Clin Oral Invest (2011) 15:89–97
DOI 10.1007/s00784-009-0359-0

ORIGINAL ARTICLE

Fracture behaviour of implant–implant- and implant–tooth-supported all-ceramic fixed dental prostheses utilising zirconium dioxide implant abutments

Frank Philipp Nothdurft · Sabine Merker · Peter Reinhard Pospiech

Received: 14 July 2009 / Accepted: 24 November 2009 / Published online: 5 January 2010

Abstract This in vitro study investigated the fracture behaviour of implant–implant-supported and implant–tooth-supported all-ceramic fixed dental prostheses (FDP) using zirconium dioxide implant abutments (FRIADENT® CERCON® abutments, DENTSPLY Friadent). Six different test groups ($n=8$) were prepared. Groups 1, 2, 4, and 5 represented an implant–implant-supported FDP condition, whereas groups 3 and 6 simulated an implant–tooth-supported FDP condition. The second right premolar of the mandible was replaced with a pontic tooth. In groups 2 and 5, implant abutments were individualised by circumferential preparation. XiVe® S plus screw implants (DENTSPLY Friadent) that were 4.5 mm (first molar) and 3.8 mm (first premolar) in diameter and 11 mm in length and metal tooth analogues with simulated periodontal mobility, representing the first right premolar, were mounted in a polymethyl methacrylate block. The FDPs were cemented with KetacCem (3 M Espe GmbH, Germany). Groups 4, 5, and 6 were thermomechanically loaded (thermal and mechanical cycling (TCML)=1.2×10^6; $10{,}000\times5°/55°$) and subjected to static loading until failure. Statistical analysis of data obtained for the force at fracture was performed using non-parametric tests. All samples tested survived TCML. In the implant–implant-supported groups, circumferential abutment preparation resulted in a tendency to lower fracture forces compared to groups with unprepared abutments (group 1, 472.75±24.71 N; group 2, 423.75±48.48 N; group 4, 647.13±39.10 N; group 5, 555.86 ±30.34 N). The implant–tooth-supported restorations exhibited higher fracture loads (group 3, 736.25±82.23 N; group 6, 720.75±48.99 N) than the implant–implant-supported restorations which did not possess circumferentially individualised abutments. Statistically significant differences were found when comparing the non-artificially aged groups. Implant–tooth-supported FDP restorations did exhibit an increased fracture load compared to implant–implant-supported FDP restorations.

Keywords All-ceramic suprastructures · Fracture resistance · Fracture mode · Implant abutments · Tooth abutment

F. P. Nothdurft (✉) · S. Merker · P. R. Pospiech
Department of Prosthetic Dentistry and Dental Materials Sciences, Dental School and Clinics, Saarland University,
Homburg Campus, Bldg. 71.2,
66421 Homburg, Saarland, Germany
e-mail: zmkfnot@uniklinikum-saarland.de

Introduction

Crestal bone stability and healthy soft tissues are considered necessary for the long-term success of implant-supported restorations. Peri-implant tissues are constantly challenged by various hazards. Bacterial plaque [1], loading [2], and prosthetic manipulation [3] are factors that can have an adverse effect on implant success. The soft tissue barrier around dental implants serves as a protective seal between the oral environment and the underlying peri-implant bone [4]. The abutment material appears to be of decisive importance for the quality of the attachment that forms between the mucosa and the abutment surface [5]. The interface between the peri-implant mucosa and implant abutments made of titanium alloy is comprised of one epithelial and one connective tissue component. The structure and function of this barrier tissue have been described previously [4]. Titanium, gold, base metals, and zirconia or alumina ceramics are available for prosthetic implant abutment fabrication [5]. In particular, ceramic materials are of increasing importance, not only due to their tooth-like colour [6], but also for their possible biological advantages. There is, however, a lack of evidence that zirconium oxide abutments perform better in maintaining stable peri-implant tissues compared to titanium alloy [7]. Data obtained from animal studies and human histological studies, however, have indicated that zirconium oxide abutments could have a more favourable effect on peri-implant soft tissue health than titanium alloy abutments [4, 5, 8]. Currently, the preferred indication for the use of ceramic implant abutments is the aesthetically demanding anterior region of the maxilla [6, 9]. For this application, in vitro investigations have revealed sufficient load-bearing capacities of zirconium dioxide abutments in different implant systems [10, 11]. In addition, a clinical trial has indicated a low risk for fracture [12]. Due to their exceptional biocompatibility and positive influence on peri-implant soft tissue health, the use of zirconium dioxide abutments for premolar and molar replacement seems to be useful and promising. Nevertheless, there is only a limited number of in vitro and in vivo studies available which investigated the indication of zirconia abutments in the load-bearing posterior region [13–16].

Therefore, the present in vitro study investigated the fracture behaviour of implant–implant and implant–tooth-supported all-ceramic fixed dental prostheses (FDPs) using zirconium dioxide implant abutments. Compared to pre-fabricated zirconium dioxide implant abutments that were not adapted to the actual clinical soft tissue height, we hypothesised that: 1) circumferential preparation of the zirconium implant abutments will lead to significantly lower load-bearing capacities in implant–implant-supported restorations, and 2) implant–tooth-supported all-ceramic restorations will display generally lower load-bearing capacities than implant–implant-supported FDPs.

The hypotheses were tested with and without simulated thermomechanical aging.

Materials and methods

Six different test groups (n=8) were prepared. Groups 1, 2, 4, and 5 represented an implant–implant-supported FDP condition, whereas groups 3 and 6 simulated an implant–tooth-supported FDP condition.

