Influence of Preparation and Wall Thickness on the Resistance to Fracture of Zirconia Implant Abutments

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ABSTRACT

Background: Studies about the effect of grinding procedures as well as material thickness on the resistance of zirconia implant abutments are in short supply.

Purpose: This study evaluated the effect of wall thickness as well as preparation on the resistance of zirconia implant abutments.

Materials and Method: Sixty-four implants received titanium (group Ti) and zirconia abutments (groups Zr-8, Zr-18, and Zr-1). The abutments of group Zr-8 had a 0.8-mm wall thickness, whereas the wall thickness of group Zr-18 was reduced by preparation from 1 mm to 0.8 mm. The abutments of group Zr-1 had a wall thickness of 1 mm. Standardized maxillary central incisor metal crowns were cemented on all abutments. All specimens were then tested in a universal testing machine for their resistance to fracture before and after masticatory simulation ($n = 8$).

Results: The median resistance to fracture values (N) before and after aging were, respectively: group Ti: 500–504; group Zr-8: 487–491; group Zr-18: 490-451; and group Zr-1: 519-480. No significant effects of group, aging, or combinations were found ($p > .05$).

Conclusion: All tested abutments have the potential to withstand physiologic occlusal forces in the anterior region (>200 N). The applicability of the results to other implant systems should be verified.

KEY WORDS: ceramic abutments, dental implant, fatigue, wall thickness preparation, zirconia

INTRODUCTION

The use of dental implants has become a routine procedure for the replacement of missing teeth. In addition to completely and partially edentulous arches, the indication range of dental implants encompasses the replacement of single missing teeth. The clinical outcome of single implants ranges between 96% and 94% after observation periods between 5 and 6 years, respectively.[1] As for the restorations, the 5-year survival rate of implant-supported crowns has been reported to be 95.4% for metal-ceramic crowns and 91.2% for all-ceramic crowns.[2,3]

In esthetically demanding anterior regions, restoring a single missing tooth with an implant-supported crown is challenging.[2,4,5] The success depends not only on intact osseointegration and on the implant having a functional load-bearing capacity but also on a harmonious and esthetic integration of the crown into the dental arch.[5] Implant-supported single-tooth restorations are subjected, especially in patients with a gummy smile or a high lip line, to direct visual comparison with the adjacent natural teeth. Therefore, optimal implant positioning and superstructure design are prerequisites for achieving optimal esthetic integration of the

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implant-restoration component.[2,5,6] Conventionally, dental implants and abutments are usually being fabricated out of commercially pure titanium or titanium alloy because of its well-documented biocompatibility and mechanical properties.[1,6] Despite the abundant number of modifications and improvements in the design and fabrication of metal abutments, there is still, however, the risk of metallic components showing through when such abutments are used.[6,7] Even when placed subgingivally, a dull grayish background may give the soft tissue an unnatural bluish appearance. The appearance of a gray gingival discoloration may be attributed to a thin gingival biotype that incapable of blocking reflective light from the metallic abutment surface.[6,8,9] To overcome this problem and improve the mucogingival esthetics, ceramic abutments were developed.[10,11]

Today, the majority of implant manufacturers offer zirconia abutments for implant-supported restorations in esthetically delicate areas. Zirconia abutments are available in prefabricated or customized form and can be prepared in the dental laboratory either by the technician or by utilizing computer aided design/computer aided manufacturing (CAD/CAM) techniques. Zirconia abutments are successors to the densely sintered high-purity alumina (Al_2O_3) abutments. Compared with the latter, zirconia abutments are radiopaque and demonstrate significantly higher resistance to fracture property.[6] As an abutment material, the biocompatibility of zirconia toward soft connective and epithelial tissue is similar to that of titanium.[6,12,13] To determine the biocompatibility or interactions at the biomaterial-tissue interface, in vitro studies using cell cultures have been carried out.[14] It is well known today that zirconia, as well as other ceramics, is highly biocompatible and is less prone to plaque accumulation than metal substrates.[15–17] Clinical studies about zirconia abutments have depicted survival rate of 100% after observation periods between 6 months and 4 years.[13] Despite encouraging short-term results, there is a need for long-term clinical data about the outcome of zirconia abutments.

