Fracture Resistance of Crowns Cemented on Titanium and Zirconia Implant Abutments: A Comparison of Monolithic Versus Manually Veneered All-Ceramic Systems

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Purpose: *To evaluate the fracture resistance of all-ceramic crowns cemented on titanium and zirconia implant abutments.* ***Material and Methods:*** *Customized implant abutments for maxillary right central incisors made of titanium (Ti) and zirconia (Zr) (n = 60, n = 30 per group) were fabricated for an internal connection implant system. All-ceramic crowns were fabricated for their corresponding implant abutments using the following systems (n = 10 per group): (1) monolithic computer-aided design/computer-assisted manufacture (CAD/CAM) lithium disilicate (MLD); (2) pressed lithium disilicate (PLD); (3) yttrium stabilized tetragonal zirconia polycrystal (YTZP). The frameworks of both PLD and YTZP systems were manually veneered with a fluorapatite-based ceramic. The crowns were adhesively cemented to their implant abutments and loaded to fracture in a universal testing machine (0.5 mm/minute). Data were analyzed using two-way analysis of variance (ANOVA) and Tukey's test (α = 0.05).* ***Results:*** *Both the abutment material (P = .0001) and the ceramic crown system (P = .028) significantly affected the results. Interaction terms were not significant (P = .598). Ti-MLD (558.5 ± 35 N) showed the highest mean fracture resistance among all abutment–crown combinations (340.3 ± 62 − 495.9 ± 53 N) (P < .05). Both MLD and veneered ceramic systems in combination with Ti abutments (558.5 ± 35 − 495.9 ± 53 N) presented significantly higher values than with Zr abutments (392.9 ± 55 − 340.3 ± 62 N) (P < .05). MLD crown system showed significantly higher mean fracture resistance compared to manually veneered ones on both Ti and Zr abutments (P < .05). While Ti-MLD and Ti-PLD abutment-crown combinations failed only in the crowns without abutment fractures, Zr-YTZP combination failed exclusively in the abutment without crown fracture. Zr-MLD and Zr-PLD failed predominantly in both the abutment and the crown. Ti-YTZP showed only implant neck distortion.* ***Conclusions:*** *The highest fracture resistance was obtained with titanium abutments restored with MLD crowns, but the failure type was more favorable with Ti-YTZP combination.* INT J ORAL MAXILLOFAC IMPLANTS 2012;27:1448–1455

Key words: *CAD/CAM, lithium disilicate, monolithic crowns, pressed ceramics, titanium, YTZP*

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Restoration of missing teeth in dentistry can be achieved with a variety of treatment options. In particular, restoration of the esthetic zone remains a challenge for clinicians. Although the least minimally invasive option is the application of resin-bonded fixed dental prostheses (FDP), their long-term survival rate is not predictable.[1,2] On the other hand, the conventional full-coverage FDP requires the preparation of abutments that result in more tissue loss.

Clinical efficacy of osseointegrated implants for single-tooth replacement has been well documented.[3–5] Several studies have demonstrated a high incidence of prosthetic complications associated with FDPs supported by implants such as screw or abutment loosening, screw or abutment fracture, or fractures in the framework or veneer parts of the FDPs.[6–10]

Implant abutments are usually fabricated from commercially pure titanium due to its well-documented biocompatibility and mechanical properties.[11] Clinical studies demonstrated excellent survival rates for fixed implant reconstructions supported by titanium abutments.[10,12] Despite the numerous improvements in the fabrication and design of titanium abutments, their metallic color may still shine through the mucosa, impairing the esthetic outcome. Even when placed subgingivally, a dull gray background may give the soft tissue an unnatural bluish appearance. The presence of a gray gingival discoloration may also be partially attributed to a thin gingival tissue thickness around the abutment that is incapable of blocking reflective light from the metal abutment surface.[13,14] Hence, although they are very stable from a biomechanical point of view, titanium abutments have limitations in esthetically delicate areas.