In groups 1, 3, 4, and 6, the implant abutments were shortened from only the occlusal face. In groups 2 and 5, in contrast, an additional circular individualisation was applied to the implant shoulder. Table 1 provides an overview of the tested groups.

A mandibular typodont model (Frasaco UK 119, A-3; Franz Sachs & Co., Tettnang, Germany) was used to simulate adequate clinical dimensions for a 3-unit FDP condition.

For groups 1, 2, 4, and 5, the right first premolar, second premolar, and first molar were removed from the model. The alveolar socket of the second premolar was obturated with wax, while the first premolar and first molar were replaced with implants.

For this study, XiVe® S plus screw implants (DENTSPLY Friadent, Mannheim, Germany) and FRIADENT® CERCON® abutments (DENTSPLY Friadent) were used. Two implants (molar diameter of 4.5 mm, premolar diameter of 3.8 mm) with a length of 11 mm were placed in the centre of the alveolar sockets and fixed with wax. We confirmed that the position and angulations of the implants corresponded to the course of the dental arch and that the position of the implant shoulder was 2 mm below the mesial and distal papilla.

For groups 3 and 6, a plastic first premolar (Frasaco, Franz Sachs & Co., Tettnang, Germany) was used instead of the implant and prepared for an all-ceramic FDP. An approximately 0.7 mm deep, 360° chamfer preparation was carried out using a parallelometer-drilling device (Degussa Dental AG, Hanau, Germany) and a 2° tapered diamond bur (998 016 F, NTI-Kahla, Germany) that followed the course of the dento-enamel junction. The anatoform preparation was completed by an occlusal reduction of approximately 1.5 mm (preparation diamond bur, 836 KR 012; finishing diamond bur, 8836 KR 012, Brasseler GmbH & Co.KG, Lemgo, Germany).

Impressions of both conditions were taken using custom impression trays made from light-curing plastic material (Profibase, Voco GmbH, Cuxhaven, Germany) and a system-specific transfer coping for the pick-up technique.

Table 1 Overview of the test groups

Groups	1	2	3	4	5	6
Support of CERCON® FDP	I–I	Ii–Ii	I–T	I–I	Ii–Ii	I–T
Diameter of CERCON® abutments (in mm)	4.5/3.8	4.5/3.8	4.5	4.5/3.8	4.5/3.8	4.5
Circumferential preparation of CERCON® abutments	No	Yes	No	No	Yes	No
Fatigue testing	No	No	No	Yes	Yes	Yes

I–I implant–implant-supported; *I–T* implant–tooth-supported; *Ii–Ii* implant–implant-supported, abutments circumferentially individualised

The putty-wash technique was then applied. Light-bodied polyether impression material (Permadyne™, 3 M Espe GmbH AG, Seefeld, Germany) was applied using a syringe around the abutments/prepared tooth, and the putty material (Impregum™ Penta™, 3 M Espe GmbH) was used on the tray. Two hours after removing the impression, casts were poured using a type 4 dental stone (Die-Stone, Heraeus Kulzer GmbH, Hanau, Germany) and trimmed to a block shape. These casts served as master casts (Figs. 1 and 2).

The preparation of the implant abutments was performed using a parallel drilling device (C.K. Telemaster Mill; C. Hafner GmbH & Co.KG, Pforzheim, D) and a high-speed laboratory hand piece with continuous air/water spray. All abutments were prepared by a single operator using special zirconia grinding diamonds (ZR 850 016, Brasseler) for occlusal reduction and 2° tapered finishing diamonds (998 016 F, NTI-Kahla, Germany) for circumferential reduction. To ensure constant wear, a new diamond bur was used for every abutment.

As indicated by the simulated clinical situation, all abutments with a diameter of 4.5 mm were reduced to 7.5 mm in height, as measured from the implant shoulder. For groups 2 and 5, abutments were prepared in a circumferential manner in order to shift the finishing line to a height of 1.5 mm, as measured from the implant shoulder. The extent of individualisation is shown in Fig. 3.

To simulate an abutment tooth with periodontal mobility, standardised metal teeth representing the right first premolar were manufactured in groups 3 and 6 (i.e., those with implant–tooth-supported FDPs). Duplicates of the original abutment teeth were made of chrome–cobalt-alloy (Remanium® 2000; Dentaurum J. P. Winkelstroeter KG, Pforzheim, Germany). To simulate physiological tooth mobility, all roots of the metal abutment teeth were covered with an artificial periodontal membrane made out of a gum resin (Anti-Rutsch-Lack; Wenko-Wenselaar GmbH, Hilden, Germany). Each tooth was dipped in the gum resin for three times with drying periods of 24 h in between. In order to conform to the biological width, the gum resin was terminated 2 mm below the finishing line.

Fig. 1 Master cast for test groups with implant–implant-supported restorations prepared for the scanning process

Fig. 2 Master cast for test groups with implant–tooth supported restorations prepared for the scanning process

Manufacturing of FDPs was performed using the computer aided design (CAD)/computer aided manufacturing (CAM) technique of the Compartis® integrated systems (Degudent GmbH, Hanau-Wolfgang, Germany). For groups with implant–implant-supported fixed partial denture (FPDs), each abutment pair was inserted into the master cast and digitised using an optical scanner (Cercon eye, DeguDent GmbH). For the groups with implant–tooth-supported restorations, each implant abutment was inserted in the corresponding master cast and scanned. Another scan was then performed from the corresponding metal tooth. All data were imported into a CAD program.