In addition to the optical properties and biocompatibility, it is commonly agreed that ceramic abutments should show proper resistance against masticatory forces raised during chewing or swallowing.[18,19] Generally, the clinical application of prefabricated zirconia abutments necessitates grinding procedures and in many cases requires a reduction in wall thickness. Consequently, it should be expected that the resistance of prepared zirconia abutments might be different than that of unprepared ones. Ceramics have a universal shortcoming in the mechanical property, as they are brittle and, therefore, less resistant against tensile forces. The reduction in the material's bulk thickness as well as the existence of surface and bulk microstructural defects may lead to crack formation and jeopardize the overall stability of the material. Unfortunately, the current literature does not provide information about this issue. Hence, there is a need to explore the effect of grinding procedures on the resistance of zirconia abutments as well as to define a minimal wall thickness that guarantees long-term stability. The purpose of this study was to evaluate the effect of wall thickness as well as preparation procedure on the resistance to fracture of zirconia implant abutments.

MATERIALS AND METHODS

Sixty-four implants with a diameter of 4 mm and a length of 13 mm (Nobel Replace Straight Groovy, Nobel Biocare, AB, Göteborg, Sweden) were used in this study. The implants were divided into four groups of 16 specimens each. Implants of Ti received 16 CAD/CAM titanium abutments (NobelProcera™ Titanium RP, Nobel Biocare AB), whereas implants of Zr (Zr-8, Zr-18, and Zr-1) received 16 CAD/CAM zirconia abutments with different wall thickness (NobelProcera Zirconia RP, Nobel Biocare AB). Group Zr-8 received zirconia abutments with a wall thickness of 0.8 mm. Group Zr-18 received zirconia abutments that were prepared from 1 mm to 0.8 mm wall thickness. Group Zr-1 received zirconia abutments with a 1-mm wall thickness. Regardless of the wall thickness, the abutments of all groups had standard dimensions: a deep chamfer finish line of 0.5-mm depth and a total height of 9.5 mm with a clinical height of 7 mm and a gingival height of 2.5 mm (Figure 1). The fabrication of the abutments was made by a wax-up of two reference abutments according to the above-mentioned dimensions using a light-cured resin (Visio™-FORM, 3 M ESPE, Seefeld, Germany). The first abutment, representing abutments of the control group (Ti) as well as of group Zr-8, had a wall thickness of 0.8 mm. The second abutment, representing groups Zr-1 and Zr-18, had a wall thickness of 1 mm. The dimensions of the abutments were controlled using a precise thickness-measuring device (Digitmatic Micrometer, Mitsutoyo, Hama-matsu, Japan). Then, the

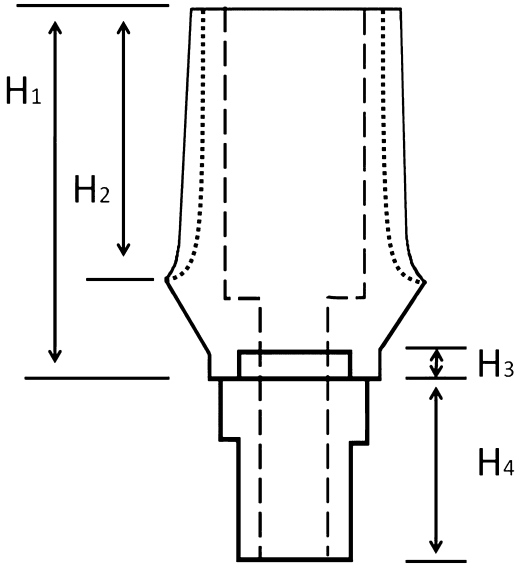

Figure 1 A schematic drawing of the abutment configuration of different groups (abutment height [H1]: 9.5 mm, clinical height [H2]: 7 mm, height of metal basis [H3]: 1 mm, height of intra-implant portion [H4]: 3.75 mm). Dotted line denotes the reduction of wall thickness from original abutment size in group Zr-18. Zr = zirconia.

