocare, Yorba Linda, Calif
Lava Zirconia Abutment	Zirconia + Ti insert (Bonded)	Titanium/Titanium	3M ESPE, St Paul, Minn



1 Example of specimens depicting 3 various implant-abutment interfaces. (A) GC. (B) Procera. (C) Lava.



2 Cross sections of specimens depicting various implant-abutment interfaces. A, GC. B, Procera. C, Lava.

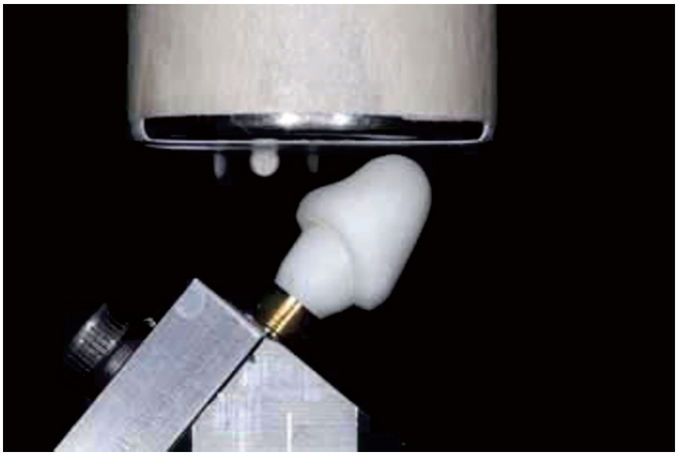


3 Example of specimens with standardized dimensions from 3 manufacturers. (A) GC. (B) Procera. (C) Lava.

55°C, with a dwell time of 20 seconds.[35]

Sixty test implants made of titanium with a standard diameter internal tri-channel connection (Dummy NobelReplace Tapered Groovy 4.3 × 13 mm; Nobel Biocare, Yorba Linda, Calif) were used for this study. These were embedded in autopolymerizing acrylic resin (Shade D3 JetTooth Shade Powder and Jet liquid; Lang Dental Manufacturing Co, Inc, Wheeling, Ill) by using a custom-made positioning device to standardize the test implant within the acrylic resin. The platforms of the test implants were 3.0 mm away from the acrylic resin to simulate 3.0 mm of bone loss according to the ISO 14801 standard.[36] A preload of 35 Ncm was applied to all the abutments to anchor them to the test implant, according to the manufacturer's instructions. A zirconia coping with a uniform thickness of 2.0 mm (Lava Zirconia; 3M ESPE) was fabricated for all 60 abutments by scanning the individual abutments (3M ESPE Lava Scan ST Dental Scanner; 3M ESPE). The intaglio surfaces of the zirconia copings and the zirconia implant abutments were tribochemically treated (Rocatec; 3M ESPE), and ceramic primer (RelyX Ceramic Primer, 3M ESPE) was applied. Dual-polymerizing composite resin cement (RelyX Unicem Self-adhesive Universal Resin Cement; 3M ESPE) was used to bond the copings to the abutments. The specimens were kept in tap water at room temperature for at least 24 hours before loading.

The universal testing machine (Instron model 5500R; Instron Corp, Norwood, Mass) made contact with the specimen 2.0 mm from the incisal tip at a 30-degree angle to simulate maxillary anterior tooth contact, as modified from the ISO 14801 standard[36] and shown in Figure 4. A polytetrafluoroethylene (PTFE) tape (Harvey's White PTFE Thread Seal Tape; William H. Harvey Company,



4 Zirconia coping bonded on test implant and mounted in steel holder of universal testing machine at angle of 30 degrees. PTFE tape was applied between specimen and testing machine to prevent frictional force on specimens.