Especially in the anterior zone, the success of single-implant therapy is dictated by a number of factors that involve the appearance of the peri-implant soft tissues.[15] The harmony of the crown-implant complex in terms of color and form with the mucosa and neighboring teeth is essential. In that respect, tooth-colored ceramic abutments such as yttrium tetragonal zirconia polycrystals (hereon, zirconia) have been proposed as an alternative material to titanium abutments. Zirconia has superior mechanical properties, presenting fracture resistance as high as 900 to 1,200 MPa.[16] Zirconia abutments not only induce significantly less mucosal discoloration than metal abutments,[13] but also yield to less bacterial adhesion than titanium.[17] Moreover, the soft tissue integration of zirconia was found to be similar to that of titanium.[11,12] However, not only implant abutments but also implant restoration materials should be considered during prosthetic treatment planning. Metal-ceramic FDPs are commonly indicated for implant-supported reconstructions. Since dental implants do not have periodontal ligament (PDL) interposed between the bone and implant surface that eliminates the special proprioceptive nerve endings, the sensitivity and mobility of natural dentition cannot be duplicated in endosseous implants.[18] Therefore, in the absence of a neurosensory mechanism that adequately compensates for the PDL proprioception and compressibility, the stability of the prosthesis-implant complex is impaired resulting in FPD complications.

Recent developments in high strength ceramic materials and manufacturing techniques try to fulfill the expectations from both optical and biomechanical perspectives on implant reconstructions.[19] Among the many options, in the late 1990s, lithium disilicate glass-ceramics (SiO_2 - Li_2O) was introduced to dentistry as a framework material. Its flexural strength ranges between 300 and 400 MPa and its fracture toughness between 2.8 and 3.5 MPa/m$^{1/2}$.[20] Lithium disilicate glass ceramics could be typically fabricated through a combination of the lost-wax and heat-pressed techniques or milled with computer-aided design/computer-assisted manufacture (CAD/CAM) systems and used for the same indications. Using this material in conjunction with the pressed technique allows the dental technician to achieve better morphology and eliminate the purchase of CAD/CAM devices. Because of its high strength, this material offers versatile applications and can be used for the fabrication of monolithic crowns (chairside or labside) with subsequent staining and characterization. With lithium disilicate glass ceramics, limited information is available on artificial dies[21] but no information is present on implants. In fact, one clinical study reported a 93% survival rate of three-unit FDPs using pressed lithium disilicate glass-ceramics up to 8 years[22] but the survival of such ceramics on implant abutments is not known. Also, one of the most significant advances in this field has been the introduction of zirconia as a framework material that can be processed using CAD/CAM techniques. Compared to other all-ceramic systems, zirconia exhibits superior mechanical properties, owing to the transformation toughening mechanism.[23]

Since the fracture resistance of lithium disilicate glass-ceramics is in general less than zirconia, higher fracture resistance could be anticipated with the latter on implant abutments. On the other hand, due to a delamination problem related to bilayered ceramic structures, monolithic ones are considered proper alternatives. Due to the ductility of metals, bending resistance could compensate for the fracture of the ceramic restoration. Thus, less fracture resistance could be expected from zirconia abutment–ceramic compared with titanium abutment–ceramic crown combinations.

The objectives of the present study were therefore to evaluate *(1)* the fracture resistance of titanium and zirconia implant abutments restored with monolithic CAD/CAM lithium disilicate, manually veneered pressable lithium disilicate, and manually venered zirconia all-ceramic crowns, and *(2)* to identify the failure types. The tested hypotheses were that fracture resistance of crowns on titanium abutments would be higher than for the zirconia abutments, and that zirconia crowns would be more fracture resistant than lithium disilicate crowns.

MATERIALS AND METHODS

Sample Preparation

Sixty internal connection implants with a diameter of 4.1 mm and length of 12 mm (Straumann Standard Plus Implant) were obtained for this study. A clinical case was selected for the design of the master abutment with a height of 7 mm and taper of 6 degrees. This abutment was digitally designed for the patient's situation

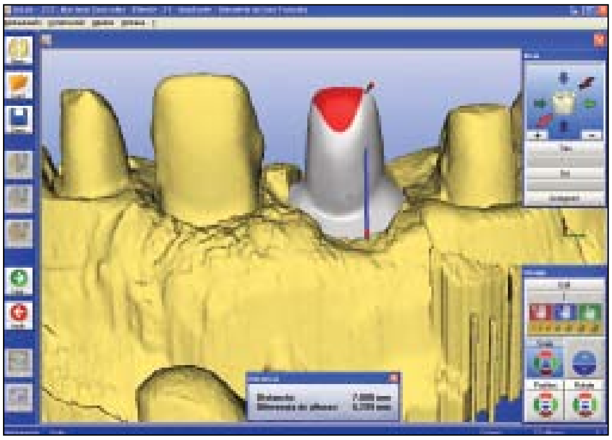


Fig 1 The digital design of the master abutment for the maxillary right central incisor using three-dimensional abutment fabrication software.

using three-dimensional abutment fabrication software (inLab 3D for Abutments, version 3.80, Sirona Dental Systems) (Fig 1).