wax-ups of the abutments were scanned using a mechanical scanner that operates by surface detection (Procera Forte™, Nobel Biocare AB). The digital data were visualized (CAD) using the software Procera (Procera CADDesign V2.0, Nobel Biocare AB). Afterward, the data were sent via the software upload interface to the Procera Sandvik AB server (Nobel Biocare AB), where the fabrication of the titanium and zirconia abutments took place. After delivery, all abutments of the test and control group(s) were placed on the implants using titanium screws (Nobel Biocare AB) and torqued to 35 Ncm according to the manufacturer's recommendation using the torque control system (Torque Tite, Nobel Biocare AB). After 1 minute, the aforementioned procedure was repeated to ensure proper tightening of the implant-abutment component. For group Zr-18, the wall thickness of all abutments was reduced from 1 mm to 0.8 mm by means of preparation using diamond rotary instruments (Set. no. 4432, Gebr. Brasseler, Lemgo, Germany) with water spray application and the help of a silicon index (Twinduo, Picodent, Wipperfürth, Germany) as well as the precise thickness-measuring device (Digitmatic Micrometer, Mitsutoyo) (see Figure 1). Sixty-four standardized maxillary central incisor crowns with a height of 11 mm and a width of 8 mm were fabricated out of a chromium-cobalt alloy (Dentitan, Krupp Medizintechnik, Essen, Germany) using a silicone index (Figure 2). Afterward, all implants were embedded with autopolymerizing acrylic resin (Technovit 4000, Heraues Kulzer, Wehrheim, Germany) at an angle of 130° to the horizontal plane to simulate clinical conditions. The resin has a modulus of elasticity of approximately 12 GPa that approximates that of human bone (18 GPa).

Before definitive placement, the inner surfaces of the crowns as well as the abutments were cleaned using 70% isopropanol. Then, all crowns were definitively placed on the abutments with finger pressure using a resin-luting cement (Panavia 21, Kuraray, Tokyo, Japan).

Half of specimens of each group were exposed to 1,200,000 cycles of thermomechanical fatigue in a computer-controlled dual-axis chewing simulator (Willytech, Munich, Germany) to simulate 5 years of clinical function. The force was applied 3 mm below the incisal edge on the palatal aspect of the crown at a frequency of 1.6 Hz using a ceramic ball with a 6-mm diameter (Steatite Hoechst Ceram Tec, Wunsiedel, Germany). The ceramic ball has a Vickers hardness that is similar to that of enamel. A force of 49 N was chosen to simulate a load within the clinical range. During testing, all specimens were subjected to simultaneous thermal cycling between 5°C and 55°C for 60 seconds each, with an intermediate pause of 12 seconds, maintained by a thermostatically controlled liquid circulator (Haake, Karlsruhe, Germany).

Afterward, all specimens were loaded compressively in a universal testing machine (Z010/TN2S, Zwick, Ulm, Germany) with force application at an angle of 130° to

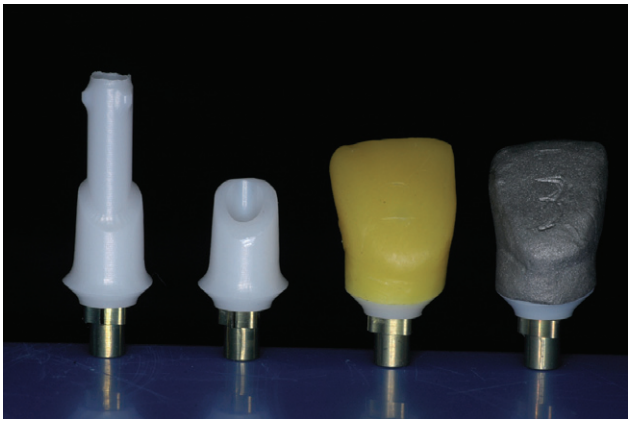

Figure 2 A representative image of a test specimen (group Zr-1). A standardized wax-up of a maxillary central incisor was used to fabricate nonprecious metal crowns. Zr = zirconia.