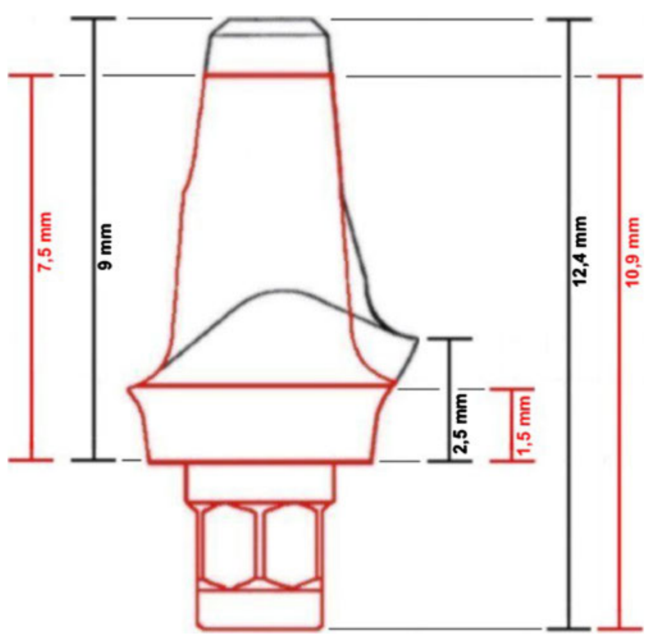

Fig. 3 Dimensions of the CERCON abutment before (*black*) and after (*red*) individualisation

Fig. 4 Implant–tooth-supported zirconium dioxide FDP before mounting in acrylic resin

The FDPs for both conditions were designed using the data from the first scans of the respective master cast (Software: Release-Version of Cercon Art 3.0, DeguDent). These FDP data served as a standard data set and were processed for the manufacturing of all test FDPs. To adapt this standard data set to the individualised zirconia abutments and to the cast metal teeth, only minor adaptations were carried out in the CAD software in order to adjust the margins of the restoration to the finishing line of each abutment.

To avoid fractures of the ceramic layering material during thermomechanical fatigue testing and static loading, the FDPs were designed to be fully anatomical. The connector cross-sections had a mesial and distal size of 11 and 13 mm^2, respectively, corresponding to the connector dimensions of a framework to be veneered (Fig. 4).

All FDPs were milled centrally in the Compartis® Centre (DeguDent, Hanau-Wolfgang, Germany).

All FDPs were connected with the correspondent implants or tooth duplicates (Fig. 4) using a silicone material and were mounted in an acrylic resin block (3 cm×1.3 cm×1.8 cm; Palapress Vario; Heraeus Kulzer GmbH, Hanau, Germany) using a custom-made silicone mould (Adisil; Siladent-technik GmbH, Munich, Germany) and a custom-made sample holder. The acrylic level was adjusted 2 mm below the chamfer finishing line of the tooth duplicates with respect to the level of the implant shoulder (Figs. 5, 6, and 7).

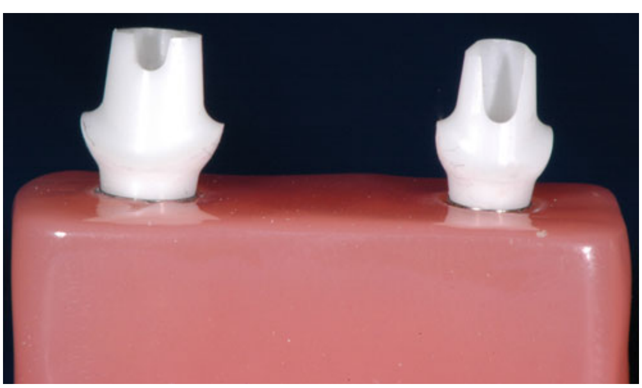

Fig. 5 Groups 1 and 4: implant–implant-supported FDP; CERCON® abutments were non-individualised

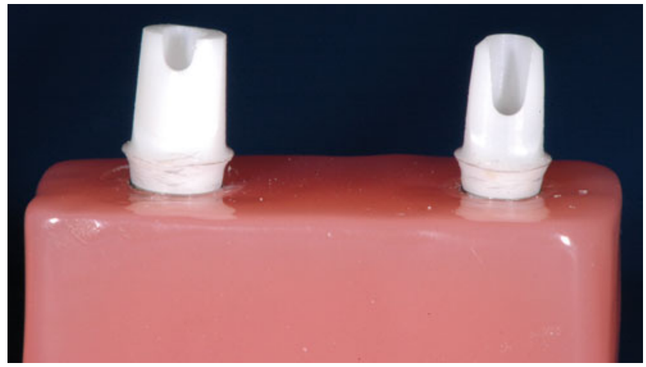

Fig. 6 Groups 2 and 5: implant–implant-supported FDP; CERCON® abutments were individualised

Before cementing the FDPs, all abutments were inserted into the implants with the system-specific ratchet and turnscrew (both Friadent) at a torque of 24 N cm placed on the corresponding screws. The screws were covered with a polyurethane foam pellet (Pele Tim®, Voco GmbH, Cuxhaven, Germany) to ensure easy access after determination of the load-bearing capacity.

The FDPs were cleaned with ethanol (70%), dried, and cemented with glass ionomer cement (Ketac Cem Maxicap; 3 M Espe GmbH & Co. KG, Seefeld, Germany). The restorations were kept on the prepared samples under finger pressure for 10 s, and then for another 7 min under applied pressure (100 N) using a universal testing device (Zwick/Roell, Ulm, Germany). Excess cement was removed with a sharp instrument. After the cementation procedures and before further processing, the samples were again maintained in a wet condition (sodium chloride solution) for 24 h at 38°C.

