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RESEARCH AND EDUCATION

Fatigue behavior of implant-supported cantilevered prostheses in recently introduced CAD-CAM polymers: An in vitro study

Mustafa Borga Dönmez, DDS, PhD,[a] Gülce Çakmak, DDS, PhD,[b] Mehmet Esad Güven, DDS, PhD,[c] Doğu Ömür Dede, DDS, PhD,[d] Samir Abou-Ayash, Prof Dr med dent,[e] and Burak Yilmaz, DDS, PhD[f]

ABSTRACT

Statement of problem. Cantilevered complete arch implant-supported prostheses are commonly fabricated from zirconia and more recently from strength gradient zirconia. Different polymer-based materials indicated for definitive fixed prostheses that could be used with additive or subtractive manufacturing have also been marketed recently. However, knowledge on the long-term fatigue behavior of cantilevered implant-supported prostheses made from these polymer-based materials and strength gradient zirconia is lacking.

Purpose. The purpose of this in vitro study was to evaluate the fatigue behavior of implant-supported cantilevered prostheses of recently introduced computer-aided design and computer-aided manufacturing polymers and zirconia.

Material and methods. A master standard tessellation language file of a 9×11×20-mm specimen with a titanium base (Ti-base) space that represented an implant-supported cantilevered prosthesis was used to fabricate specimens from additively manufactured interim resin (AM), polymethyl methacrylate (SM-PM), nanographene-reinforced polymethyl methacrylate (SM-GR), high-impact polymer composite resin (SM-CR), and strength gradient zirconia (SM-ZR) (n=10). Each specimen was prepared by following the respective manufacturer's recommendations, and Ti-base abutments were cemented with an autopolymerizing luting composite resin. After cementation, the specimens were mounted in a mastication simulator and subjected to 1.2 million loading cycles under 100 N at 1.5 Hz; surviving specimens were subjected to another 1.2 million loading cycles under 200 N at 1.5 Hz. The load was applied to the cantilever extension, 12-mm from the clamp of the mastication simulator. The Kaplan–Meier survival analysis and Cox proportional hazards model were used to evaluate the data (α=.05).

Results. Significant differences in survival rate and hazard ratio were observed among materials (P<.001). Among tested materials, SM-ZR had the highest and AM had the lowest survival rate (P≤.031). All materials had a significantly higher hazard ratio than SM-ZR (P≤.011) in the increasing order of SM-GR, SM-PM, SM-CR, and AM.

Conclusions. SM-ZR had the highest survival rate with no failed specimens. Even though most of the tested polymer-based materials failed during cyclic loading, these failures were commonly observed during the second 1.2 million loading cycles with 200 N. All materials had a higher hazard ratio than SM-ZR. (J Prosthet Dent xxxx;xxx:xxx-xxx)

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[a] Associate Professor, Department of Prosthodontics, Faculty of Dentistry, Istinye University, İstanbul, Turkey; and ITI Scholar, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, University of Bern, Bern, Switzerland.
[b] Senior Resarch Associate, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, University of Bern, Bern, Switzerland.
[c] Associate Professor, Department of Prosthodontics, Faculty of Dentistry, Necmettin Erbakan University, Konya, Turkey.
[d] Professor, Department of Prosthodontics, Faculty of Dentistry, Ordu University, Ordu, Turkey.
[e] Associate Professor, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, University of Bern, Bern, Switzerland.
[f] Associate Professor, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, University of Bern, Bern, Switzerland; Associate Professor, Department of Restorative, Preventive and Pediatric Dentistry, School of Dental Medicine, University of Bern, Bern, Switzerland and Adjunct Professor, Division of Restorative and Prosthetic Dentistry, The Ohio State University, Columbus, Ohio.

Clinical Implications

While the tested polymer-based materials may be suitable alternatives for long-term interim use in a cantilevered prosthesis with the tested dimensions, they may be prone to complications when used definitively, particularly for patients with parafunctional habits. However, the strength gradient zirconia can be considered for cantilevered implant-supported prostheses, given that it had the highest survival rate with no failed specimens with the tested dimensions.