The data generated were sent to the Straumann production center in Markkleeberg, Germany, for the construction of two groups of identical customized abutments (n = 60, 30 per abutment type), namely zirconia abutments (Straumann CARES Abutment Ceramic, Straumann) and titanium abutments (Straumann CARES Abutment Titanium, Straumann) (Fig 2).

The abutments were randomly divided into three subgroups (n = 10 per group) for the fabrication of all-ceramic crowns using the following systems: *(1)* monolithic CAD/CAM lithium disilicate (MLD; IPS e.max CAD, Ivoclar Vivadent); *(2)* heat-pressed lithium disilicate (PLD; IPS e.max Press); and *(3)* yttrium stabilized tetragonal zirconia polycrystal (YTZP; IPS e.max ZirCAD). Standardized maxillary central incisor crowns (height, 11 mm; mesiodistal width, 8.5 mm; wall thickness, 2 mm) were fabricated with the help of a silicone index. All ceramic crowns were fabricated according to their manufacturer's recommendations by one experienced dental technician.

Fully anatomically shaped MLD and YTZP frameworks were designed and milled with a CAD/CAM system (CEREC InLab, Sirona Dental Systems) from presintered blocks. After the milling procedure, MLD crowns and YTZP frameworks were sintered according to the manufacturer's guidelines. PLD frameworks (thickness, 0.6 mm) were fabricated using the heat-pressing technique. YTZP and PLD frameworks were then veneered manually using a fluorapatite veneering ceramic (IPS e.max Ceram, Ivoclar Vivadent).

Thereafter, all implants were embedded in special specimen holders using epoxy resin (Epoxicure Resin, Buehler) with 3 mm of vertical distance from the most coronal bone-to-implant border to the top of the holder, simulating vertical bone resorption of 3 mm according to ISO Norm 14801.[24] The implants were placed in the center of the specimen holders and at an angle of 90 degrees to the horizontal plane. The embedding resin had a modulus of elasticity of approximately 12 GPa, which approximates that of human bone (18 GPa).[25] While the zirconia abutments were connected to the implants using secondary titanium abutments (SynOcta 1.5 mm, Straumann), the titanium abutments were directly connected to the implants. All abutments were torqued to 35 Ncm according to the manufacturer's recommendation using a torque control system (no. 046.049 Straumann). The screw cavities were filled with polytetrafluoroethylene (PTFE) tape and provisional restorative material (Fermit N, Ivoclar Vivadent).

To ensure maximum adhesion between the all-ceramic crowns and the abutments, the abutment surfaces of all groups and the inner surfaces of the zirconia crowns were air-abraded with Al_2O_3 particles (100 µm, 1 bar). The inner surfaces of lithium disilicate crowns were etched with 4.5% hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar Vivadent) for 20 seconds and rinsed thoroughly. Bonding areas of abutments and crowns were silanized (Monobond Plus, Ivoclar Vivadent) and the crowns were cemented using adhesive resin cement (Multilink Implant, Ivoclar Vivadent) according to the manufacturer's instructions. Finally, the restorations were stored at 37°C for 48 hours until testing.

Fracture Resistance Measurement and Failure Type Analysis

All specimens were mounted in a steel holder at an angle of 30 degrees in relation to the loading cell in the universal testing machine (Shimadzu AG-X Series, Shimadzu) (Fig 3). A piece of tin foil with a thickness of 0.5 mm was applied on the crowns. With this procedure, an even distribution of the load was achieved until fracture or deformation occurred. The load was applied at a crosshead speed of 0.5 mm/minute at the incisal edge according to ISO Norm 14801.[24] The fracture load was registered as soon as fracture load decreased by 10% of the maximum load (Fmax). The fracture load was noted in Newton (N) calculated by the specific software (Trapezium X Software, Shimadzu).

After fracture resistance tests, the failure types were observed by two operators and categorized as follows: Score 1, complete crown fracture without abutment fracture; Score 2, only abutment fracture without any destruction in the crown; Score 3, screw fracture; Score 4, crown and abutment fracture; and Score 5, implant neck distortion.