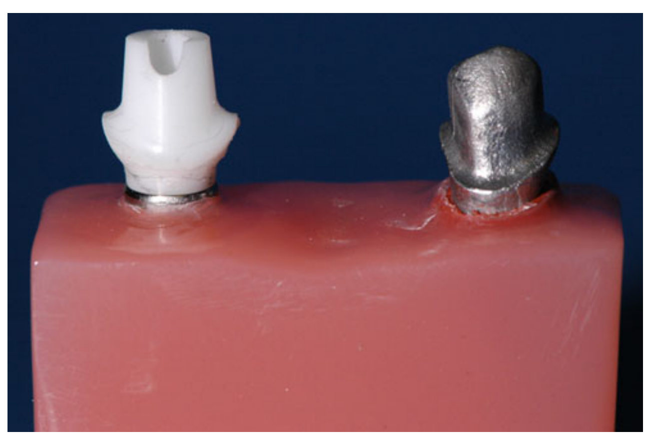

Fig. 7 Groups 3 and 6: implant–tooth-supported FDPs

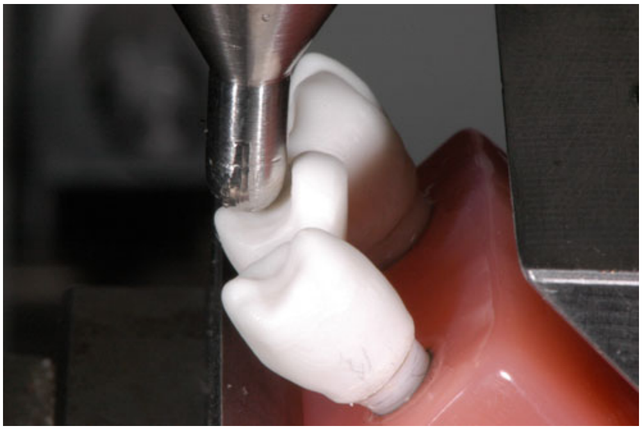

Fig. 8 Static loading of an implant–implant-supported FDP

The samples were subjected to thermocycling (SD Mechatronic GmbH, Feldkirchen-Westerham, Germany) using 10,000 cycles at 5–55°C and a dwell time of 30 s. Due to the transfer time of 5 s, the total time for one complete cycle was 70 s.

Mechanical aging was performed in a chewing simulator (SD Mechatronic GmbH) with a stainless steel spherical antagonist (diameter, 4 mm) at a 45° angle and with contact at the middle of the mesiodistal width of the buccal cusp of the pontic. Eight specimens were loaded simultaneously and put through 1,200,000 cycles with a force of 50 N and a crosshead speed of 10 mm/s downward and 70 mm/s upward. During the aging process, the specimens were maintained permanently in a wet environment (Aqua dest.) at room temperature.

Following fatigue testing, the samples were fixed in a metal holder in a universal testing device (Zwick/Roell, Ulm, Germany). The long-axis of the roots and implants were positioned at a 45° angle to the direction of the load (Fig. 8). A stainless steel spherical antagonist (diameter, 4 mm) was used to load the samples until failure at a crosshead speed of 0.5 mm/min, with the force transferred to the middle of the mesiodistal width of the buccal cusp of the pontic on an interposed polycarbonate foil (0.5 mm in thickness; Duran®, Scheu Dental GmbH, Isarlohn, Germany).

A sudden decrease in force of more than 30 N was regarded as an indication of failure, and the maximum force up to this point was recorded as the force at fracture.

Due to the chosen sample size, statistical analysis of the force at fracture data was performed using non-parametric Kruskal–Wallis and Mann–Whitney *U* tests. The data obtained for fracture patterns are reported as descriptive. All analyses were performed with SPSS, version 17.0 (SPSS GmbH Software, Munich, Germany).

All implant abutments were unscrewed after drilling an access cavity through the occlusal face of the FDPs and assessed for failure modes by visual inspection. The fracture lines were documented on a schematic drawing of the experimental setting.

Results

All samples tested survived the artificial aging process.

Table 2 and Fig. 9 show the results of the load-bearing capacity testing. Specimens fractured at failure loads of 293–1,210 N. Fatigue testing led to a significant increase in the load-bearing capacity of group 1 (Table 3). In the implant–implant-supported groups, circumferential preparation of the abutments led to lower fracture forces compared to the groups without circumferential individualisation. The difference, however, was not significant before or after artificial aging (Table 3). The implant–tooth-supported restorations showed higher fracture loads than the implant–implant-supported restorations without circumferentially individualised abutments. Statistically significant differences were found when comparing the non-artificially-aged groups (Table 3).