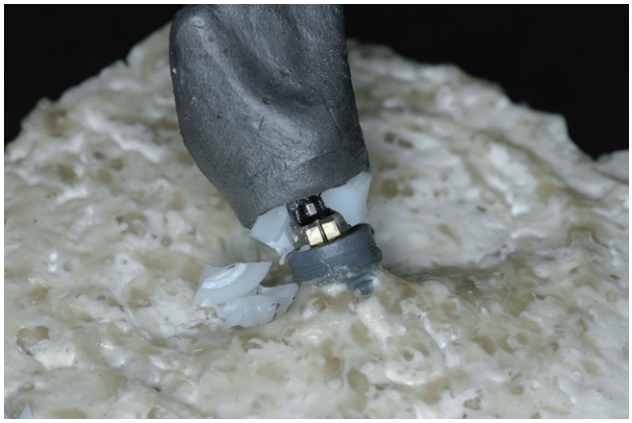

Figure 3 A representative image of fractured test specimen (group Zr-8). Metal part of the abutment is shown. Zr = zirconia.

the horizontal axis and a cross-head speed of 2 mm/min ($n = 8$). The semispherical loading stamp was centrally positioned in the median plane of the crown between the upper end of the cingulum and the incisal edge. A 1-mm-thick tin foil was placed between loading stamp and crown to achieve homogenous stress distribution. The applied force was graphically recorded on an x-t recorder (Zwick testXpertÒ V.7.1, Zwick), with failure defined as a deviation from graphic linearity. After loading in the universal testing machine, the location and mode of failure for each test specimen were recorded by visual examination with the help of a ×5 magnifying glass (Carl Zeiss, Aalen, Germany) (Figure 3).

For descriptive exploration of the data, box plots were calculated and graphically displayed, stratified by status and group. An analysis of variance (ANOVA) was used to compare fracture resistance among all groups. The continuous response variable (load) was modeled as a function of status and group and the corresponding interactions as explanatory variables. Least square means were calculated, and the level of significance was set as $p < .05$. Model assumptions were graphically checked by residuals and other regression diagnostics (including Cook's distance). The normality of error terms was assumed. All calculations were made using PROC MIXED from the statistical software SAS 9.1.2 (SAS Institute Inc., Cary, NC, USA).

RESULTS

All specimens survived 1,200,000 cycles of dynamic loading and thermal cycling in the artificial mouth. No screw loosening was recorded.

The smallest fracture resistance value before aging was observed in test group Zr-8, whereas the smallest value after aging was observed in control group Ti (Table 1). The highest median fracture resistance value before aging occurred in test group Zr-1, followed by groups Ti, Zr-18, and Zr-8, respectively. After aging, the highest median fracture resistance value occurred in control group Ti, followed by groups Zr-8, Zr-1 and Zr-18, respectively (see Table 1). The fracture resistance values before and after artificial aging are represented in the box plots (see Figure 4).

The comparisons of the fracture resistance values within and between different groups, before and after artificial aging, showed no statistically significant differences. The repeated measures ANOVA did not yield significant effect of group, status (initial, aged) or combinations ($p > .05$).

The location and mode of failure of the different groups before and after the exposure to the artificial

TABLE 1 Groupwise Fracture Resistance Values in N after the Load-to-Fracture Test

Group	Status	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum	Standard Deviation
Ti	Initial	395	473	500	519	570	668	85
	Aged	223	411	504	484	550	718	144
Zr-1	Initial	370	446	519	493	541	567	73
	Aged	393	434	480	481	519	599	66
Zr-8	Initial	368	424	487	488	560	598	82
	Aged	335	360	491	479	544	613	101
Zr-18	Initial	373	412	490	473	522	566	68
	Aged	367	407	451	478	535	674	102

Ti = titanium; Zr = zirconia.