Table II. Mean (SD) maximum load capacity in N after 20 000 thermal cycles (n=20)

Maximum load capacity (Standard)				
Group	**Mean**	**SD**	**Min**	**Max**
GC	503.9	46.3	424.0	650.3
Lava	729.2	35.9	651.0	788.0
Procera	484.6	56.6	369.3	589.1

Table III. Tukey Studentized Range (HSD) Test for Maximum load capacity

Group Comparison	Difference Between Means	Simultaneous 95% Confidence Limits	
Lava -GC	225.3	189.5	261.1*
Lava -Procera	244.6	208.8	280.4*
GC -Procera	19.3	-16.5	55.1

Comparisons significant at the .05 level are indicated by *

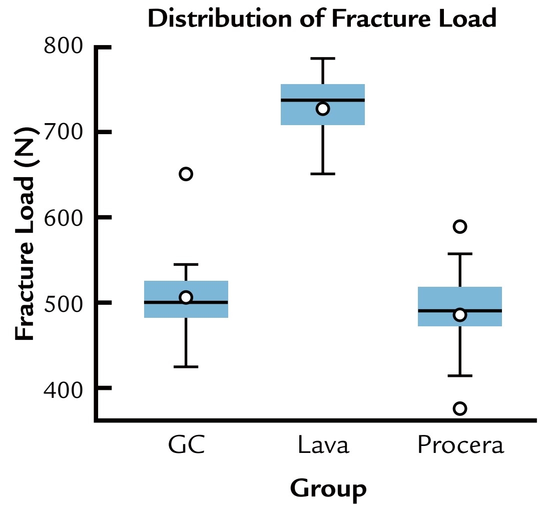
Omaha, Neb) was used on the interface between the testing machine and copings to prevent any friction. Static loading was performed at a crosshead speed of 1.0 mm/min. The crosshead motion was stopped after the load started to decrease because of the fracture of abutments or the plastic deformation of the screw or implant. The maximum load was recorded and used as the failure load. Three specimens from each group were randomly chosen and were recorded with a high-speed camera (Keyence Corp of America, Elmwood Park, NJ) at between 800 and 1000 frames per second (fps) during static loading. Representative fractured specimens from each group were mounted on aluminum blocks with colloidal silver liquid (Electron Microscopy Sciences, Hatfield, Pa), sputtered with platinum in an argon gas environment (SPI Module Sputter Coater; Structure Probe, Inc, West Chester, Pa), and examined with a scanning electron microscope (SEM) (JEOL JSM-7000; JEOL Ltd, Tokyo, Japan) with secondary electron imaging and backscattered electron imaging. Digital images of these specimens were recorded at various magnifications to evaluate the fracture surfaces and to determine the mode of failure.

RESULTS

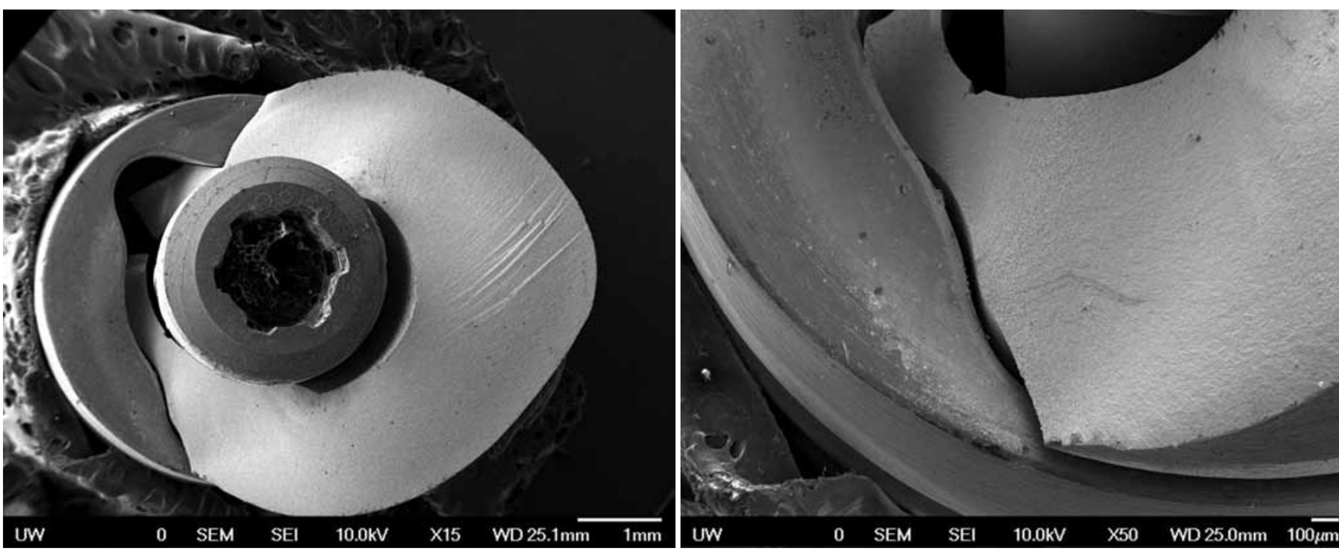
The mean maximum load capacity (SD) was 484.6 (56.6) N for NobelProcera, 503.9 (46.3) N for Aadva, and 729.2 (35.9) N for Lava (Table II). There were significant differences in maximum load capacity among the 3 groups (1-way ANOVA $P<.001$, F value=167.2, df=2 and 57). The mean maximum load capacity was significantly higher for the Lava abutments than for both Aadva and NobelProcera abutments *(P<* 05; Tukey HSD). The difference in maximum load capacity between Aadva and NobelProcera was not statistically significant (Table III) (Fig. 5). The modes of failure among the Aadva, NobelProcera, and Lava abutments were all different. The Aadva abutments displayed fractures, which emanated from the area between the buccal and distal lobes of the tri-channel connection, where the zirconia thickness is the thinnest (Fig. 6). The NobelProcera abutments displayed fractures, which emanated from the internal aspect of the contact area of zirconia and the screw head at the lateral and posterior aspects (Fig. 7). The Lava abutments displayed separation between the zirconia and the titanium insert (Fig. 8).