Conventional complete arch implant-supported prostheses consist of a metal framework veneered with ceramic or resin (polymethyl methacrylate or composite resin) for artificial teeth and gingiva.[1] Computer-aided design and computer-aided manufacturing (CAD-CAM) technologies have facilitated the use of different restorative materials, which may also be used for complete arch implant-supported prostheses[2] with esthetic outcomes. The accurate and passive fit of prostheses in these materials has been reported, given that the fabrication process is digitized.[3–5] Among those CAD-CAM fabricated materials, zirconia has been commonly preferred because of its excellent mechanical properties,[6] and a recently introduced strength gradient zirconia (IPS e.max ZirCAD Prime; Ivoclar AG) combines more translucent cubic zirconia with stronger monolithic zirconia in the same disk,[7] minimizing veneer chipping.[8] Nevertheless, polymer-based materials are also an option for implant-supported frameworks. Their advantages include less wear of milling burs, the high resiliency of the materials, and reduced costs. High-impact polymer composite resin (breCAM.HIPC; bredent group GmbH Co KG) is a recently introduced cross-linked composite resin that has been used for the fabrication of monolithic definitive prostheses with excellent optical properties.[9] In addition, in those situations that require the replication of gingiva, pink resin may be layered on the framework.[9] Nanographene-reinforced polymethyl methacrylate (G-CAM; Graphenano DENTAL SL) is another newly introduced polymer-based material with graphene in its chemical structure.[10] Graphene is an allotrope of carbon,[11] has a honeycomb-shaped arrangement of atoms,[12] and has been shown to have more favorable mechanical properties than polymethyl methacrylate.[11,13,14] Even though subtractive manufacturing has been the standard for the fabrication of frameworks in polymer-based materials,[2] additive manufacturing, based on layer by layer fabrication, has become a feasible alternative for the fabrication of polymer-based prostheses,[15,16] as less waste is produced and the fabrication process is not limited to the diameter of the milling burs.[17] The additive manufacturing of polymers enables monolithic prosthesis fabrication, eliminating the risk of veneer chipping.

The clinical longevity of an implant-supported prosthesis depends on a biomechanically sustainable design.[18] In a cantilevered prosthesis, the highest stress values accumulate at the prosthesis and the most distal implant connection,[19] which might lead to complications such as screw loosening or fracture of the screw or other prosthetic components.[20,21] Considering that cantilevered prostheses have become a common treatment option for providing patients with sufficient functional units with fewer implants and avoiding bone augmentation procedures,[22–24] it is essential to comprehensively evaluate newly introduced materials.

Previous studies on cantilevered frameworks have mostly investigated fatigue behavior and fracture resistance after the aging of zirconia and polymer-based materials.[3,10,21,23,25,26] However, the authors are unaware of studies that investigated strength gradient zirconia or the recently introduced CAD-CAM polymers and are aware of only one that has evaluated additively manufactured resins.[23] Therefore, the present in vitro study aimed to evaluate how monolithic implant-supported cantilevered prostheses in 4 different polymer-based materials (additively manufactured resin for interim prostheses, subtractively manufactured polymethyl methacrylate, subtractively manufactured nanographene-reinforced polymethyl methacrylate, and subtractively manufactured high-impact polymer composite resin) and a subtractively manufactured strength gradient zirconia perform under cyclic loading. The null hypothesis was that the material type would not significantly affect the survival of implant-supported cantilevered prostheses during cyclic loading.

MATERIAL AND METHODS

A CAD software program (Geomagic Freeform; 3D Systems) was used to design a rectangle-shaped 9×11×20-mm master standard tessellation language (STL) file with an integrated 8-mm-high Ti-base space and rounded edges to represent a distal cantilevered implant-supported fixed prosthesis. This master STL was used to fabricate a total of 50 specimens in additively manufactured interim resin (AM, FREEPRINT temp; DETAX GmbH Co. KG), polymethyl methacrylate (SM-PM, Ivotion Dent; Ivoclar AG), graphene reinforced polymethyl methacrylate (SM-GR, G-CAM; Graphenano DENTAL SL), high-impact polymer composite resin (SM-CR, breCAM.HIPC; bredent group GmbH Co KG), and strength gradient zirconia (SM-ZR, IPS e.max ZirCAD Prime; Ivoclar AG) (n=10).