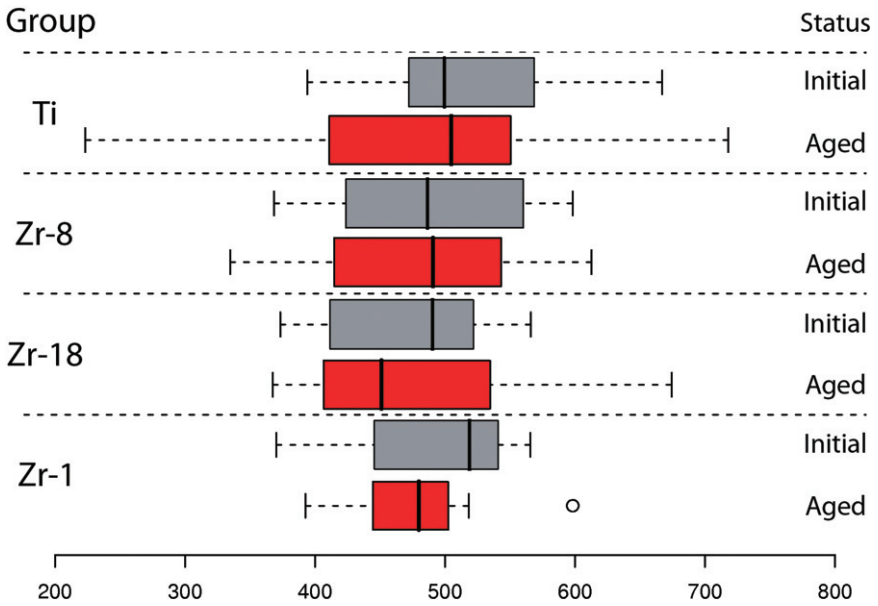

Figure 4 Box plots of the results after the load-to-fracture test in N before and after the fatigue loading ($n = 8$). Pairwise comparisons did not yield statistical differences between and within groups, before and after artificial aging ($p > .05$). Ti = titanium abutments (control group); Zr-1 = zirconia abutments with a wall thickness of 1 mm; Zr-8 = zirconia abutments with a wall thickness of 0.8 mm; Zr-18 = zirconia abutments with a wall thickness reduced from 1 mm to 0.8 mm.

mouth are shown in Table 2. In group Ti, the abutment screws failed without any destruction of the abutments. In group Zr-8, the failure was represented by either abutment screw failure or abutment fracture, with the majority of specimens depicting abutment screw failure. One test specimen in the aged group Zr-8 failed because of an implant neck distortion. In test group Zr-18, a greater number of abutment failure than abutment screw failure was observed. This was more obvious in this specific group after artificial aging, with nearly all specimens failing because of abutment fracture. Similar to test group Zr-8, the failures in test group Zr-1 were represented by either abutment screw failure or abutment fracture, with one specimen failing because of abutment screw fracture.

The fracture mode of the abutments in all test groups was in a homogenous manner. The failure was in a form of a total destruction of the ceramic component of the abutment's basis. Here, a uniform fracture mode response was recorded. The zirconia abutments failed first in the proximity of the implant platform over the metal part of the abutment, which connects the ceramic to the implant (see Figure 3).

The abutment screw was identified as the weakest component in the control group (Ti) and test group Zr-8, whereas the zirconia abutment was identified as the weakest component in group Zr-18. Because of the symmetric distribution of the data, it was not possible to identify the weakest component in the Zr-1 group.

TABLE 2 Location and Mode of Failure after the Load-to-Fracture Test

Failed Component	Status	Group Ti	Group Zr-8	Group Zr-18	Group Zr-1
Abutment	Initial	0	3	5	3
	Aged	0	2	7	4
Screw bending	Initial	8	5	3	5
	Aged	8	5	1	3
Screw fracture	Initial	0	0	0	0
	Aged	0	0	0	1
Implant neck distortion	Initial	0	0	0	0
	Aged	0	1	0	0

Ti = titanium; Zr = zirconia.

DISCUSSION

Prefabricated zirconia abutments are being implemented as an easy-to-use and an economic foundation for implant-supported rehabilitation. In esthetically demanding regions, especially in areas where the implants have not been placed in an ideal three-dimensional position, the use of a prefabricated abutment may limit the esthetic outcome.[2,9] This is mainly because that these abutments usually allow for a limited freedom in modifying the abutment's design such as wall reduction or relocation of the margins to a level below the peri-implant marginal mucosa.[9] Compared with prefabricated abutments, custom-made zirconia abutments offer an improved esthetic integration, as various design characteristics can be manipulated according to the esthetic requirements. These abutments are generally being fabricated by means of CAD/CAM techniques. Despite improvements in the design software and industrial milling, postfabrication modifications, namely manual abutment preparation in the dental lab, may be additionally required for further improvement of the esthetic integration of the abutment. Here, it is well known that zirconia grinding or milling might induce surface flaws or microcracks that can influence the mechanical properties of the material negatively and jeopardize the abutment's stability.[20,21] To the authors' knowledge, studies about the effect of the preparation and wall thickness on the stability of zirconia implant abutments are not available.

