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Influence of Implant Angulation on the Fracture Resistance of Zirconia Abutments

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Abstract

Purpose: To investigate the effects of abutment design to correct for implant angulation and aging on the fracture resistance of zirconia abutments. Greater understanding of the fracture strength of the zirconia abutments under various clinical conditions may lead to improvement of clinical protocols and possibly limit potential failures of implant prosthetics.
Materials and Methods: Test specimens consisted of an implant-zirconia abutment-zirconia crown assembly with implant apex positioned at 0°, 20° to the facial (20F), and 20° to the lingual (20L) with respect to a constant crown contour. To keep the abutment design as the only variable, CAD/CAM technology was used to generate monolithic zirconia crowns identical both in external and internal dimensions and marginal contours to precisely fit all the abutments in an identical fashion. The monolithic zirconia abutments were designed to fit the constant crown contours and the internal connection of the implant at the three angulations. The customized abutments for the three implant angulations varied in emergence profile, screw hole location, and material thickness around the screw hole. Half the specimens from each group were subjected to steam autoclaving and thermocycling to simulate aging of the restorations in vivo. To mimic the off-axis loading of the central incisor, the specimens were loaded at the recommended cephalometric interincisal relationship of 135° between the long axis of the crown supported by the implant and the Instron force applicator simulating the mandibular incisor. The force applicator was positioned 2 mm from the incisal edge and loaded at a 1 mm/min crosshead speed. Data were evaluated by 2-way ANOVA ($\alpha = 0.05$) and Tukey's HSD.
Results: The 20F group had the highest fracture values followed by the 0° group, and the 20L group had the lowest fracture values. Aging did not yield any significant difference in fracture force magnitudes.
Conclusion: Within the limitations of this study, tilting the implant apex to the lingual significantly reduced the fracture strength of angle-corrected zirconia abutments. Accordingly, while the angle between the occlusal force application and the long axis of the implant decreases, the resistance (force) to fracture decreases.

Effective implant-supported prosthetics have evolved into an interdisciplinary treatment modality where every effort is taken by the surgeon and the restorative dentist to maximize a patient's esthetic and functional demands. When the implant fixture is placed in an ideal position, the restorative dentist can create an illusion of a natural tooth with the implant crown.[1] Nonideal implant position in the anterior maxilla often poses challenges to the restorative dentist where implant placement in resorbed alveolar bone frequently results in a facial emergence of the abutment compared to the adjacent dentition. In the esthetic zone, a custom-made zirconia abutment can accommodate a nonideal implant position while simultaneously supporting the morphologic features of the soft tissues and overlying crown. Prefabricated abutments often do not provide patient-specific support unique to each implant placement. Zirconia, an inherently brittle ceramic material, is sensitive to tensile forces and breakage. An example of a clinical fracture of a monolithic zirconia abutment after 2 years of clinical use is

Table 1 Study design

Group	No. of specimens	Implant	Implant angle	Abutment	Aging treatment
1	10	BH 4.6 × 15	0°	Custom milled	No treatment
2	10	BH 4.6 × 15	20° facial (20F)	Custom milled	No treatment
3	10	BH 4.6 × 15	20° lingual (20L)	Custom milled	No treatment
4	10	BH 4.6 × 15	0°	Custom milled	Steam autoclave & thermocycling
5	10	BH 4.6 × 15	20° facial (20F)	Custom milled	Steam autoclave & thermocycling
6	10	BH 4.6 × 15	20° lingual (20L)	Custom milled	Steam autoclave & thermocycling

BH 4.6 × 15: BioHorizons implant (4.6 × 15 mm, tapered internal, catalog # TLXP4615).

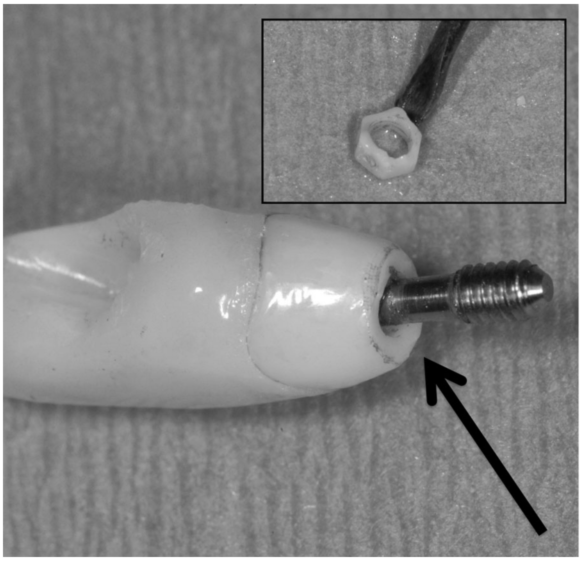

Figure 1 Clinical fracture of zirconia abutment through the hex portion that engages the implant body.