DISCUSSION

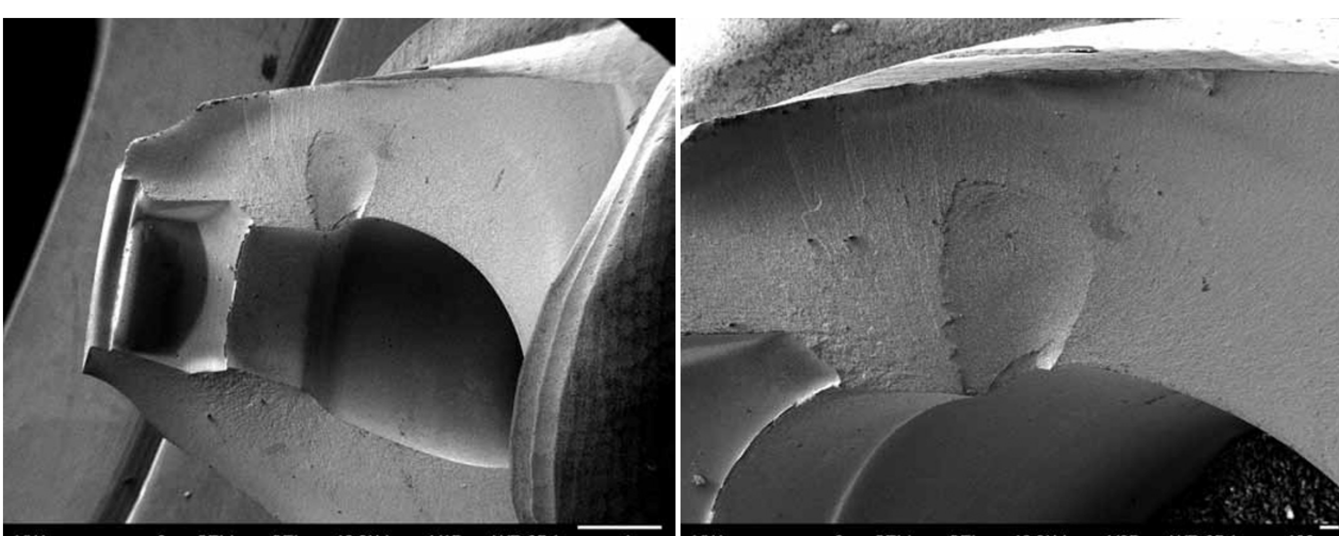
This in vitro study demonstrated that zirconia abutments with various implant-abutment interfaces have a different maximum load capacity and mode of failure under static load for standard platform tri-channel implants. Therefore, the null hypothesis was rejected. Even though significant differences in the maximum load capacity existed among some groups, all of them exceeded the physiologi-