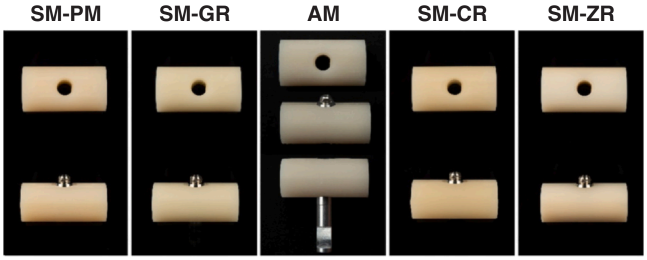

Figure 1. Representative specimens from each group before (top) and after (bottom) insertion of titanium base abutment, also when tightened to analog (middle bottom). AM, additively manufactured interim resin; SM-CR, high-impact polymer composite resin; SM-GR, graphene- reinforced polymethyl methacrylate; SM-PM, polymethyl methacrylate; SM-ZR, strength gradient zirconia.

To fabricate AM specimens, the master STL was imported into a nesting software program (Composer; Asiga) and positioned horizontally on the build platform. After generating support structures automatically and manually removing those generated at the Ti-base spaces, this design was duplicated for standardization. After fabricating the specimens with a digital light processing-based 3-dimensional printer (MAX UV; Asiga), they were ultrasonically cleaned in 98% isopropanol for 6 minutes (3 minutes of precleaning and 3 minutes of main cleaning in fresh alcohol) and polymerized by using a xenon polymerization device (Otoflash G171; NK Optik) for 4000 flashes (2000×2). The remaining specimens were fabricated by using a 5-axis milling unit (PrograMill7; Ivoclar AG), and the milling settings were selected according to the milling unit manufacturer's recommendations for each material. The supports were placed away from the Ti-base space, and, after fabrication, the specimens were removed from the disks, and the supports were removed with a small bur (Round carbide bur; Glin Medical). The SM-ZR specimens were sintered in the manufacturer's proprietary zirconia furnace (Programat S2; Ivoclar AG), and all fabrication processes were performed by a single operator (G.Ç.) (Fig. 1).

The intaglio surfaces of all specimens were airborne-particle abraded with 110-µm aluminum oxide (Al_2O_3) from a 10-mm distance with 0.2 MPa pressure. After steam cleaning, a resin primer (Visio.link; Bredent Medical GmbH Co KG) was applied to the Ti-base space of each specimen as a uniform single coat and polymerized by using a polymerization unit (Labolight DUO; GC Corp) for 90 seconds according to the manufacturer's recommendations. The 8-mm-long Ti-base abutments (Provisional Titanium Abutments SP Ø4.5 mm; Neoss GmbH) were airborne-particle abraded in the same way as the test specimens, cleaned with an alcohol-soaked microbrush, and dried with oil-free compressed air for 1 minute. The intaglio surfaces of Ti-base abutments were then treated with a primer (MKZ primer; bredent group GmbH Co KG) for 30 seconds. An autopolymerizing dental luting composite resin (Multilink Hybrid Abutment H0; Ivoclar AG) was used for the cementation of the components. The luting resin was dispensed with a mixing tip directly onto the intaglio surfaces to be bonded, and the parts were pressed together with firm finger pressure for 5 seconds. After removing excess luting composite resin with a microbrush, the specimen-Ti-base complex was placed under a brass rod that applied a constant load of 2 N for 7 minutes until the resin had polymerized. Then, the cementation joint was cleaned of excess cement.

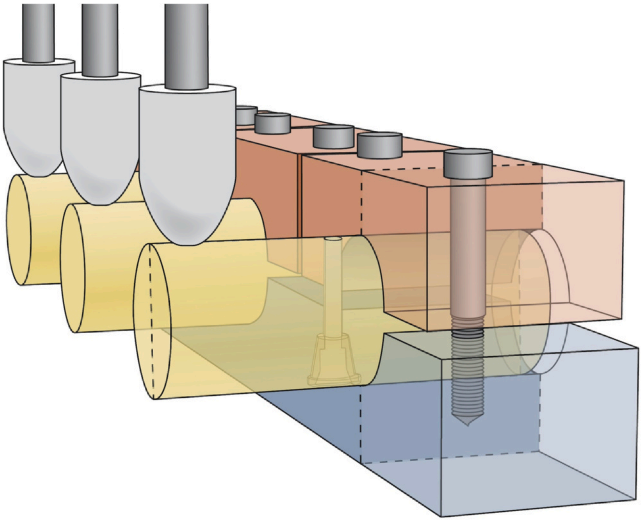

Figure 2. Schematic representation of cyclic loading design in which load is applied 12-mm from clamp to simulate cantilevered prosthesis.