Fig 2 Customized titanium and zirconia abutments for the maxillary right central incisor with identical dimension.

Fig 3 Representative photo of an implant with its abutment and the cemented crown mounted in the holder at the universal testing machine at an angle of 30 degrees in relation to the loading cell. To ensure an even distribution of the static forces, a tin foil (thickness, 0.5 mm) was placed on the crowns.

Table 1 Results of Two-way ANOVA (α = 0.05)

Effect	df	Sum of squares	Mean square	F	*P*
Abutments	1	194011.1	194011.1	65.1	.0001*
All-ceramic crowns	2	23767.4	11883.7	3.9	.028*
Interaction	2	3110.9	1555.4	0.5	.598
Residue	54	101225.5	2977.2		
Total	59	350125.6			

Statistical Analysis

Statistical analysis was performed using SPSS 14.0 software for Windows (IBM). The data were submitted to two-way analysis of variance (ANOVA) with the fracture resistance as the dependent variable and the abutment type (two levels) and all-ceramic crown material (three levels) as independent variables. Multiple comparisons were made using Tukey's post hoc test. *P* values < .05 were considered to be statistically significant in all tests.

RESULTS

Both the abutment material (P = .0001) and the all-ceramic crown system (P = .028) significantly affected the results. Interaction terms were not significant (P = .598) (Table 1).

Ti-MLD (558.5 ± 35 N) showed the highest mean fracture resistance among all abutment–crown combinations (340.3 ± 62 – 495.9 ± 53 N) (P < .05) (Table 2, Fig 4). Both monolithic and veneered ceramic systems in com-

Table 2 Mean (Standard Deviation) Fracture Resistance Values (N) Recorded for the Experimental Groups

	All-ceramic crown type		
Abutment type	Monolithic CAD/CAM lithium disilicate (MLD)	Manually veneered pressable lithium disilicate (PLD)	Manually veneered zirconia (YTZP)
Titanium (Ti)	558.5 (35.2)[a]	482.2 (58.4)[b]	495.9 (53.4)[c]
Zirconia (Zr)	392.9 (55.3)[d]	363.0 (50.5)[e]	340.3 (61.8)[e]

*Same superscripts do not show significant differences in the column and row ($P < .05$).

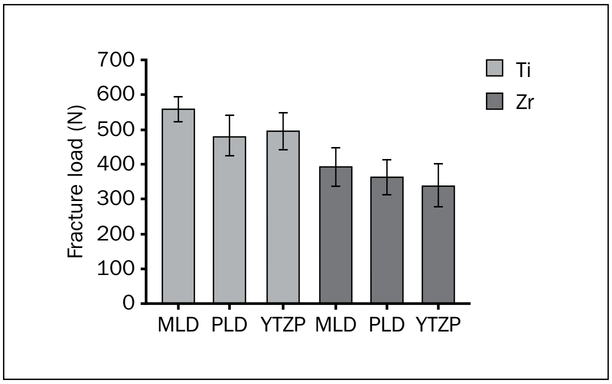


Fig 4 Mean fracture resistance (N) and standard deviations of all experimental groups.

bination with Ti abutments (558.5 ± 35 – 495.9 ± 53 N) presented significantly higher values than with Zr abutments (392.9 ± 55 - 340.3 ± 62 N) ($P < .05$). MLD crown system showed significantly higher mean fracture resistance compared to manually veneered ones on both Ti and Zr abutments ($P < .05$).

While Ti-MLD and Ti-PLD abutment–crown combinations failed only in the crowns without abutment fractures, Zr-YTZP combination failed exclusively in the abutment without crown fracture (Table 3). Zr-MLD and Zr-PLD failed predominantly in both the abutment and the crown. Ti-YTZP showed neither crown nor abutment fracture where only implant neck distortion was observed. In none of the samples was screw fracture observed.

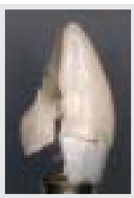
DISCUSSION

This study evaluated the fracture resistance of titanium and zirconia implant abutments restored with monolithic CAD/CAM lithium disilicate, manually veneered pressable lithium disilicate, and manually venered zirconia all-ceramic crowns. The results showed significantly higher fracture resistance values for all types of all-ceramic crown systems when they were cemented on the titanium abutments. Thus, the first hypothesis could be accepted. Since the mean fracture resistance of the monolithic lithium disilicate all-ceramic crowns presented significantly higher results compared to the veneered lithium disilicate and zirconia ceramic systems, the second tested hypothesis was rejected.