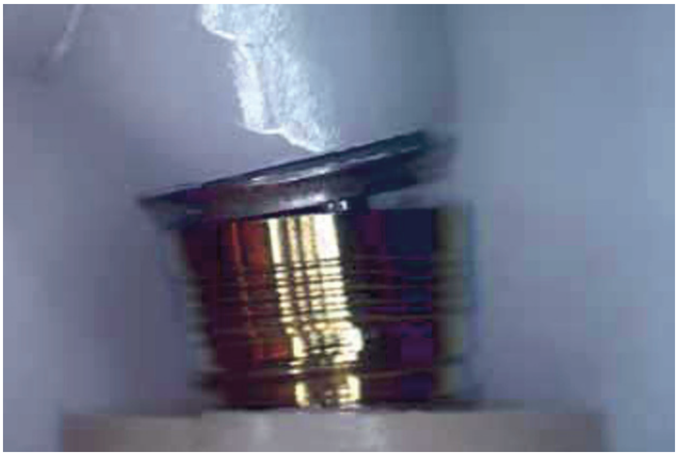
5 Box plot of maximum load capacity for each group.



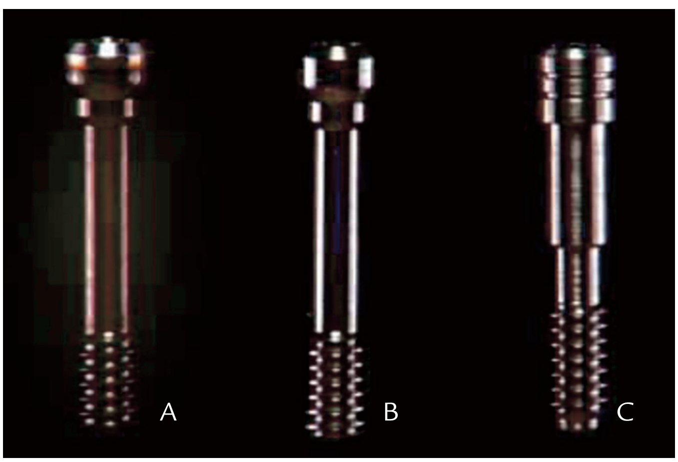
6 SEM image of fracture surface of GC abutment. A, Fracture origin (magnification ×15). B, Close-up of fracture origin (magnification ×50).



7 SEM image of fracture surface of Procera abutment. A, Fracture origin at junction of intaglio surface of zirconia component and screw head (magnification ×15). B, Close-up of fracture origin (magnification ×35).



8 Lava abutment displaying separation between zirconia and titanium insert.



9 Various screw designs used for specimens. (A) GC. (B) Procera. (C) Lava.

cal incisal force in the anterior region, which is known to be aproximately 90 to 370 N.[20-24] The zirconia abutments used were either made entirely of zirconia, zirconia with a friction-fitted titanium insert, or zirconia with a bonded titanium insert. The dimensions of all the abutments were standardized because the abutments were fabricated with CAD/CAM technology, instead of manually. The test implants used in this study were composed of commercially pure titanium, which is the equivalent of an implant used clinically. It was used rather than a replica to exclude one more variable and to assist in localizing the load effect of the implant-abutment interface so that fracture resistance could be measured.

One variable, the screw design, could not be standardized. For the Aadva and NobelProcera abutments, the screw head had a tapering design, whereas the Lava abutment screw head had a butt-joint design. In addition, the Lava abutment screw had more threads than the other two (Fig. 9).