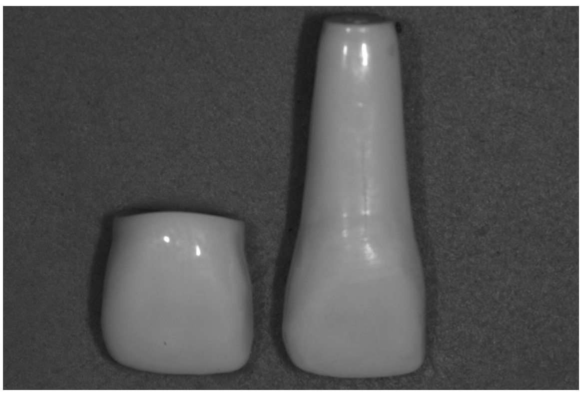

Figure 2 CAD/CAM-generated monolithic zirconia crown using typodont as the prototype.

shown in Figure 1, revealing a fracture through the hexagonal connection.

Various in vitro studies have evaluated the fracture resistance of zirconia abutments under simulated clinical conditions.[2-7] Differences in study designs complicate comparison of conclusions regarding the fracture strength of zirconia abutments; however, common factors are identified that affect the resistance to fracture load and include the type of implant-abutment connection and angle and point of loading. The abutment design is also critical, especially regarding the angulation to the implant as well as use of a monolithic design or two-piece design with zirconia bonded to a metallic sleeve containing the connecting interface to the implant. Finally, aging considerations are also common concerns with long-term resistance to fracture.

Despite a high elastic modulus of approximately 215 GPa and flexural strength often exceeding 1000 MPa, thin sections of zirconia should be avoided in high-stress areas due to zirconia's characteristic brittleness.[8] The oral cavity is a dynamic environment where applied force, temperature, and salivary chemistry are constantly changing. These factors may contribute to the well-known processes of aging often described as a low-temperature degradation (LTD) phenomenon unique to zirconia.[9,10] LTD is considered to occur as a spontaneous transformation of the tetragonal to monoclinic phases occurring over time at low temperatures that is not triggered by a local mechanical stress resulting in a lower resistance to fracture.[11]

While the literature presents a number of studies to evaluate the mean fracture load of zirconia abutments under varying loading conditions and angulations, limited investigations have considered the combined effects of varied implant angulation on the fracture resistance of zirconia abutments with artificial aging to simulate the structural changes occurring in vivo. Therefore, the purpose of this study was to investigate the effects of both varied abutment designs that occur with varying implant angulations and aging on the fracture strength of zirconia abutments while maintaining the crown contours as a constant factor.

Materials and methods

Study design

The number of specimens, type of implant, implant angle, abutment details, and treatment type are shown in Table 1.

Test specimens

Specimens used in this study consisted of implant–abutment–crown assemblies mounted in an aluminum square specimen holder. A total of 60 zirconia custom abutments and 60 zirconia crowns were CAD/CAM milled by TurboDent System (Pou Yu Biotechnology, Fuxing Shiang, Taiwan). Implant angulations were varied at 0° (0 degree), 20° to the facial (20F), and 20° to the lingual (20L) with respect to the implant crown.

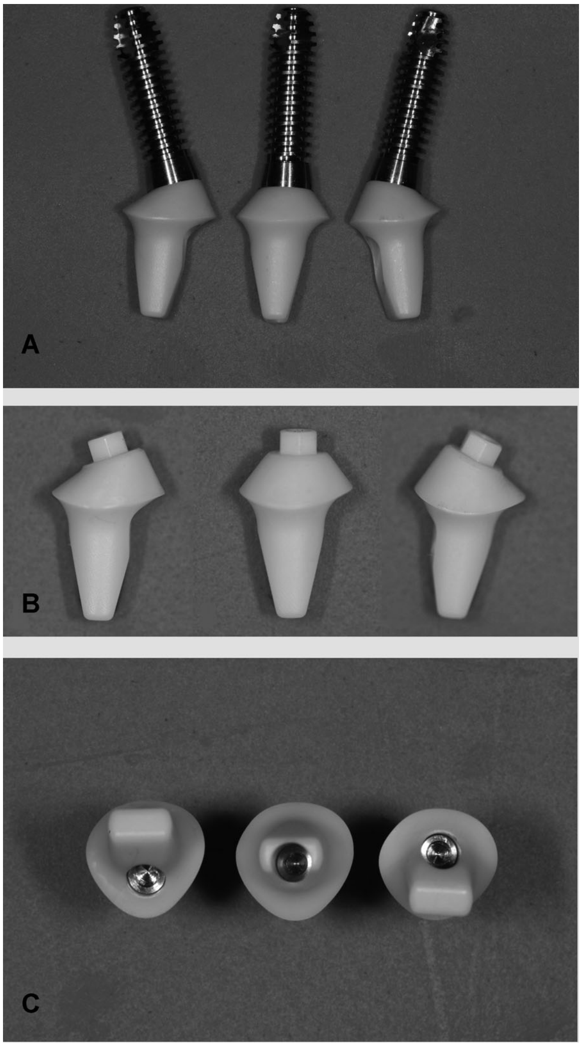

Figure 3 Customized angle corrected abutments designed to fit the constant crown contour (from left to right) 20° facial, 0°, 20° lingual (A) with analogs, (B) exhibiting connecting interface, and (C) exhibiting screw paths.