Each specimen-Ti base complex was randomly (Excel; Microsoft Corp) mounted to a mastication simulator[27] to subject it to an initial loading of 1.2 million loading cycles at 100 N, which represents 5 years intraorally.[28,29] The load was applied on the distal cantilever, 12-mm from the clamped part of the specimens (Fig. 2). The specimens that survived the initial loading were subjected to another 1.2 million loading cycles at 200 N, and, after cyclic loading was completed, the surviving specimens were evaluated with a stereomicroscope (M420; Leica) integrated with a light source (CLS 150X; Leica) and a fiber optic illuminator (Intralux 150 H; Volpi) under ×10 magnification to check for any micromovement or failure. Any micromovement between the specimen and the Ti-base was noted as bond failure.

Kaplan–Meier analysis was performed to estimate the survival of each material, followed by a log-rank test to compare test groups. The Cox proportional hazards model was used to estimate the effect of the total number of loading cycles on each material's survival (relative risk or hazard ratio). A statistical analysis

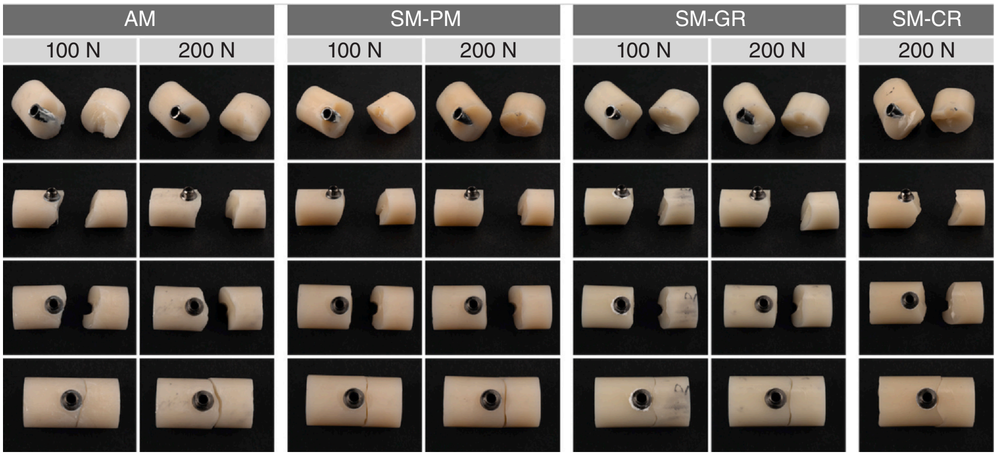

Figure 3. Representative specimens from each group that failed during cyclic loading. AM, additively manufactured interim resin; SM-CR, high-impact polymer composite resin; SM-GR, graphene-reinforced polymethyl methacrylate; SM-PM, polymethyl methacrylate.

software program (Jamovi v2.3.21; The Jamovi Project) was used for the analyses (α=.05).

RESULTS

Figure 3 shows a representative specimen from each group that failed during cyclic loading. Two SM-PM, 2 SM-GR, and all 10 SM-ZR specimens survived 2.4 million loading cycles of loading (Table 1). Kaplan–Meier analysis revealed that, after 2.4 million loading cycles, the survival rate of SM-ZR was 100% and that of AM was 0% (Fig. 4). The log-rank test revealed a difference among test groups (*P*<.001). SM-ZR had the highest (*P*≤.017) and AM had the lowest survival rate (*P*≤.034). No other pairwise comparison was statistically significantly different (*P*>.05) (Table 2).

The Cox regression analysis revealed significant differences in hazard ratio (HR) among test groups (Fig. 5). After 2.4 million loading cycles, all materials had

Table 1. Failure analysis of each specimen within each material during cyclic loading