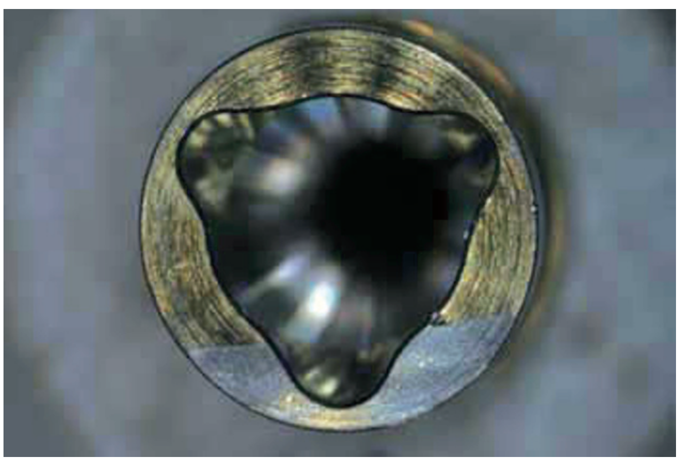
It can be speculated that the stress distribution under static load for all 3 abutments was different. When force was applied from the palatal aspect of the abutment-coping complex, the palatal-cervical region was under tension and the labial-cervical region was under compression. After observation with the stereomicroscope and SEM, the fractures in the Aadva abutments were found to have emanated from the axial wall of the tri-channel connection, between the channels where the zirconia is the thinnest (0.3 mm). This may imply that for a monolithic zirconia abutment such as the Aadva abutment, the weak link may be where the material is the thinnest and in an area of tension.

For the NobelProcera abutments, the high-speed camera demonstrated separation between the zirconia component and the titanium insert before the fracture of the zirconia. This separation may have transferred the stress to the contact area between the screw head and the zirconia component, causing fracture. SEM images also demonstrated that the fracture originated where the screw head contacts the zirconia on the lateral and palatal aspect of the intaglio surface of the abutments. For zirconia abutments with a titanium insert that can separate from the zirconia component under static load, the screw head design may play a role in the fracture resistance of the abutment complex.

For the Lava abutments, the high-speed camera demonstrated separation of the zirconia component from the titanium insert. Only 2 of the Lava abutments fractured. Even though it is difficult to pinpoint the cause of these fractures, a misfit or a bonding compromise between the titanium insert and the zirconia component may be suspected. Observation with the stereomicroscope showed that the origin of the crack propagation in the zirconia matched that of the titanium insert where surface roughness and distortion are present. Although titanium abutments were not used, the maximum load capacity of Lava abutments may be comparable to that of titanium abutments. Previous studies have shown similar results for zirconia abutments with a cemented titanium insert.[19,37]

Additionally, the test implant platforms were subjectively assessed with a stereomicroscope. The NobelProcera abutment group demonstrated significant damage to the implant platforms perhaps because the interface with the platform of the implant was in zirconia and the friction-fitted titanium led the zirconia component of the abutment to bend away, causing the zirconia to dig into the titanium platform. (Fig. 10). The Aadva abutment group did not demonstrate as much implant platform damage as the NobelProcera abutment group.

10 Representative specimen displaying damage to implant platform of Procera abutment.



11 Representative specimen displaying damage to implant platform of GC abutment.

12 Representative specimen displaying severe distortion of test implant of Lava abutment.

The abutment fractured without any prior bending, thus leaving less contact area and less damage to the implant platform (Fig. 11). The implant platforms interfaced with the Lava abutments could not be evaluated because the titanium inserts did not fracture off the implants. However, because the highest compressive force was applied to the abutment-implant complex, the implant dummies demonstrated severe distortion (Fig. 12). Conclusions may not be drawn from this finding since a high magnitude of force, which may not be clinically relevant, was applied to the abutment-implant complex.

Multiple limitations of the study need to be addressed for proper clinical correlation. The first was that only static loading was used. Static loading may only be one type of force among many that can be applied to the abutment-coping complex; thus different results may be demonstrated when fatigue loading is applied. However, to design a fatigue loading test, static loading is essential to provide a starting point and calculate the load that will be applied to the abutment-coping complex. Therefore, this static loading test may be considered a preliminary study for future fatigue loading projects. Second, the precision of the fit of the abutments from different manufacturers to the test implants was not compared. This factor was a variable that may have contributed to the difference in the maximum load capacity or the fracture behavior of the abutments. Third, nonanatomic copings were used rather than anatomically contoured crowns. Thick zirconia copings (2.0 mm) were used to concentrate the forces being applied to the specimens to the cervical region and to prevent any coping fractures, which may introduce another variable and complicate the data analysis. In addition, this study used only one type of implant system with a specific connection type and diameter; thus the results may not be applicable to other implant systems. Additional clinical studies are needed to conducted to identify the mode of failure of such implant abutments and to provide guidelines for the use of zirconia abutments with different connections and different implant platform designs.