A typodont tooth #8 (Columbia Dentoform Corporation, Long Island City, NY) was scanned to facilitate CAD for the zirconia crowns (Fig 2). Crown dimensions were kept as a constant factor simulating clinical conditions where the abutment design compensates for the angle of the implant. Each crown was CAD/CAM generated to have an identical emergence profile, marginal contours, and external and internal morphology to precisely fit all the abutments in the three angulation groups in the same manner. The monolithic zirconia abutments were designed to connect the zirconia crown contours and the internal connection of an endosseous dental implant (BioHorizons 4.6 × 15 mm tapered internal; BioHorizons, Inc., Birmingham, AL) at three implant angulations (Fig 3A). The angle-corrected customized abutments from each group differed primarily in terms of emergence profile (Fig 3B) and screw hole location (Fig 3C) but were similar in terms of marginal contours and facial and lingual axial wall dimensions (Fig 3B) to fit the internal aspect of the crowns precisely.

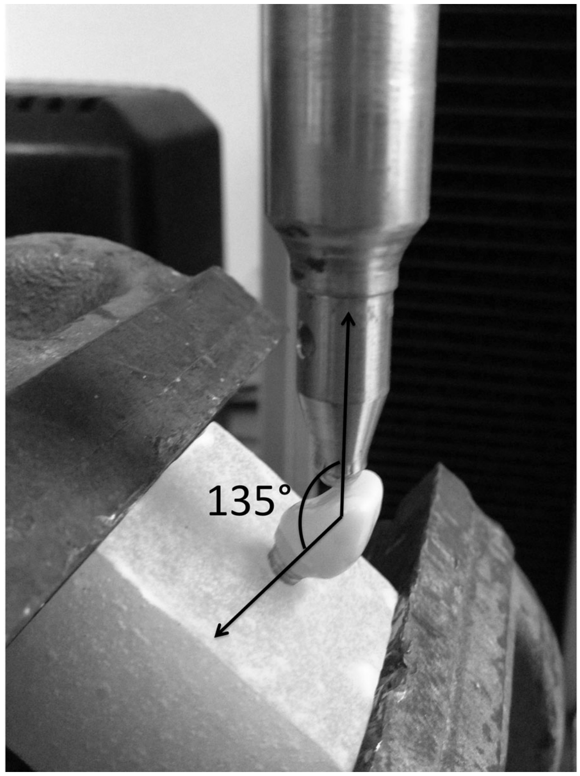

Figure 4 Indenter-crown orientation to simulate the interincisal angle of 135°.

Specimen fabrication

Once the abutments and crowns were CAD/CAM milled, the abutments were torqued into the fixture at the manufacturer's recommended torque force of 30 N-cm. Each implant was secured in a custom torquing device made out of polyether ether ketone (PEEK) in which the implant threads were predrilled to facilitate subsequent implant placement. Zirconia crowns were then cemented on each abutment under 2 kg force (19.6 N) using resin-modified glass ionomer cement (RelyX Luting Plus Cement; 3M ESPE, St. Paul, MN). Half of the implant–abutment–crown assemblies were identified for an aging treatment, which consisted of autoclaving (8 hours, 123.5°C, 2.35 bars). Subsequently, the aging treatment group specimens were thermocycled for 10,000 cycles between 5°C and 50°C, with a dwell time of 30 seconds and transfer time of 10 seconds. The other half were not treated and preserved as a control group (Table 1).

The test specimens were then secured in an aluminum holder using a custom mounting jig with polymethyl methacrylate (PMMA). The custom mounting device was designed to fit the crown contours and was used in conjunction with a modified dental surveyor to mount all the specimens with identical crown orientations.

Table 2 Summary of load to fracture (N) experimental results

Specimen number	0° group 1	20F group 2	20L group 3	0° group 4	20F group 5	20L group 6
1	130.25	143.41	123.59	103.56	243.30	130.96
2	203.90	138.25	114.27	134.15	208.81	94.03
3	214.22	129.40	107.69	176.21	290.29	114.06
4	96.93	117.93	110.75	107.76	216.44	110.39
5	114.99	107.96	108.59	107.89		122.89
6	97.47	116.28	117.76	112.52	216.44	120.89
7	164.88	126.84	162.03	120.32	233.44	129.30
8	107.36	115.05	119.35	96.42	230.15	129.92
9	159.67	119.72	111.55	129.72	239.19	105.08
10		153.16	125.90	93.45	255.05	108.14
Mean	143.30	126.80	120.15	118.20	237.01	116.57
Std. dev.	44.65	14.30	15.95	24.28	24.77	12.30