The fracture patterns in the different groups are depicted in Figs. 10, 11, 12, 13, 14, and 15. With one exception, all abutments fractured above the implant shoulder. No fracture of the FDPs occurred in the implant–implant-supported groups, and a difference in the fracture mode of premolar and molar implant abutments was obvious. In the molar implants, the abutments failed horizontally in proximity to the head of the screw, whereas in the premolar implants more oblique fracture lines were observed. Furthermore, a number of abutments did not demonstrate any failure in the premolar implants. In the implant–tooth-supported test groups, nearly all FDPs failed in the area of the mesial connector. A loosening of the implants was

Table 2 Mean force at fracture with standard deviations

Groups	Number	Mean	SD	Median	Minimum	Maximum
1. Implant–implant, nFT	8	472.75	24.71	478.00	334.00	587.00
2. Implant–implant, CP, nFT	8	423.75	48.48	347.00	293.00	661.00
3. Implant–tooth, nFT	8	736.25	82.23	698.50	378.00	1,210.00
4. Implant–implant, FT	8	647.13	39.10	667.00	410.00	780.00
5. Implant–implant, CP, FT	8	555.86	30.34	561.50	419.00	665.00
6. Implant–tooth, FT	8	720.75	48.99	668.00	590.00	1,000.00

CP circumferential preparation of the zirconia abutment; *FT* fatigue testing; *nFT* no fatigue testing

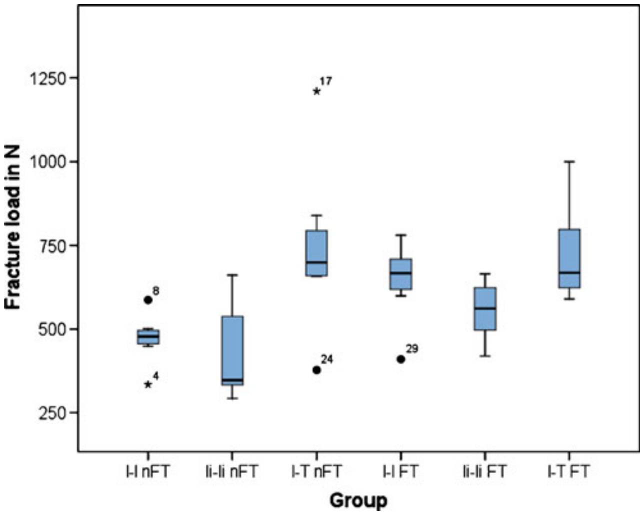

Fig. 9 Box-plot diagram of the load-bearing capacities of groups 1 to 6

observed following static fracture loading, but only in the test groups subjected to artificial aging.

Discussion

Previous laboratory studies regarding the fracture resistance of implant abutments made from zirconium dioxide are available. It must be considered, however, whether past studies evaluated samples that were zirconium dioxide abutments with titanium alloy carry bases [10, 13, 17, 18] or if they were in fact real all-ceramic components.

To our knowledge, all published investigations on all-ceramic implant abutments made from zirconium dioxide were dependant on simulated incisor replacement [11, 19–21], reporting load-bearing capabilities between 429 and 793 N under 30° to 60° load angles. In our review of the literature, in vitro studies examining real all-ceramic abutments used in the posterior region could not be found.

To avoid too much co-factors, the frameworks of the FDPs were not layered. An additional layer of silicate ceramics could have been the weakest link in the test set-up, though not in the main focus of this study. Nevertheless, we are aware of a possible strengthening effect of higher framework dimensions on the overall fracture load [22], which should not influence the drawn conclusions on the evaluated zirconia abutments.

Table 3 *P* values from the Mann–Whitney *U* test

Groups	Ii–Ii nFT	I–T nFT	I–I FT	Ii–Ii FT	I–T FT
1. I–I nFT	0.344	0.009	0.009	x	x
4. I–I FT	x	x	x	0.59	0.674

x not tested; *Ii–Ii* implant–implant-supported, abutments circumferentially individualised

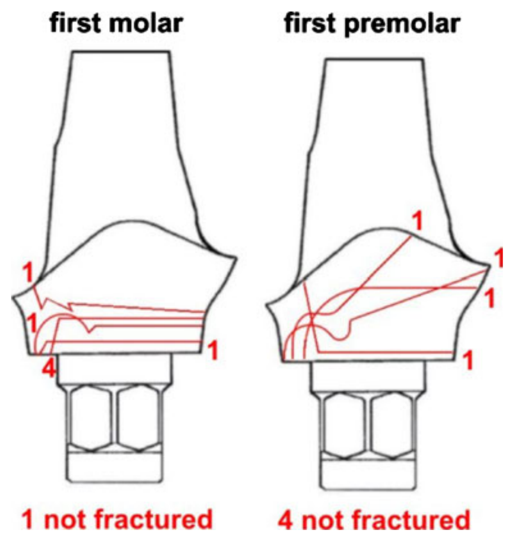

Fig. 10 Fracture mode in group 1 (implant–implant-supported, non-individualised, no fatigue testing)

The connector cross-sections had a mesial and distal size of 11 and 13 mm^2, which exceeds the usually demanded 9 mm^2. In our eyes, an implant–tooth-supported FDP seems to be comparable with a cantilever FDP from a biomechanical point of view. Therefore, we have chosen a cross-section size comparable to suggestions from other authors for a cantilever situation [23].

To judge the failure risk of various implant-supported restorative concepts based on their load-bearing capacities determined in an ex vivo setting, it is important to consider what forces can be expected in realistic clinical situations. Ferrario et al. [24] measured single-tooth bite forces in healthy young male adults, reporting forces of 250 and 290 N for the first and second premolars, respectively.