CONCLUSION

Within the limitations of this in vitro study, the following conclusions were drawn:

1. Lava zirconia abutments demonstrated a higher maximum load ca-

pacity under static load than Aadva and NobelProcera zirconia abutments.

2. Aadva and NobelProcera zirconia abutments did not demonstrate any significant difference in maximum load capacity under static load.

3. The mode of failure for all 3 types of zirconia abutments was different.

REFERENCES

1. Lewis S, Beumer J 3rd, Hornburg W, Moy P. The "UCLA" abutment. Int J Oral Maxillofac Implants 1988;3:183-9.
2. Beumer J 3rd, Hamada MO, Lewis S. A prosthodontic overview. Int J Prosthodont 1993;6:126-30.
3. Yildirim M, Edelhoff D, Hanisch O, Spiekermann H. Ceramic abutments-a new era in achieving optimal esthetics in implant dentistry. Int J Periodontics Restorative Dent 2000;20:81-91.
4. Glauser R, Sailer I, Wohlwend A, Studer S, Schibli M, Schärer P. Experimental zirconia abutments for implant-supported single-tooth restorations in esthetically demanding regions: 4-year results of a prospective clinical study. Int J Prosthodont 2004;17:285-90.
5. Su H, Gonzalez-Martin O, Weisgold A, Lee E. Considerations of implant abutment and crown contour: critical contour and subcritical contour. Int J Periodontics Restorative Dent 2010;30:335-43.
6. Park SE, Da Silva JD, Weber HP, Ishikawa-Nagai S. Optical phenomenon of peri-implant soft tissue. Part I. Spectrophotometric assessment of natural tooth gingiva and peri-implant mucosa. Clin Oral Implants Res 2007;18:569-74.
7. Kapos T, Ashy LM, Gallucci GO, Weber HP, Wismeijer D. Computer-aided design and computer-assisted manufacturing in prosthetic implant dentistry. Int J Oral Maxillofac Implants 2009;24:110-8.
8. Lindhe J, Berglundh T. The interface between the mucosa and the implant. Periodontol 2000 1998;17:47-54.
9. Linkevicius T, Apse P, Grybauskas S, Puisys A. Influence of thin mucosal tissues on crestal bone stability around implants with platform switching: a 1-year pilot study. J Oral Maxillofac Surg 2010;68:2272-7.
10. Anusavice KJ. Phillips' science of dental materials. 11th ed. Saunders; 2003. p. 769-70.
11. Lekholm U, Gunne J, Henry P, Higuchi K, Lindén U, Bergström C, et al. Survival of the Brånemark implant in partially edentulous jaws: a 10-year prospective multicenter study. Int J Oral Maxillofac Implants 1999;14:639-45.
12. Ekelund JA, Lindquist LW, Carlsson GE, Jemt T. Implant treatment in the edentulous mandible: a prospective study on Brånemark system implants over more than 20 years. Int J Prosthodont 2003;16:602-8.
13. Jung RE, Holderegger C, Sailer I, Khraisat A, Suter A, Hämmerle CH. The effect of all-ceramic and porcelain-fused-to-metal restorations on marginal peri-implant soft tissue color: a randomized controlled clinical trial. Int J Periodontics Restorative Dent 2008;28:357-65.
14. Prestipino V, Ingber A. All-ceramic implant abutments: esthetic indications. J Esthet Dent 1996;8:255-62.
15. Bressan E, Paniz G, Lops D, Corazza B, Romeo E, Favero G. Influence of abutment material on the gingival color of implant-supported all-ceramic restorations: a prospective multicenter study. Clin Oral Implants Res 2011;22:631-7.
16. Prestipino V, Ingber A. Esthetic high-strength implant abutments. Part I. J Esthet Dent 1993;5:29-36.
17. Prestipino V, Ingber A. Esthetic high-strength implant abutments. Part II. J Esthet Dent 1993;5: 63-8.
18. Yildirim M, Fisher H, Marx R, Edelhoff D. In vivo fracture resistance of implant-supported all-ceramic restorations. J Prosthet Dent 2003;4:325-31.