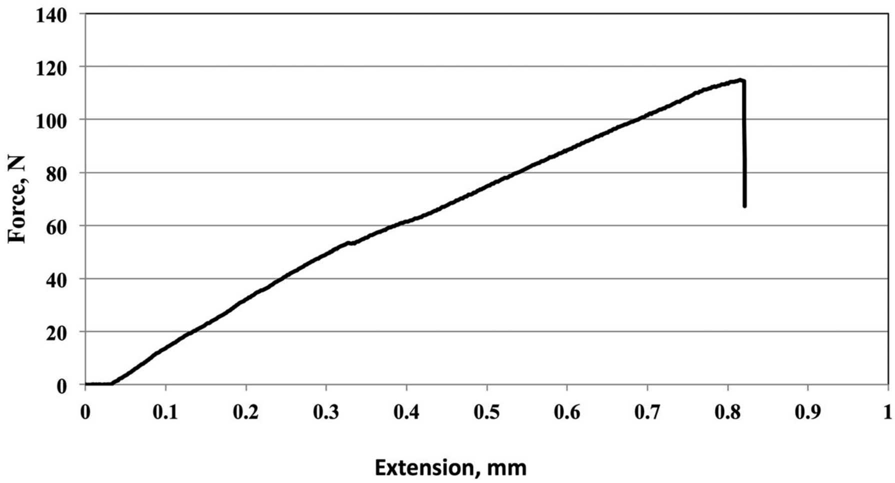

Figure 5 Typical loading curve.

Mechanical testing

For mechanical testing, specimens were oriented to provide a 135° relationship between the long axis of the simulated maxillary incisor (supported by the implant) and the mandibular incisor (the force applicator) according to well-established cephalometric interincisal relationships.[12] This was done to closely mimic the off-axis loading of the central incisor in the mouth (Fig 4). An Instron 811 Universal Testing System (Instron Corporation, Norwood, MA) was used to load the abutments to failure with a 1 mm/min crosshead speed. The force applicator was positioned 2 mm from the incisal edge. To prevent inadvertent surface damage by the loading stylus to the crown, a thin layer of mylar film (0.1 mm thickness) was inserted between the stylus and the crown prior to loading. The load cell was calibrated to zero load, and the test commenced by loading until fracture occurred as detected by an audible crack and a sudden drop in the force as seen in the graph. Force (N) and displacement (mm) were recorded via an attached computer.

Statistical analysis

Data were analyzed using a nonparametric two-factor ANOVA based on rankings, as the data were not normally distributed. Comparisons between the groups were performed with Tukey's HSD ($\alpha = 0.05$).

Results

A plot of the applied force versus distance was generated for all experimental trials. A typical loading curve is illustrated in Figure 5, and the fracture of the abutment is indicated by a sudden drop in the force value. The force value (N) at abutment fracture was determined and is listed in Table 2. In group 1, one specimen was loaded incorrectly and the experiment did not go to completion. In group 5, one specimen was aligned incorrectly. Hence these specimens were discarded from the analysis.

The mean fracture value and the standard deviation obtained for the untreated and for the treated groups are given in Table 3.

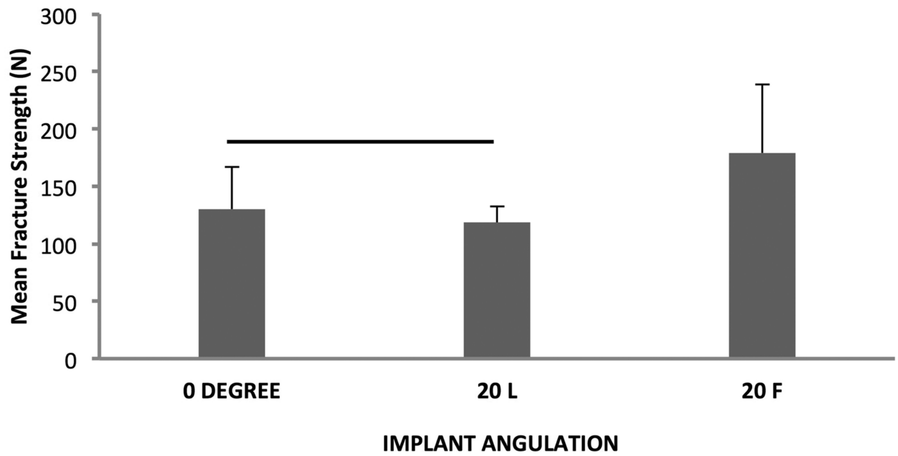

Figure 6 Mean fracture strength and standard deviation (N) for implant angulation. The horizontal line joins statistically similar groups ($\alpha = 0.05$).

Table 3 Mean fracture strength (N) based on aging treatment

	Number of specimens	Mean fracture strength	Std. dev.
Untreated	29	129.61	28.51
Treated	29	154.51	59.89

Table 4 Mean fracture strength (N) based on implant angulation

	Number of specimens	Mean fracture strength	Std. dev.
0°	19	130.07	36.71
20F	19	179.01	59.76
20L	20	118.36	13.99

The mean fracture value and the standard deviation obtained for the 0°, 20F, and 20L groups are given in Table 4 and Figure 6. The results of nonparametric two-factor ANOVA to evaluate the influence of implant angulation and aging on the fracture strength is given in Table 5.