The artificial mouth is a useful tool to evaluate the performance of different restorations under fatigue.[22] In this study, all specimens survived the exposure to the artificial mouth. The results of fatigue loading are in accordance with a previous in vitro study, where zirconia abutment survived the aging process as well.[23]

Despite common clinical practice, the abutments were restored with metal crowns instead of all-ceramic crowns. This allowed not to obscure the cause of failure, that is, abutment related or crown related. This specific design has been favored in other studies as well.[23,24] The results of the load-to-fracture test showed no significant effect of artificial aging, wall thickness, or preparation on the resistance of the tested zirconia abutments. All groups showed mean resistance-to-fracture values greater than 470 N. In this context, several studies reported a mean loading force of approximately 206 N and maximum biting forces of up to 290 N in the esthetic zone.[25,26] In an in vitro study, unprepared titanium-reinforced zirconia and pure alumina abutments were compared for their outcome. After fatigue and static loading, the median fracture loads were 294 N, 239 N, and 324 N for the zirconia, alumina, and titanium abutment groups, respectively.[23] The authors concluded that titanium-reinforced zirconia abutments perform in a similar manner to metal abutments, and can therefore be recommended as an esthetic alternative for the restoration of single implants in the anterior region. In another in vitro study, different implant-zirconia abutment combinations were tested for their load fatigue performance. While no significant differences were found between the implant systems, differences were observed between the implant diameters. The authors concluded that rotational load fatigue testing performance of zirconia abutments is dependent on the abutment diameter.[27] A recent systematic review evaluating laboratory studies about the resistance of implant abutments with/without restorations identified nine studies evaluating zirconia abutments.[13] The authors of the current study additionally identified one further study.[28] The majority of studies identified used implant-supported single crowns. The resistance-to-fracture values for samples not subjected to fatigue loading and samples subjected to fatigue loading ranged from 131 N to 737 N and from 57 N to 593 N, respectively.[20] Due to the heterogeneity in study design and testing methods employed in different studies, no meta analysis of the data was carried out.[13] Observing the identified laboratory studies, it can be noticed that all zirconia abutments tested were not modified in their dimensions. Due to the difference in study design, that is, implementation of preparation and reduction in wall thickness, no comparison can be preformed between the current study and previous studies.

Although a common procedure, clinical recommendations about the minimal wall thickness of zirconia abutments are not available. In this study, the reduced wall thickness did not yield statistically significant differences between and within the tested groups. The smallest wall thickness used was 0.8 mm. It cannot be confirmed, however, whether a smaller wall thickness will lead to a detrimental effect on the stability of the abutments. Because of different design of zirconia abutments as well as connection characteristics, the current

results cannot be generalized for other implant systems. The lack of knowledge about the minimal wall thickness of zirconia abutments that guarantees proper resistance implicates the necessity for further evaluation under laboratory conditions before clinical application.

Generally, it is well known that zirconia material is highly susceptible to surface modifications and improper laboratory and clinical handling techniques.[21] For example, any subtractive procedure performed after final sintering of the zirconia ceramic, that is, sandblasting or grinding, will likely result in a monoclinic phase to appear on the treated surface.[29,30] This monoclinic transformation will in the first instance increase the strength of the restoration.[31,32] However, when a crack initiates in that area, there is no transformation toughening mechanism to oppose crack propagation available anymore because the tetragonal phase was already transformed.[33,34] Furthermore, grinding or sandblasting of zirconia surfaces is discussed to induce the formation of surface microcracking that could be detrimental to the long-term performance of the material and lead to unexpected failures.[30,35] In an in vitro study, alumina toughened zirconia and tetragonal zirconium dioxide poylcrystal-A implants were evaluated for their fracture load before and after preparation procedure as well as after fatigue loading.[36] The modification of the implant head using diamond burs and increased loading time led to a significant decrease in fracture strength of both implant materials. The authors discussed the subcritical crack growth as a possible cause for the reduction of fracture strength. In this study, the preparation of the zirconia abutments did not yield statistically significant difference compared with unprepared abutments. Observing the failure mode, however, it can be noticed that the prepared zirconia abutments became the weakest component after fatigue loading. This shift in the mode of failure can be explained by the effect of preparation, combined with fatigue loading, in triggering the above-mentioned mechanism in the zirconia and consequently leading to degradation in the material's resistance to a level below that of the abutment screw. Hence, if an abutment preparation is required, the guidelines for zirconia surface grinding are highly recommended. These guidelines advocate a stress-free preparation under water cooling using a fine-grained cutting diamonds, as followed in the current study, which may decrease the critical flow size.[31,32]