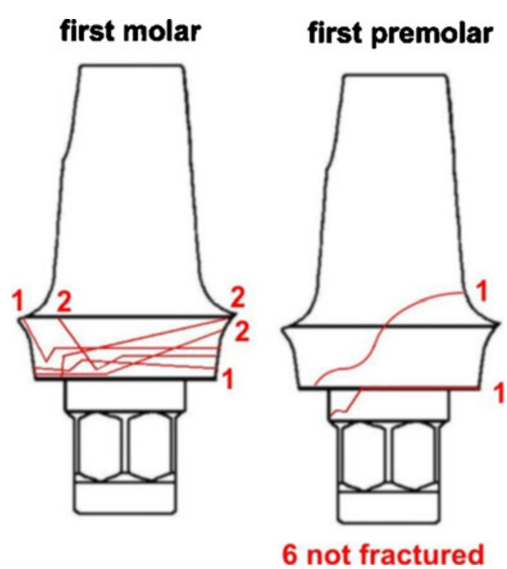

Fig. 11 Fracture mode in group 2 (implant–implant-supported, individualised, no fatigue testing)

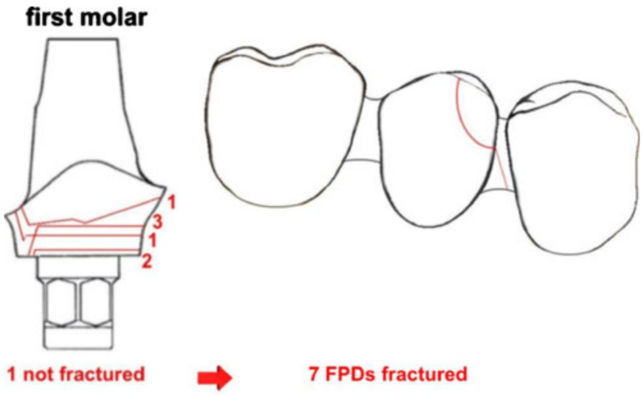

Fig. 12 Fracture mode in group 3 (implant–tooth-supported FDP, non-individualised, no fatigue testing)

Higher bite forces must be expected in subjects with functional disorders such as bruxism [25]. During static loading, the force was applied slowly with a crosshead speed of 0.5 mm/min. This corresponded to the load in a para-functional manner rather than to a chewing or impact-type load.

In the present study, the above-mentioned bite forces were exceeded in all restoration groups; however, uncertainty remains when predicting the performance of restorations in individuals with functional disorders. Keeping such restorations free from dynamic occlusion seems to be of major importance.

The mean load-bearing capability of the zirconium dioxide abutments was not significantly affected by individualisation of the cervical portion, but circumferential abutment preparation resulted in a tendency to lower fracture forces compared to groups with unprepared abutments. No significant differences were found between the individualised and non-individualised implant–implant-supported FDP restorations, regardless of whether they were assessed before or after fatigue testing. Our first hypothesis must therefore be rejected.

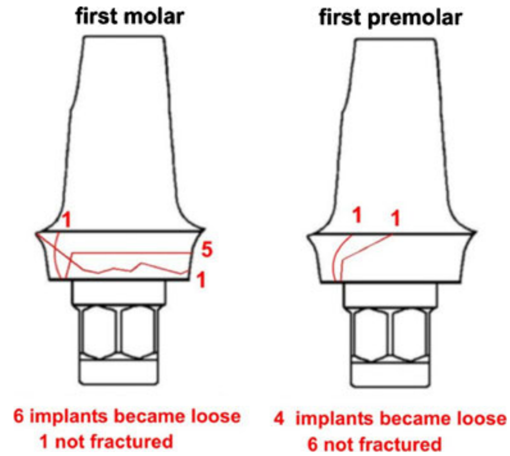

Fig. 14 Fracture mode in group 5 (implant–implant-supported, individualised, fatigue testing)

Besides single-tooth implant replacement, restoration with implant–implant- or implant–tooth-supported fixed dental prostheses is a rational treatment option in cases with missing premolars or molars [26, 27]. Controversial opinions can be found in the literature regarding whether implants should be connected to natural abutments or whether they should be self-supporting [28–32]. Recent studies have shown that, in addition to solely implant-supported FDPs, tooth implant-connected prostheses also show promise as a successful and predictable therapy [33–35]. Nevertheless, the dissimilar mobility patterns of the osseointegrated implants and natural teeth complicate the biomechanical behaviour of the entire system [36]. An osseointegrated implant is rigidly fixed to bone and can move only 10 µm in the apical direction, whereas teeth with healthy periodontal ligaments can move 25–100 µm [37, 38]. This movement disparity may cause relative motion of the tooth superstructure when the splinted system is loaded by occlusal force. During loading, higher bending moment induced by the mismatch between the implant and tooth

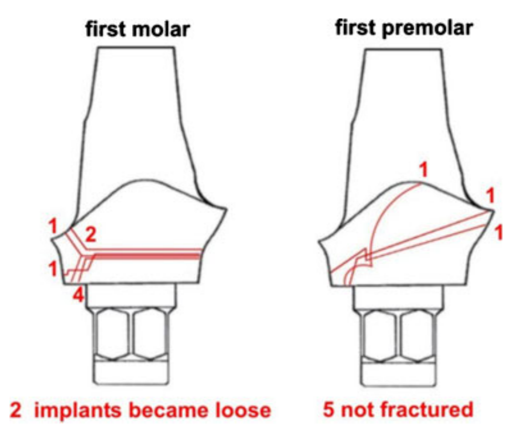

Fig. 13 Fracture mode in group 4 (implant–implant-supported, non-individualised, fatigue testing)

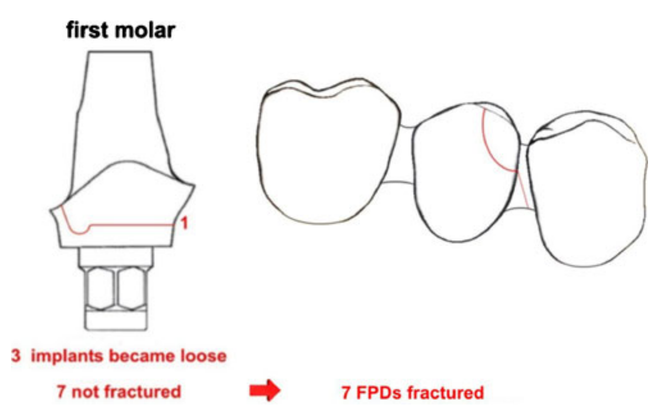

Fig. 15 Fracture mode in group 6 (implant–tooth-supported FDP, non-individualised, fatigue testing)

may result in abutment screw loosening or fracture of the implants or the superstructure [38, 39].