Statistical analysis (Table 5) showed that the effect of implant angle on the fracture strength is statistically significant ($p < 0.001$). Treatment alone did not affect the fracture strength ($p = 0.207$). The higher fracture strength exhibited by 20F in group 5 is contingent upon treatment, as demonstrated by the significant first-order interaction term between treatment and angulation ($p < 0.001$). Comparison between groups (Tukey's HSD) showed that whereas the variation between 0° and 20F and between 20L and 20F were statistically significant, the variation between 0° and 20L was not statistically significant.

Fracture analysis

Three patterns of fracture were noted following testing. The first pattern (Fig 7) occurred in 93.7% of the specimens demonstrating fracture of both the hex portion and portion slightly above the platform. In 5.1% of the specimens a second facture pattern was identified where only the hex portion fractured, but the remainder of the abutment was intact. The final pattern was observed in 1.7% of the specimens with an abutment fracture slightly above the implant platform and an intact hexed component. In the specimens where the abutment fractured slightly above the implant platform, light microscopy observation at 40× magnification revealed that the fracture was single planar on the lingual side and multiplanar on the facial side (Fig 8).

Discussion

The test specimens in this study consisted of an implant–zirconia abutment–zirconia crown assembly. Care was taken to keep the abutment design as the primary variable. This was intended to eliminate all the other variables that could potentially arise from variations in the crown or implant design. The crowns and the abutments from every group were standardized in terms of material and dimensions by CAD/CAM technology. The monolithic zirconia crown was chosen to avoid veneering porcelain fracture during the loading procedure. The results of this study showed that none of the crowns fractured during the loading process.

Angulation and fracture strength

The hypothesis of this study was that varied emergence profiles and screw hole locations of the abutment produced by three implant angulations have an effect on the abutment fracture strength. The lingual dimension of the customized abutment is critical, as the lingual side is subjected to tension while the facial side is subjected to compression during occlusal loading.

1. **Screw hole location and fracture strength:** Results showed that the fracture strength and the thickness at the lingual aspect (from the middle of the screw to the external surface (Fig 3C) have an inverse relationship to each other (Table 6). This observation reveals that variation in lingual dimensions because of the varied screw hole location is not a controlling factor in the fracture

Table 5 Results for two-factor ANOVA

	DF	Sum of squares	Mean square	F	*p*	Lambda	Power
Treatment	1	286.667	286.667	1.633	0.207	1.633	0.227
Angle	2	4301.663	2150.831	12.251	$<$0.001	24.502	0.997
Treatment × angle	2	2777.979	1388.989	7.912	$<$0.001	15.823	0.955
Residual	52	9129.389	175.565				

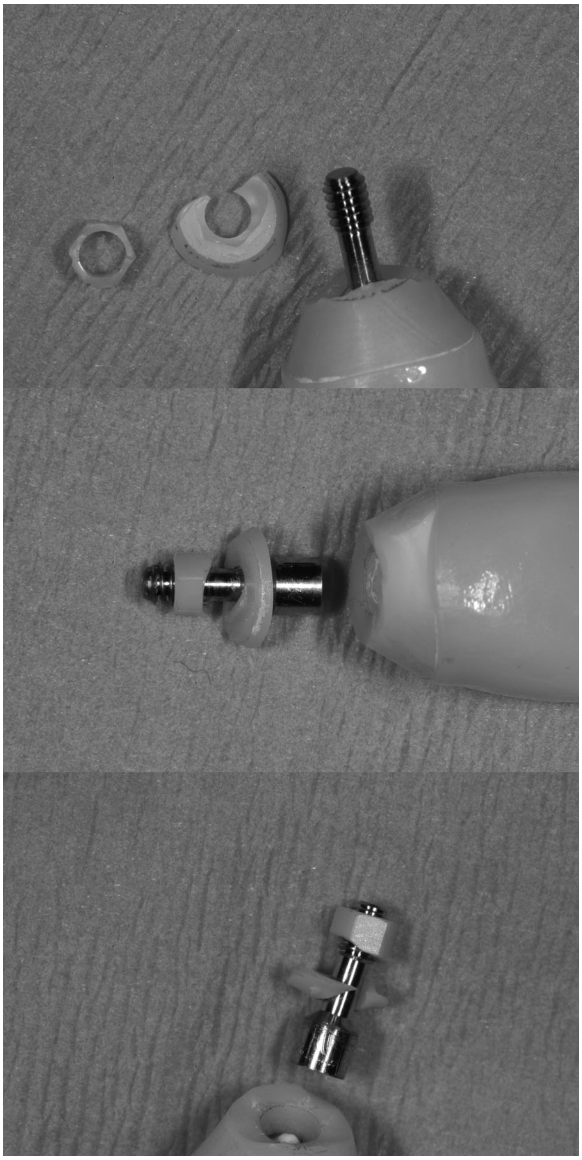

Figure 7 Multiple views of the pattern of fracture occurring in 93.2% of specimens where both hex portion and area slightly above the platform broke.