CONCLUSION

Within the limits of this in vitro study, it can be concluded that all tested zirconia abutments have the potential to withstand physiologic occlusal forces in the anterior region. As the results of this study cannot be generalized to other implant systems, further studies are needed to verify the effect of abutment preparation as well as the wall thickness on the stability of zirconia implant abutments.

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REFERENCES

1. Iqbal MK, Kim S. For teeth requiring endodontic treatment, what are the differences in outcomes of restored endodontically treated teeth compared to implant-supported restorations? Int J Oral Maxillofac Implants 2007; 22(Suppl):96–116.
2. Jung RE, Pjetursson BE, Glauser R, Zembic A, Zwahlen M, Lang NP. A systematic review of the 5-year survival and complication rates of implant-supported single crowns. Clin Oral Implants Res 2008; 19:119–130.
3. Pjetursson BE, Bragger U, Lang NP, Zwahlen M. Comparison of survival and complication rates of tooth-supported fixed dental prostheses (FDPs) and implant-supported FDPs and single crowns (SCs). Clin Oral Implants Res 2007; 18(Suppl 3):97–113.
4. Koutayas SO, Vagkopoulou T, Pelekanos S, Koidis P, Strub JR. Zirconia in dentistry: part 2. Evidence-based clinical breakthrough. Eur J Esthet Dent 2009; 4:348–380.
5. den Hartog L, Slater JJ, Vissink A, Meijer HJ, Raghoebar GM. Treatment outcome of immediate, early and conventional single-tooth implants in the aesthetic zone: a systematic review to survival, bone level, soft-tissue, aesthetics and patient satisfaction. J Clin Periodontol 2008; 35:1073–1086.
6. Kohal RJ, Att W, Bachle M, Butz F. Ceramic abutments and ceramic oral implants. An update. Periodontol 2000 2008; 47:224–243.
7. Linkevicius T, Apse P. Influence of abutment material on stability of peri-implant tissues: a systematic review. Int J Oral Maxillofac Implants 2008; 23:449–456.
8. Jung RE, Sailer I, Hammerle CH, Attin T, Schmidlin P. In vitro color changes of soft tissues caused by restorative materials. Int J Periodontics Restorative Dent 2007; 27:251–257.
9. Sailer I, Zembic A, Jung RE, Hammerle CH, Mattiola A. Single-tooth implant reconstructions: esthetic factors influencing the decision between titanium and zirconia abutments in anterior regions. Eur J Esthet Dent 2007; 2:296–310.