Clinical failures of dental restorations most commonly result from fatigue [40]. We therefore artificially aged all the specimens, applying dynamic thermal and mechanical loading with similar parameters to those found in the literature [41]. Dynamic and static loading were performed at an angle of 45° to the long-axis of the roots, which is representative of the worst-case scenario. In general, reduced fracture load values after cervical individualisation and increased load-bearing capacity were found after splinting an implant and a tooth analogue with physiological mobility. This finding was evident both before and after thermomechanical loading, even though a significant difference was only observed when comparing the non-individualised implant–implant-supported FDPs and the implant–tooth supported FDPs that did not undergo artificial aging. Fractured FDPs were observed in 14 out of 16 specimens in the implant–tooth-supported test groups. This was not observed in any other test group, indicating that a significant portion of the applied forces was transferred in the mesial connector area of the FDP. It is possible that this led to certain relief of the implant abutment and to a primary determination of the load-bearing capacity of the entire restoration according to the fracture resistance of the FDP. Our second hypothesis must therefore be rejected.

The increase in the fracture load values of the non-individualised implant–implant-supported restorations after artificial aging remains to be elucidated. The zirconia abutments are partially yttrium stabilized in order to become more resistant against damages by phase transformation toughening mechanisms [42]. Perhaps, the non-individualised abutments became more resistant against fracture load because of phase transition effects induced by the artificial aging process. But this explanation is speculative.

Conclusions

Within the limitations of this study, it can be concluded that:

1. Artificial aging had no weakening effect on the fracture load of implant–implant and implant–tooth-supported FDP restorations utilising zirconium dioxide all-ceramic abutments.
2. Circular individualisation of zirconium dioxide all-ceramic abutments could result in a decrease in the fracture load of implant–implant-supported FDP restorations.
3. Implant–tooth-supported FDP restorations did exhibit an increased fracture load compared to implant–implant-supported FDP restorations.
4. Measured fracture loads of implant–implant and implant–tooth-supported FDPs utilising zirconium dioxide all-ceramic abutments exceeded average bite forces in the premolar region. Nevertheless, dynamic occlusion should be avoided, especially in patients exhibiting functional disorders, such as bruxism.

Acknowledgements The authors gratefully acknowledge Dentsply Friadent and DeguDent for contribution of materials, as well as MDT Martin Propson for his support in preparing the tested specimens.

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Barboza EP, Caula AL, Carvalho WR (2002) Crestal bone loss around submerged and exposed unloaded dental implants: a radiographic and microbiological descriptive study. Implant Dent 11:162–169
2. Misch CE, Dietsh-Misch F, Hoar J, Beck G, Hazen R, Misch CM (1999) A bone quality-based implant system: first year of prosthetic loading. J Oral Implantol 25:185–197
3. Abrahamsson I, Berglundh T, Lindhe J (1997) The mucosal barrier following abutment dis/reconnection. An experimental study in dogs. J Clin Periodontol 24:568–572
4. Welander M, Abrahamsson I, Berglundh T (2008) The mucosal barrier at implant abutments of different materials. Clin Oral Implants Res 19:635–641
5. Abrahamsson I, Berglundh T, Glantz PO, Lindhe J (1998) The mucosal attachment at different abutments. An experimental study in dogs. J Clin Periodontol 25:721–727
6. Watkin A, Kerstein RB (2008) Improving darkened anterior peri-implant tissue color with zirconia custom implant abutments. Compend Contin Educ Dent 29(238–240):242
7. Linkevicius T, Apse P (2008) Influence of abutment material on stability of peri-implant tissues: a systematic review. Int J Oral Maxillofac Implants 23:449–456
8. Degidi M, Artese L, Scarano A, Perrotti V, Gehrke P, Piattelli A (2006) 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 77:73–80
9. Brodbeck U (2003) The ZiReal post: a new ceramic implant abutment. J Esthet Restor Dent 15:10–23 discussion 24
10. Butz F, Heydecke G, Okutan M, Strub JR (2005) Survival rate, fracture strength and failure mode of ceramic implant abutments after chewing simulation. J Oral Rehabil 32:838–843
11. Gehrke P, Dhom G, Brunner J, Wolf D, Degidi M, Piattelli A (2006) Zirconium implant abutments: fracture strength and influence of cyclic loading on retaining-screw loosening. Quintessence Int 37:19–26
12. Glauser R, Sailer I, Wohlwend A, Studer S, Schibli M, Scharer P (2004) Experimental zirconia abutments for implant-supported single-tooth restorations in esthetically demanding regions: 4-year results of a prospective clinical study. Int J Prosthodont 17:285–290