The critical load of implanted-supported ceramic and metal abutments restored with all-ceramic crowns has been evaluated in previous studies, with the results ranging between 170 N and 1454 N.[26–35] Yildirim et al[27] investigated the fracture resistance of leucite reinforced heat-pressed glass ceramic (IPS Empress 1, Ivoclar Vivadent) crowns adhesively cemented on alumina and zirconia abutments on the external connection implants. Similar to the present study, in that study no artificial aging was practiced. The results showed significant differences between the mean fracture load of crowns cemented on alumina abutments (280 N) and those cemented on zirconia abutments (737 N). Although stronger ceramic systems were used compared to leucite reinforced ceramic, the mean fracture resistance of all-ceramic systems on zirconia abutments (340 to 393 N) in the present investigation was lower than those reported by Yildirim et al.[27] This might be due to differences in the testing protocols. In this study, the implants were embedded in the epoxy resin molds simulating vertical bone loss of 3 mm, according to ISO Norm 14801,[24] whereas in the former investigation,[27] the implants were embedded in autopolymerizing composite up to the implant shoulder. Consequently, the loads applied in these two studies might have caused different lever arms. Furthermore, different to that study where external connection implants were used, in the present study internal connection implants with a neck height of 1.8 mm were used, possibly further increasing the bending moment.

The embedding parameters simulating vertical bone loss of 3 mm described in ISO Norm 14801[24] represents the worse-case scenario. In fact, marginal bone level can move apically following implantation to a relatively steady-state level in clinical practice, marginal bone loss > 3 mm are fortunately rare.[36] Therefore, this simulated bone loss can be considered excessive as it exposes the implant threads, making it more susceptible to early failure. It is possible that the results would have been different in this study if the implants had been placed at the nominal bone level, which requires further investigation.

Table 3 Distribution of Failure Types after Fracture Resistance Test

Failure types		Experimental groups Ti-MLD	Ti-PLD	Ti-YTZP	Zr-MLD	Zr-PLD	Zr-YTZP
Score 1		10	10	0	0	0	0
Score 2		0	0	0	0	1	10
Score 3		0	0	0	0	0	0
Score 4		0	0	0	10	9	0
Score 5		0	0	10	0	0	0

Score 1 = complete crown fracture without abutment fracture; Score 2 = only abutment fracture without any destruction in the crown; Score 3 = screw fracture; Score 4 = crown and abutment fracture; Score 5 = implant neck distortion.

In another study[34] with similar testing conditions and the abutments (CARES), milled leucite reinforced glass-ceramic crowns adhesively cemented on zirconia abutments presented a mean fracture resistance value (283 N) lower than that reported by Yildirim et al.[27] Since stronger ceramics were used in the present study, the results were higher than that investigation.[34]

Sundh and Sjögren[32] evaluated the bending resistance of implant-supported titanium and zirconia abutments restored with all-ceramic copings. They reported that the bending resistance of the magnesia and yttrium stabilized zirconia ceramic specimens was equal or superior to that of the titanium control (> 300 N). These results are not in accordance with the present findings. The difference may be due to the mode of load application. In the present investigation, the fracture load was applied at 30 degrees to the long axis of the implants, whereas in the former study, the load was applied perpendicular to the long axis of the specimens by means of a chisel-shaped steel blade, which probably aggravated the stress on the coping-implant assembly. Since the tests were performed on copings only, the lack of anatomical restoration might have also contributed to the differences between the two studies. According to Cho et al,[26] under vertical loading, the fracture resistance of restorations on titanium abutments was almost twice that of those on ceramic abutments. However, under oblique loading (45 degrees) no statistically significant differences in fracture resistance were seen between the restorations on titanium and ceramic abutments.[26]