10. Prestipino V, Ingber A. Esthetic high-strength implant abutments. Part I. J Esthet Dent 1993; 5:29–36.
11. 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.
12. Abrahamsson I, Berglundh T, Glantz PO, Lindhe J. The mucosal attachment at different abutments. An experimental study in dogs. J Clin Periodontol 1998; 25:721–727.
13. Sailer I, Philipp A, Zembic A, Pjetursson BE, Hammerle CH, Zwahlen M. A systematic review of the performance of ceramic and metal implant abutments supporting fixed implant reconstructions. Clin Oral Implants Res 2009; 20(Suppl 4):4–31.
14. Meyer U, Buchter A, Wiesmann HP, Joos U, Jones DB. Basic reactions of osteoblasts on structured material surfaces. Eur Cell Mater 2005; 9:39–49.
15. Degidi M, Artese L, Scarano A, Perrotti V, Gehrke P, Piattelli A. Inflammatory infiltrate, microvessel density, nitric oxide synthase expression, vascular endothelial growth factor expression, and proliferative activity in peri-implant soft tissues around titanium and zirconium oxide healing caps. J Periodontol 2006; 77:73–80.
16. Rimondini L, Cerroni L, Carrassi A, Torricelli P. Bacterial colonization of zirconia ceramic surfaces: an in vitro and in vivo study. Int J Oral Maxillofac Implants 2002; 17:793–798.
17. Scarano A, Piattelli M, Caputi S, Favero GA, Piattelli A. Bacterial adhesion on commercially pure titanium and zirconium oxide disks: an in vivo human study. J Periodontol 2004; 75:292–296.
18. Att W, Kurun S, Gerds T, Strub JR. Fracture resistance of single-tooth implant-supported all-ceramic restorations after exposure to the artificial mouth. J Oral Rehabil 2006; 33:380–386.
19. Att W, Kurun S, Gerds T, Strub JR. Fracture resistance of single-tooth implant-supported all-ceramic restorations: an in vitro study. J Prosthet Dent 2006; 95:111–116.
20. Guess PC, Att W, Strub JR. Zirconia in fixed implant prosthodontics. Clin Implant Dent Relat Res 2010. DOI: 10.1111/j.1708-8208.2010.00317.x [Epub ahead of print].
21. Luthardt RG, Holzhuter MS, Rudolph H, Herold V, Walter MH. CAD/CAM-machining effects on Y-TZP zirconia. Dent Mater 2004; 20:655–662.
22. Kern M, Strub JR, Lu XY. Wear of composite resin veneering materials in a dual-axis chewing simulator. J Oral Rehabil 1999; 26:372–378.
23. 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; 32:838–843.
24. Strub JR, Gerds T. Fracture strength and failure mode of five different single-tooth implant-abutment combinations. Int J Prosthodont 2003; 16:167–171.
25. 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.
26. Kiliaridis S, Kjellberg H, Wenneberg B, Engstrom C. The relationship between maximal bite force, bite force endurance, and facial morphology during growth. A cross-sectional study. Acta Odontol Scand 1993; 51:323–331.
27. Nguyen HQ, Tan KB, Nicholls JI. Load fatigue performance of implant-ceramic abutment combinations. Int J Oral Maxillofac Implants 2009; 24:636–646.
28. Nothdurft FP, Doppler KE, Erdelt KJ, Knauber AW, Pospiech PR. Fracture behavior of straight or angulated zirconia implant abutments supporting anterior single crowns. Clin Oral Investig 2011; 15:157–163.
29. Rekow D, Thompson VP. Near-surface damage – a persistent problem in crowns obtained by computer-aided design and manufacturing. Proc Inst Mech Eng [H] 2005; 219:233–243.
30. Wang H, Aboushelib MN, Feilzer AJ. Strength influencing variables on CAD/CAM zirconia frameworks. Dent Mater 2008; 24:633–638.
31. Kosmac T, Oblak C, Jevnikar P, Funduk N, Marion L. The effect of surface grinding and sandblasting on flexural strength and reliability of Y-TZP zirconia ceramic. Dent Mater 1999; 15:426–433.
32. Kosmac T, Oblak C, Jevnikar P, Funduk N, Marion L. Strength and reliability of surface treated Y-TZP dental ceramics. J Biomed Mater Res 2000; 53:304–313.
33. Rekow D, Thompson VP. Engineering long term clinical success of advanced ceramic prostheses. J Mater Sci Mater Med 2007; 18:47–56.
34. Shah K, Holloway JA, Denry IL. Effect of coloring with various metal oxides on the microstructure, color, and flexural strength of 3Y-TZP. J Biomed Mater Res B Appl Biomater 2008; 87:329–337.
35. Zhang Y, Lawn BR, Malament KA, Van Thompson P, Rekow ED. Damage accumulation and fatigue life of particle-abraded ceramics. Int J Prosthodont 2006; 19:442–448.
36. Kohal RJ, Wolkewitz M, Mueller C. Alumina-reinforced zirconia implants: survival rate and fracture strength in a masticatory simulation trial. Clin Oral Implants Res 2010; 21:1345–1352.