13. Kolbeck C, Behr M, Rosentritt M, Handel G (2008) Fracture force of tooth–tooth- and implant–tooth-supported all-ceramic fixed partial dentures using titanium vs. customised zirconia implant abutments. Clin Oral Implants Res 19:1049–1053
14. Andersson B, Glauser R, Maglione M, Taylor A (2003) Ceramic implant abutments for short-span FPDs: a prospective 5-year multicenter study. Int J Prosthodont 16:640–646
15. Zembic A, Sailer I, Jung RE, Hammerle CH (2009) Randomized-controlled clinical trial of customized zirconia and titanium implant abutments for single-tooth implants in canine and posterior regions: 3-year results. Clin Oral Implants Res 20:802-808
16. Sailer I, Zembic A, Jung RE, Siegenthaler D, Holderegger C, Hammerle CH (2009) Randomized controlled clinical trial of customized zirconia and titanium implant abutments for canine and posterior single-tooth implant reconstructions: preliminary results at 1year of function. Clin Oral Implants Res 20:219–225
17. Canullo L, Morgia P, Marinotti F (2007) Preliminary laboratory evaluation of bicomponent customized zirconia abutments. Int J Prosthodont 20:486–488
18. Att W, Kurun S, Gerds T, Strub JR (2006) Fracture resistance of single-tooth implant-supported all-ceramic restorations after exposure to the artificial mouth. J Oral Rehabil 33:380–386
19. Aramouni P, Zebouni E, Tashkandi E, Dib S, Salameh Z, Almas K (2008) Fracture resistance and failure location of zirconium and metallic implant abutments. J Contemp Dent Pract 9:41–48
20. Adatia ND, Bayne SC, Cooper LF, Thompson JY (2009) Fracture resistance of yttria-stabilized zirconia dental implant abutments. J Prosthodont 18:17–22
21. Yildirim M, Fischer H, Marx R, Edelhoff D (2003) In vivo fracture resistance of implant-supported all-ceramic restorations. J Prosthet Dent 90:325–331
22. Lawn BR, Pajares A, Zhang Y, Deng Y, Polack MA, Lloyd IK et al (2004) Materials design in the performance of all-ceramic crowns. Biomaterials 25:2885–2892
23. Ohlmann B, Marienburg K, Gabbert O, Hassel A, Gilde H, Rammelsberg P (2009) Fracture-load values of all-ceramic cantilevered FPDs with different framework designs. Int J Prosthodont 22:49–52
24. Ferrario VF, Sforza C, Serrao G, Dellavia C, Tartaglia GM (2004) Single tooth bite forces in healthy young adults. J Oral Rehabil 31:18–22
25. Nishigawa K, Bando E, Nakano M (2001) Quantitative study of bite force during sleep associated bruxism. J Oral Rehabil 28:485–491
26. Schwartz-Arad D, Samet N, Samet N (1999) Single tooth replacement of missing molars: a retrospective study of 78 implants. J Periodontol 70:449–454
27. Nickenig HJ, Schafer C, Spiekermann H (2006) Survival and complication rates of combined tooth–implant-supported fixed partial dentures. Clin Oral Implants Res 17:506–511
28. Gross M, Laufer BZ (1997) Splinting osseointegrated implants and natural teeth in rehabilitation of partially edentulous patients. Part I: laboratory and clinical studies. J Oral Rehabil 24:863–870
29. Laufer BZ, Gross M (1998) Splinting osseointegrated implants and natural teeth in rehabilitation of partially edentulous patients. Part II: principles and applications. J Oral Rehabil 25:69–80
30. Becker CM, Kaiser DA, Jones JD (2000) Guidelines for splinting implants. J Prosthet Dent 84:210–214
31. Lin CL, Wang JC (2003) Nonlinear finite element analysis of a splinted implant with various connectors and occlusal forces. Int J Oral Maxillofac Implants 18:331–340
32. Astrand P, Borg K, Gunne J, Olsson M (1991) Combination of natural teeth and osseointegrated implants as prosthesis abutments: a 2-year longitudinal study. Int J Oral Maxillofac Implants 6:305–312
33. Fugazzotto PA, Kirsch A, Ackermann KL, Neuendorff G (1999) Implant/tooth-connected restorations utilizing screw-fixed attachments: a survey of 3, 096 sites in function for 3 to 14years. Int J Oral Maxillofac Implants 14:819–823
34. Hosny M, Duyck J, van Steenberghe D, Naert I (2000) Within-subject comparison between connected and nonconnected tooth-to-implant fixed partial prostheses: up to 14-year follow-up study. Int J Prosthodont 13:340–346
35. Lindh T, Back T, Nystrom E, Gunne J (2001) Implant versus tooth-implant-supported prostheses in the posterior maxilla: a 2-year report. Clin Oral Implants Res 12:441–449
36. Pesun IJ (1997) Intrusion of teeth in the combination implant-to-natural-tooth fixed partial denture: a review of the theories. J Prosthodont 6:268–277
37. Nyman SR, Lang NP (1994) Tooth mobility and the biological rationale for splinting teeth. Periodontol 2000 4:15–22
38. Lin CL, Wang JC, Chang WJ (2008) Biomechanical interactions in tooth–implant-supported fixed partial dentures with variations in the number of splinted teeth and connector type: a finite element analysis. Clin Oral Implants Res 19:107–117
39. Pjetursson BE, Bragger U, Lang NP, Zwahlen M (2007) 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 18(Suppl 3):97–113
40. Torbjorner A, Fransson B (2004) A literature review on the prosthetic treatment of structurally compromised teeth. Int J Prosthodont 17:369–376
41. Heydecke G, Butz F, Hussein A, Strub JR (2002) Fracture strength after dynamic loading of endodontically treated teeth restored with different post-and-core systems. J Prosthet Dent 87:438–445
42. Piconi C, Maccauro G (1999) Zirconia as a ceramic biomaterial. Biomaterials 20:1–25