In the present investigation, no artificial aging or dynamic loading was applied to the test specimens that could be considered as the limitation of the study. Dynamic loading might lead to crack propagation in the ceramics and if it were involved, it could have affected the outcome of the study or ranking of the materials tested. Therefore, the results in its current form could represent possible early clinical failures that may result not as a consequence of fatigue. Cyclic loading or thermo-mechanical fatigue conditions could reduce the fracture resistance of zirconia implant abutments significantly. Gehrke et al[30] reported decreased strength of zirconia abutments from 672 N without cyclic loading, to less than 405 N after 5,000,000 cyclic loading. In two other studies, the static fracture resistance of different implant-supported all-ceramic restorations was tested after chewing simulation.[28,29] Ninety-six implants with an internal connection design received titanium, alumina, and zirconia abutments. All abutments were restored with alumina and zirconia all-ceramic crowns. The specimens were exposed to 1,200,000 cycles in a chewing simulator to simulate 5 years of clinical service. The median fracture loads after aging were 1251 N and 457 N for titanium abutment-zirconia crown and zirconia abutment-zirconia crown combinations, respectively. Although specimens in the present study were not aged, the results were surprisingly lower than those obtained by Att et al.[28,29] Theoretically, the aging effect through environmental stresses could alter the metastable tetragonal crystalline phase of the YTZP-based ceramics. The consequences of this process are multiple and include surface degradation with grain pullout and microcracking and degradation in strength. Long-term exposure of zirconia ceramics to humidity and thermal cycling leads to a low-temperature degradation (LTD) of the material.[23] However, there is controversy over whether this would lead to a reduction in the fracture resistance of zirconia. Although it may be speculated that no water could seep into the implant body during chewing simulation,[35] the presence of water is necessary to initiate the LTD. Therefore, even though no aging was practiced in this study, the lower results may be explained on the grounds that in the above mentioned studies, the implants were placed at the nominal bone level. In the present study, the vertical bone loss of 3 mm together with the 1.8 mm implant neck resulted in the bone level almost 4.8 mm below the upper implant shoulder. All this makes a direct comparison difficult between studies on fracture resistance of implant supported reconstructions. Future studies should suggest some more standardization.

The fracture resistance results should also be coupled with the failure type analysis. The failure types were fairly uniform in each group. When monolithic or manually veneered lithium disilicate crowns were used on titanium abutments, only the crowns fractured. In bilayered ceramic structures, veneering ceramic is expected to fracture more frequent than the monolithic ones.[37] However, the exclusive crown fracture failure type in the monolithic crowns cemented on titanium abutments indicates that these ceramics do not present advantages over bilayered ones even though the highest mean fracture resistance value was obtained with this ceramic. Due to lower load-bearing capacity of glass-ceramics than titanium, lithium disilicate crowns were identified as the weakest components in abutment-crown assemblies. From the clinical point of view, using glass-ceramic crowns on titanium abutments may not fulfil the esthetic requirements in the anterior region. Hence, the performance of lithium disilicate crowns on zirconia abutments may be of more relevance. In these groups, unfortunately both the crowns and their corresponding abutments showed fractures.

Among all testing groups, manually veneered zirconia on zirconia abutments failed exclusively in the abutments without any destruction in the crowns. The esthetic outcome would probably be better with zirconia abutments in combination with zirconia crowns. However, this failure type also indicates that the risk of zirconia abutment damage is more likely to occur. Interestingly, the same manually veneered zirconia crowns did not demonstrate any crown fractures on titanium abutments. In this group, no fractures of the crowns and the abutments but only implant neck distortions were observed. Since the translucency of zirconia ceramics are less than that of lithium disilicate ceramics, esthetic outcome on titanium abutments may be perhaps not perfect, but acceptable. Therefore, considering both the fracture resistance values and failure types, the most stable abutment-ceramic crown combination seem to be manually veneered zirconia on titanium abutments.

It is not always possible to extrapolate the findings of in vitro studies to clinical situations since the stresses and strains of dental restorations in vivo are complex. However, with the increasing number of implants, abutments, and ceramic systems in the dental market, in vitro studies may help ranking material combinations before they are experimented clinically. The tests were performed only in maxillary central incisors and the results may vary in posterior teeth due to morphological differences. Early and long-term clinical failure types in implant dentistry should be reported in more detail in order to verify the findings of in vitro studies.

CONCLUSION

Based on the results of the present study, overall titanium abutments showed better durability than zirconia abutments. Titanium abutments restored with monolithic lithium disilicate crowns presented the highest fracture resistance with complete crown fractures without abutment fractures. Titanium abutment–manually veneered zirconia crown combinations presented no crown fracture but only implant neck distortion.

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