Table 6 Relationship between screw-hole location, emergence profile, and fracture strength

	20F	0°	20L
Mean fracture strength (N)	179.01	130.07	118.36
Mean thickness at the lingual aspect (from middle of the screw to external surface; mm)	1.46	2.53	2.71
Mean occluso-gingival height (mm)	3.17	2.52	2.09

strength of the abutment. This could possibly be due to the stress shielding effect of the monolithic zirconia crown covering the abutment from the effects of occlusal forces during loading.

2. **Emergence profile and fracture strength:** The effect of varied emergence profile of the abutment on the fracture strength was also examined in this study. The fracture strength values were directly proportional to the abutment dimension in the occluso-gingival aspect from the implant platform to the crown margin (Table 6). The results of this study showed that the increased occluso-gingival dimension of the abutment on the lingual side might have a positive effect on the fracture strength of the abutment.

Angulation and the resultant force vectors

The varied angulation of the implants combined with uniquely differing abutments presented a complex geometry of implant–abutment–crown assembly. It is important to observe any correlation between a particular geometry and the ability to withstand high occlusal force. Quantitative biomechanical analysis of the resultant forces to an applied 100 N occlusal force (Fig 9) revealed that when the implant apex is tilted toward the facial, as in the 20F group, the force perpendicular to the long axis of the implant (F_y) is considerably less. F_y may be considered a shearing force across the implant/abutment interface and could be critical to the initiation and propagation of fracture. This suggests the resulting geometry of the 20F group can resist more occlusal force before it fractures compared to the 0° and 20L groups. The analysis shows that for a given amount of force applied to the crown, the geometry of the 20F group allows only 42.2% of the applied occlusal force to be transmitted across the abutment/implant interface compared to 70.7% for the 0° group and 90.6% for the 20L group. These findings raise

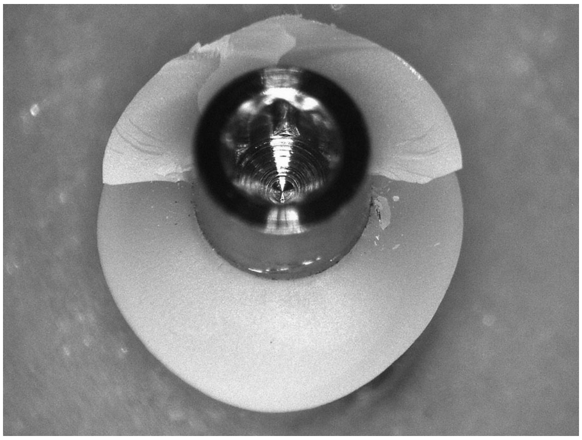

Figure 8 Multiplanar fracture on the facial side and single-planar fracture on the lingual side.

concerns, as many clinical scenarios for the maxillary anterior tend to result in an implant-to-crown angulation more similar to the 20L group due to osseous resorption and implant placement following tooth loss.

Angulation and fracture mode

The most common crack pattern was observed on the lingual aspect, which is the side subjected to tension during loading. The fracture of the zirconia abutments typically occurred at the cervical portion of the abutment, near the screw and platform of the implant. According to previous studies, this area of the abutment has been shown to have the highest torque and stress concentrations due to levering effects.[2-7] In the majority of the specimens used in this investigation, the hex portion of the abutment completely fractured, suggesting the hex as the weakest portion of the entire abutment and probable site for crack initiation. In our study, the thickness of the hex portion of the abutment was measured to be 0.14 mm. A previous study investigating the effect of thickness of zirconia on fracture strength reported that fracture strength drops significantly when the thickness is reduced beyond 0.5 to 0.7 mm.[13] Abutment designs that include a milled zirconia connection are commonly used in current clinical practice; however, a zirconia connection may have limited thickness at the hex portion at the implant/abutment interface and could be a reason for the consistent fracture at this location.

Implant abutment connection and fracture resistance

Force values measured in the anterior region of the mouth range from 90 to 370 N.[14] The mean fracture strength of an abutment obtained in this study for the 20F group was 179.01 N, 130.07 N for the 0° group, and 118.36 N for the 20L group. The mean zirconia abutment fracture resistance values recorded in this study are lower than the values (184 to 793 N) obtained in comparable studies.[2,3,5-7] This variation may be due to differences in the study designs. The connection between the implant and the abutment may be a controlling factor for the location, mode, and possible resistance to fracture of a particular abutment. Sailer et al[15] concluded that the type of connection significantly influenced the strength of zirconia abutments. The connection geometry of the implant determines the mating abutment design in terms of morphology and dimension. Therefore, the configuration of an abutment designed to fit connections such as an external-hex, internal short-bevel with a hex, or an internal long-bevel with hex results in differing thickness of zirconia at the implant interface. Nearly every currently available connection design yields excellent clinical performance with titanium base abutments; however, limitations of the monolithic zirconia abutment connection may place critically thin areas too close to the horizontal resultant forces initiating fracture as shown in this study. Studies investigating other interface designs, such as a long internal bevel,[5,7,16] suggest improved resistance to zirconia fracture when thin areas of the ceramic material are located farther from the interface. Titanium abutment bases with a custom zirconia superstructure to avoid a ceramic-to-implant interface may decrease fracture risk.[15] Additionally, critically thin areas of zirconia are more probable with narrow diameter implants.