	Materials				
Specimen Number	**AM**	**SM-PM**	**SM-GR**	**SM-CR**	**SM-ZR**
1	100 N 80 000 loading cycles	100 N 890 000 loading cycles	100 N 853 000 loading cycles	200 N 80 000 loading cycles	*
2	100 N 869 000 loading cycles	200 N 145 000 loading cycles	100 N 945 000 loading cycles	200 N 50 000 loading cycles	*
3	100 N 870 000 loading cycles	200 N 215 000 loading cycles	100 N 869 000 loading cycles	200 N 120 000 loading cycles	*
4	100 N 95 000 loading cycles	200 N 66 000 loading cycles	200 N 10 000 loading cycles	200 N 180 000 loading cycles	*
5	200 N 120 000 loading cycles	200 N 10 000 loading cycles	200 N 1 100 000 loading cycles	200 N 450000 loading cycles	*
6	200 N 50 000 loading cycles	200 N 216 000 loading cycles	200 N 459 000 loading cycles	200 N 6180 000 loading cycles	*
7	200 N 145 000 loading cycles	200 N 120 000 loading cycles	200 N 450 000 loading cycles	200 N 190 000 loading cycles	*
8	200 N 85 000 loading cycles	200 N 106 000 loading cycles	200 N 450 000 loading cycles	200 N 320 000 loading cycles	*
9	200 N 10 000 loading cycles	*	*	200 N 215 000 loading cycles	*
10	200 N 55 000 loading cycles	*	*	200 N 200 000 loading cycles	*
Mean number of loading cycles until fail	957 000	1 592 200	1 693 717	1 537 200	

* Did not fail during cyclic loading

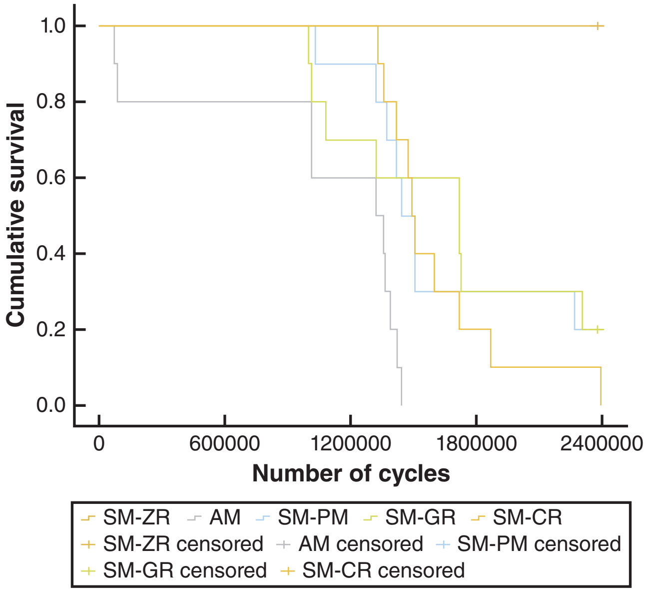

Figure 4. Cumulative survival curves of tested materials after cyclic loading. AM, additively manufactured interim resin; SM-CR, high-impact polymer composite resin; SM-GR, graphene-reinforced polymethyl methacrylate; SM-PM, polymethyl methacrylate; SM-ZR, strength gradient zirconia.

Table 2. Results of Kaplan–Meier survival analysis after 2.4 million loading cycles

Materials	Number of Events	Survival	95% Confidence Interval	
			Lower	Upper
AM	10	0%	-	-
SM-PM	8	20.0%	5.8%	69.1%
SM-GR	8	20.0%	5.8%	69.1%
SM-CR	10	0%	-	-
SM-ZR	0	100%	88.6%	100.0%

significantly higher HR than SM-ZR (*P*≤.011). AM had the highest HR (85.08) followed by SM-CR (23.60), SM-PM (17.26), and SM-GR (15.55) (Table 3).

DISCUSSION

The survival rate of tested cantilevered implant-supported specimens differed according to the tested material, as either all or most of the specimens in the AM, SM-PM, SM-GR, and SM-CR groups failed during cyclic loading. Based on these findings, the null hypothesis that the material type would not significantly affect the survival of implant-supported cantilevered prostheses during cyclic loading was rejected.