19. Butz F, Heydecke G, Okutan M, Strub JR. Survival rate, fracture strength and failure mode of ceramic implant abutments after chewing simulation. J Oral Rehabil 2005;32:838-43.
20. Gibbs CH, Mahan PE, Mauderli A, Lundeen HC, Walsh EK. Limits of human bite strength. J Prosthet Dent 1986;56:226-9.
21. Paphangkorakit J, Osborn JW. The effect of pressure on a maximum incisal bite force in man. Arch Oral Biol 1997;42:11-7.
22. Helkimo E, Carlsson GE, Helkimo M. Bite force and state of dentition. Acta Odontol Scand 1977;35:297-303.
23. Haraldson T, Carlsson GE, Ingervall B. Functional state, bite force and postural muscle activity in patients with osseointegrated oral implant bridges. Acta Odontol Scand 1979;37:195-206.
24. Waltimo A, Könönen M. A novel bite force recorder and maximal isometric bite force values for healthy young adults. Scand J Dent Res 1993;101:171-5.
25. Baldissara P, Llukacej A, Ciocca L, Valandro FL, Scotti R. Translucency of zirconia copings made with different CAD/CAM systems. J Prosthet Dent 2010;104:6-12.
26. Canullo L. Clinical outcome study of customized zirconia abutments for single-implant restorations. Int J Prosthodont 2007;20:489-93.
27. Zembic A, Sailer I, Jung RE, Hämmerle CH. Randomized-controlled clinical trial of customized zirconia and titanium implant abutments for single-tooth implants in canine and posterior regions: 3-year results. Clin Oral Implants Res 2009;20:802-8.
28. Aboushelib MN, Salameh Z. Zirconia implant abutment fracture: clinical case reports and precautions for use. Int J Prosthodont 2009;22:616-9.
29. Kerstein RB, Radke, J. A comparison of fabrication precision and mechanical reliability of 2 zirconia implant abutments. Int J Oral Maxillofac Implants 2008;23:1029-36.
30. Sailer I, Sailer T, Stawarczyk B, Jung RE, Hämmerle CH. In vitro study of the influence of the type of connection on the fracture load of zirconia abutments with internal and external implant-abutment connections. Int J Oral Maxillofac Implants 2009;24:850-8.
31. Seetoh YL, Tan KB, Chua EK, Quek HC, Nicholls JI. Load fatigue performance of conical implant-abutment connections. Int J Oral Maxillofac Implants 2011;26:797-806.
32. Nguyen HQ, Tan KB, Nicholls JI. Load fatigue performance of implant-ceramic abutment combinations. Int J Oral Maxillofac Implants 2009;24:636-46.
33. Brodbeck U. The ZiReal Post: A new ceramic implant abutment. J Esthet Restor Dent 2003;15:10-23.
34. Klotz MW, Taylor TD, Goldberg AJ. Wear at the titanium-zirconia implant-abutment interface: a pilot study. Int J Oral Maxillofac Implants 201;26:970-5.
35. Gale MS, Darvell BW. Thermal cycling procedures for laboratory testing of dental restorations. J Dent 1999;27:89-99.
36. International Organization for Standardization. ISO 14801:2003. Dentistry fatigue test for endosseous dental implants. Geneva: International Organization for Standardization, 2003.
37. Aramouni P, Zebouni E, Tashkandi E, Dib S, Salameh Z, Almas K. Fracture resistance and failure location of zirconium and metallic implant abutments. J Contemp Dent Pract. 2008;9:41-8.

Corresponding author:
Dr Jae Seon Kim
Georgia Regents University
College of Dental Medicine
1120 15th St, GC-4212
Augusta, GA 30912
Fax: 706-721-8349
Email: jkim1@gru.edu

Acknowledgments
The authors thank 3M ESPE and Nobel Biocare for their support in terms of implant components and zirconia blanks and Issaquah Dental Lab for their support.