Aging and fracture strength

Steam autoclaving was used to induce LTD to simulate the effects of aging, and thermocycling simulated the thermal changes in vivo. Steam autoclaving may induce a tetragonal-to-monoclinic (t–m) phase transformation. It was anticipated that LTD combined with the effects of low-cycle thermal fatigue from thermocycling might result in some structural deterioration of the abutment, yielding lower fracture strength for the treated group compared to the untreated group. Based on the results from this study, it was concluded that aging treatments minimally influence the fracture strength of zirconia abutments; however, under certain angulation conditions in this study design, aging did have a positive effect on the abutment fracture strength with the 20F group. This was demonstrated by the significant first-order interaction term between treatment and angulation ($p < 0.001$). LTD is a highly complex and multifactorial process. A number of studies are in agreement that the t–m phase transformation is a surface phenomenon, which has been confirmed by x-ray diffraction (XRD) analysis.[17-19] Multiple investigations of the effect of LTD on the flexural strength of zirconia agree that the surface flaws created by LTD were not significant enough to affect the flexural strength.[20-22] However, Kim et al[23] concluded that low-temperature aging affected the mechanical properties of yttria-stabilized tetragonal zirconia polycrystaline (Y-TZP) ceramics depending on the temperature applied. An applied aging temperature of 125°C for 10 hours resulted in an increased flexural strength of Y-TZP ceramics, while aging above 150°C decreased the flexural strength.[23]

Clinical significance

The model used in this study was carefully designed with zirconia crowns and zirconia abutments representing the current state of art in implant prosthodontics. The loading angle, loading point, aging treatments, and implant angulation were incorporated into the design to simulate common intraoral conditions. In designs where critically thin areas of zirconia are close to

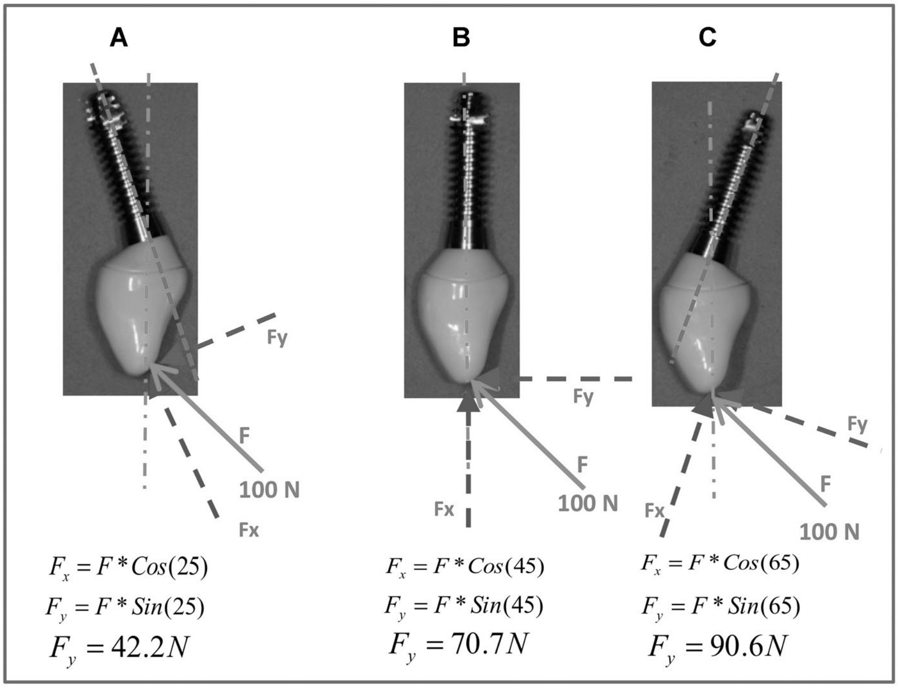

Figure 9 Influence of angulation on the resultant force vectors through the implant/abutment connection, (A) 20° facial, (B) 0°, (C) 20° lingual.

the implant interface, minimizing the risk of fracture may be desired through the use of zirconia abutments with a secondary titanium abutment base, although further investigation is warranted. The results of this study demonstrated improved resistance to fracture was obtained with increased distance from the implant platform to the gingival crown margin on the lingual side. In the anterior zone, where off-axial loading is often unavoidable due to osseous resorption, these factors must be carefully considered to reduce risk. Grafting is often a recommended treatment when there is resorption of the facial bone to decrease tilting the implant apex in the lingual direction. Finally, use of a surgical guide is suggested to optimize implant placement.