Only 4 polymer-based specimens survived the entire cyclic loading in the present study, possibly because of the cyclic loading protocol with 2.4 million loading cycles of 100 N and 200 N load application. This protocol has been used in a previous study with similar specimen geometry[30] and can be considered high. Cyclic loading is commonly performed with loads of 49 N or 98 N for 1.2 million cycles.[28,29,31] The total of 1.2 million loading cycles with 98 N have been reported to simulate 5 years intraorally.[28,29] Higher loads were deliberately chosen in the present study because masticatory forces may be higher in patients with complete arch implant-supported prostheses than in those with tooth-supported prostheses because of the absence of periodontal receptors.[32] Even though the parameters used in the present study to evaluate the fatigue behavior and suitability of the tested materials when used for a definitive implant-supported prosthesis simulated a longer duration with higher loads, the number of studies with implant-supported cantilevered prostheses that have follow-up periods similar to or longer than the cyclic loading duration of the present study is limited.[33,34]

Most of the failures were observed after the load had been increased to 200 N, which may have generated more stress than the direct loading of an implant-supported crown according to the International Organization for Standardization (ISO) standard 14801:2016.[35] Another

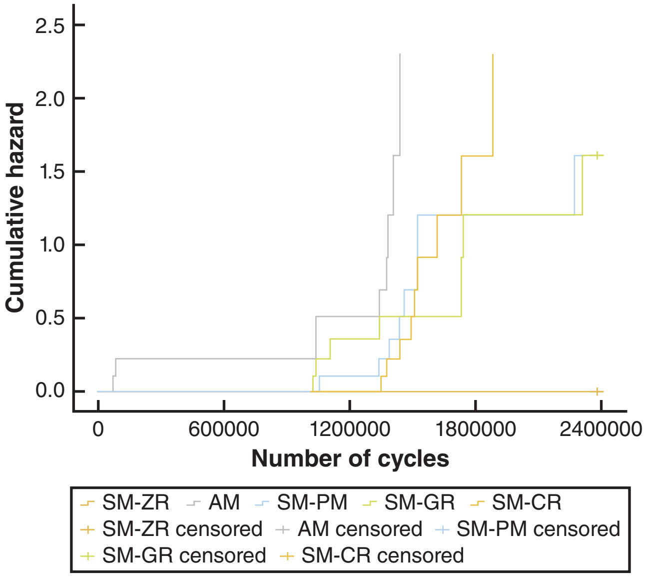

Figure 5. Cumulative hazard curves of tested materials after cyclic loading. AM, additively manufactured interim resin; SM-CR, high-impact polymer composite resin; SM-GR, graphene-reinforced polymethyl methacrylate; SM-PM, polymethyl methacrylate; SM-ZR, strength gradient zirconia.

Table 3. Results of Cox regression analysis after 2.4 million loading cycles

Materials	Hazard Ratio	95% Confidence Interval	
		Lower	Upper
AM	85.08	9.76	608.55
SM-PM	17.26	2.01	140.48
SM-GR	15.55	2.17	125.35
SM-CR	23.60	2.91	189.56
SM-ZR	-	-	-

reason for the high number of failures may be the length of the cantilever. Clinically, both molars and premolars can be replaced with cantilevered prostheses,[36] and, considering that a premolar is narrower than a molar, tested polymer-based materials may be more resistant to failure when the cantilever length is decreased. Increasing the cross-sectional thickness of the cantilever may also increase the failure resistance of the tested materials. The cantilever length can be smaller or a cantilever can be avoided to prevent fractures with polymer-based frameworks. Considering that SM-ZR specimens survived 2.4 million loading cycles under high loads with tested dimensions confirms the rationale for the clinical choice of SM-ZR as a definitive material for implant-supported complete arch prostheses with small cantilevers. The tested polymer-based materials mostly survived the initial 1.2 million loading cycles, and they may at least be considered for long-term interim restorations with a cantilever of the tested dimensions. Nevertheless, these recommendations should be substantiated with in vivo studies with long-term follow-ups.