Conclusions

Within the limitations of this study, the following conclusions may be made:

1. Variation in implant angulation affected the fracture strength (force) of the zirconia abutments. When the implant apex was tilted 20° to the facial, the highest fracture strength was obtained, followed by 0° and 20° to the lingual inclinations.
2. For the aging protocol used in this study, the time, temperature, and pressure did not significantly affect the fracture strength of these zirconia abutments.
3. A mechanical analysis of the model revealed that implants with the apex titled 20° to the facial withstood higher magnitude forces (stresses) than 0° and 20° to the lingual inclinations.

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References

1. Lazzara RJ: Immediate implant placement into extraction sites: Surgical and restorative advantages. Int J Periodontics Restorative Dent 1989;9:332-343
2. Yildrium M, Fischer H, Marx R, et al: In vivo fracture resistance of implant supported all ceramic restorations. J Prosthet Dent 2009;90:325-331
3. Aramouni P, Zebouni E, Tashkandi E, et al: Fracture resistance and failure location of zirconium and metallic implant abutments. J Contemp Dent Pract 2008;9:41-48
4. Kerstein RB, Radke J: A comparison of fabrication precision and mechanical reliability of two zirconia implant abutments. Int J Oral Maxillofac Implants 2008;23:1029-1036
5. Adatia ND, Bayne SC, Cooper LF: Fracture resistance of yttria-stabilized zirconia dental implant abutments. J Prosthodont 2009;18:17-22
6. Nothdurft FP, Doppler KE, Erdelt KJ, et al: Fracture behavior of straight or angulated zirconia implant abutments supporting anterior single crowns. Clin Oral Invest 2011;15:157-163
7. Sailer I, Sailer T, Stawarczyk B, et al: 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;24:850-858

8. Wang H, Aboushelib MN, Feilzer AJ: Strength influencing variables on CAD/CAM zirconia framework. Dent Mater 2008;24:633-638
9. Turp V, Tuncelli B, Sen D, et al: Evaluation of hardness and fracture toughness, coupled with microstructural analysis of zirconia ceramics stored in environments with different pH values. Dent Mater J 2012;31:891-902
10. Kobayashi K, Kuwajima H, Masaki T: Phase change and mechanical properties of ZrO2-Y2O3 solid electrolyte after aging. Solid State Ionics 1981;3/4:489-493
11. Lughi V, Sergo V: Low temperature degradation -aging- of zirconia: a critical review of the relevant aspects in dentistry. Dent Mater 2010;26:807-820
12. Proffit WR, Fields HW, Sarver DM: Contemporary Orthodontics (ed 4). St. Louis, Mosby, 2000.
13. Aboushelib MN, Salameh Z: Zirconia implant abutment fracture: clinical case reports and precaution for use. Int J Prosthodont 2009;22:616-619
14. Paphangkorakit J, Osborn JW: The effect of pressure on a maximum incisal bite force in man. Arch Oral Biol 1997;42:11-17
15. Sailer I, Philipp A, Zembic A, et al: A systematic review of the performance of ceramic and metal implant abutments supporting fixed implant reconstructions. Clin Oral Impl Res 2009;20(Suppl.4):4-31
16. Merz BR, Hunenbart S, Belser UC: Mechanics of the implant-abutment connection: an 8-degree taper compared to a butt joint connection. Int J Oral Maxillofac Implants 2000;15:519-526
17. Ardlin BI: Transformation-toughened zirconia for dental inlays, crowns and bridges: chemical stability and effect of low-temperature aging on flexural strength and surface structure. Dent Mater 2002;18:590-595
18. Guazzato M, Albakry M, Ringer SP, et al: Strength, fracture toughness and microstructure of a selection of all ceramic materials. Part II. Zirconia based dental ceramics. Dent Mater 2004;20:449-456
19. Guazzato M, Quach L, Albakry M, et al: Influence of surface and heat treatments on the flexural strength of Y-TZP dental ceramic. J Dent 2005;33:9-18
20. Alghazzawi TF, Lemons J, Liu P-R, et al: Influence of low temperature environmental exposure on the mechanical property and structural stability of dental zirconia. J Prosthodont 2012;21:363-369
21. Shimizu K, Oka M, Kumar P, et al: Time-dependent changes in the mechanical properties of zirconia ceramic. J Biomed Mater Res 1993;27:729-734
22. Papanagiotou HP, Morgano SM, Giordano RA, et al: In vitro evaluation of low-temperature aging effects and finishing procedures on the flexural strength and structural stability of Y-TZP dental ceramics. J Prosthet Dent 2006;96:154-164
23. Kim H-T, Han J-S, Yang J-H, et al: The effect of low temperature aging on the mechanical property & phase stability of Y-TZP ceramics. J Adv Prosthodont 2009;1:113-117