Previous studies on cantilevered implant-supported prostheses have focused mainly on the load to failure analysis of zirconia or polymer-based materials with or without Ti-base abutments.[3,10,21,23,25,26] Yilmaz et al[25] compared different high-density polymers, an autopolymerized acrylic resin, and an injection-molded acrylic resin after thermocycling and concluded that high-density polymers of different brands had varying load-to-fracture values. In another study,[21] increased thickness and decreased cantilever length were shown to result in higher fracture loads of thermocycled rectangular prism-shaped translucent zirconia specimens without a Ti-base space. Alshahrani et al[23] reported that an additively manufactured resin for denture teeth had a lower fracture load than polymethyl methacrylate and had mostly higher fracture loads than zirconia-reinforced heat-polymerized polymethyl methacrylate. However, those studies[21,23,25] were performed on rectangular prism-shaped specimens without considering the Ti-base space. Selva-Otaolaurruchi et al[10] recently evaluated SM-GR in a fixed partial denture with a molar cantilever and concluded that SM-GR had higher fracture load and resisted cyclic loading for a longer duration than subtractively manufactured polymethyl methacrylate. However, in the present study, 2 specimens from both SM-PM and SM-GR survived the cyclic loading, and there was no clear trend as to which material resisted loading for a longer duration. This difference between the present study and that of Selva-Otaolaurruchi et al[10] may be related to the differences in specimen geometry, the tested polymethyl methacrylate, and the fact that the specimens were subjected to 240 000 loading cycles by Selva-Otaolaurruchi et al.[10] Two studies focused on the fracture load of Ti-base integrated specimens.[3,26] Yilmaz et al[26] concluded that the integration of the Ti-base space reduced the fracture load of high-performance polymers of different chemical compositions and also of cubic zirconia. Batak et al[3] tested high-density polymers, which had similar fracture load values that were lower than those of zirconia. Based on the results of the present and those previous studies that involved zirconia,[3,26] it can be stated that zirconia is more resistant to fracture in a cantilevered situation than polymer-based materials and that the Ti-base space is a potential area of fracture.

The authors are unaware of a previous study that tested materials in an implant-supported cantilevered situation when subjected to cyclic loading. Therefore, a priori power analysis to determine the number of specimens in each group could not be performed. Nevertheless, the study design and sample size enabled the detection of significant differences for cumulative survival and hazard ratio. The methodology of the present study has been used in previous studies investigating the load-to-failure performance of cantilevered fixed prostheses with a Ti-base space.[3,25,26] However, this design does not involve an implant that supports the Ti-base that acts as a fulcrum, and the number of loading cycles in which the specimens failed during loading may be lower in an actual clinical situation. In addition, a standard Ti-base abutment with 4.5-mm diameter was used. However, an abutment with a larger diameter, such as a custom abutment, may also lead to a reduced number of loading cycles, considering that a wider Ti-base space would weaken the material, even though the bond strength would have been increased. Nevertheless, the current arrangement enabled comparisons of the performance of tested polymer-based specimens with zirconia specimens as the control.

Limitations of the study included that, even though all specimens were fabricated and cemented according to the manufacturers' recommendations, only one 3D printer, one milling unit, and one luting composite resin were used. Another limitation was that the tested additively manufactured resin was marketed for interim restorations only. Additively manufactured resins for definitive prostheses, containing ceramic fillers and possibly with a higher fracture resistance, have been marketed recently.[16] These more recent resins should be tested with a similar study design to understand whether claimed reinforcement enables improved survival rates. The cyclic loading methodology did not involve a liquid medium or thermal changes. Even though the specimen design tested in the present study has been used previously,[30] cylinder-shaped specimens do not fully simulate clinical conditions. Therefore, future studies that involve saliva and thermal changes with more specimens with actual cantilevered fixed partial designs and different resin cements are needed to corroborate the findings of the present study.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. Material type affected the survival and hazard ratio of tested materials in a simulated cantilevered implant-supported fixed prosthesis situation. Strength gradient zirconia had the highest survival rate with no failed specimens during cyclic loading.
2. Most of the polymer-based specimens failed during cyclic loading; however, most of these failures occurred when the load was 200 N. Tested polymer-based materials had a significantly higher hazard ratio than strength gradient zirconia, additively manufactured resin having the highest ratio. Nevertheless, survival possibility may increase with increased cross-sectional prosthesis dimensions.

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Corresponding author:

Dr Mustafa Borga Dönmez
Department of Reconstructive Dentistry and Gerodontology
School of Dental Medicine
University of Bern
Freiburgstrasse 7
Bern 3010
SWITZERLAND
Email: mustafa-borga.doenmez@unibe.ch

CRediT authorship contribution statement

Mustafa Borga Donmez: Drafting article, Critical revision of article. **Gülce Çakmak**: Concept/Design, Methodology, Investigation. **Mehmet Esad Güven**: Data collection, Investigation. **Doğu Ömür Dede**: Methodology, Investigation. **Samir Abou-Ayash**: Drafting article. **Burak Yilmaz**: Concept/Design, Data interpretation, Critical revision of the article, Approval of the submitted and final versions.

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