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ORIGINAL ARTICLE

Are implants more reliable than severely compromised endodontically treated teeth as abutments for zirconia-based FPDs?

In vitro results of long-term preclinical load simulation

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Abstract
Objectives The aim was to study the impact of the defect size of endodontically treated incisors compared to dental implants as abutments on the survival of zirconia two-unit anterior cantilever-fixed partial dentures (2U-FPDs) during 10-year simulation.
Materials and methods Human maxillary central incisors were endodontically treated and divided into three groups (n=24): I, access cavities rebuilt with composite core; II, teeth decoronated and restored with composite; and III as II supported by fiber posts. In group IV, implants with individual zirconia abutments were used. Specimens were restored with zirconia 2U-FPDs and exposed to two sequences of thermal cycling and mechanical loading. Statistics: Kaplan–Meier; log-rank tests.
Results During TCML in group I two tooth fractures and two debondings with chipping were found. Solely chippings occurred in groups II (2×), IV (2×), and III (1×). No significant different survival was found for the different abutments (p=0.085) or FPDs (p=0.526). Load capability differed significantly between groups I (176 N) and III (670 N), and III and IV (324 N) (p<0.024).
Conclusion Within the limitations of an *in vitro* study, it can be concluded that zirconia-framework 2U-FPDs on decoronated teeth with/without post showed comparable in vitro reliability as restorations on implants. The results indicated that restorations on teeth with only access cavity perform worse in survival and linear loading.
Clinical relevance Even severe defects do not justify *per se* a replacement of this particular tooth by a dental implant from load capability point of view.

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Keywords Implant · Dynamic loading · Post-and-core technique · Dowel · All-ceramic · Dental abutment

Introduction

The clinical survival rates of endodontic treatment are well documented [1–3]. When it comes to prosthetic treatment, endodontically treated teeth (EET) are often judged as less valuable abutments with regard to reliability and cost-effectiveness compared to vital teeth [4]. As endosseous dental implants gain acceptance due to their high success, the question arises, whether a tooth with a more or less questionable prognosis should be preserved—including endodontic treatment—or be rather strategically extracted in preparation for a dental implant [5–7]. However, it has been stated that extraction frequently leads to changes of the alveolar ridge due to bone remodeling [8], which often requires reconstructive surgery to create a functional pontic area [9], or to establish a functional and esthetical soft tissue around dental implants [10]. In particular when bone grafting procedures [11] or adjacent implants [12, 13] are involved, it is a clinical disadvantage of implant-based restoration that it may be difficult and challenging to establish sufficient soft tissue.

In contrast, Holm-Pedersen et al. [14] demonstrated that the 10-year survival rate of teeth surpasses that of implants, when failures before loading were included in the analysis. Survival rates of single-tooth implants and EET after 5 to ~8 years were not statistically different. Systematically reviewed data over 3 to 25 years showed that the survival rates after endodontic treatment followed by coronal restoration were ~81 to 100 % [15]. Three systematic reviews [15–17] confirmed that teeth with endodontic treatment and implant-supported restorations have similar long-term survival.

Thus, for a sound clinical recommendation, it would be necessary to directly compare these different treatment options. Therefore, a first efficient step is a long-term preclinical loading, which appears appropriate to simulate mechanical loading during clinical function [18, 19]. In a second step, promising treatment approaches should be compared in clinical pilot studies and after that, long-term clinical trials with decent large sample size were defined by power analysis with clearly defined outcome criteria [16]. Therefore this in vitro study was designed to investigate the survival of all-ceramic zirconia-framework two-unit anterior cantilever-fixed partial dentures (2U-FPDs), which were fixed either on endodontically treated maxillary central incisor abutments or implants. The null hypothesis tested was that there is no difference regarding the long-term survival of all-ceramic zirconia-framework 2U-FPD when endodontically treated maxillary central incisors and dental implants were used as abutments during 10 years of preclinical load simulation. Fracture load of the surviving restorations was determined to estimate the load capability of the restorations after thermal cycling and mechanical loading (TCML).

Material and methods

Specimen pre-treatment

Human maxillary incisors were selected and stored at room temperature in a 0.5 % chloramine solution. To ensure the use of teeth of comparable dimension within the groups, mesio-distal (MD) and facial-lingual (FL) dimensions were measured at the level of the cemento–enamel junction (CEJ). A size assessment was calculated from the product of MD×FL. Extremely small or large teeth were excluded. Specimens were randomly distributed into three groups (n=8) by means of a ten-digit random table [20]. Root canals were enlarged using the X-Smart (Dentsply DeTrey, Konstanz, Germany) and NiTi-files to size F2 (Protaper, Dentsply DeTrey) and rinsed with 3 % sodium hypochlorite. Root canal was filled by corresponding size F2 of gutta-percha (F2, Protaper, Dentsply Maillefer, Konstanz, Germany) and sealer (AH 26 Plus Jet, Dentsply Maillefer, Konstanz, Germany).

The roots of the specimens were blocked out with wax 2 mm below the CEJ. To imitate a human periodontium and physiological tooth mobility, the roots of the teeth were covered with a layer of silicone (Mollosil Plus; Detax, Ettlingen, Germany) as described elsewhere [21]. All teeth and implants (group IV, n=8) were embedded in acrylic resin (Technovit 4004, Kulzer, Wehrheim, Germany) directing their axes 45° from the horizontal line. To prevent overheating, the teeth were submerged in water for 5 min during resin polymerization. To simulate a neighboring tooth and avoid distortion of the restoration within the simulated alveolar socket, a duroplast tooth analog (canine, Frasaco, Tettnang, Germany) was placed with a tight proximal contact.

Preparation

Group I access cavity only

All restorative steps were performed using the Dentsply Core & Post System (CTS, Dentsply DeTrey, Konstanz, Germany). The etch-and-rinse and bonding procedure was performed according to the manufacturers' instruction. The root canal and the coronal tooth surface were etched with 37 % phosphoric acid (Conditioner 36, Dentsply DeTrey) and bonded (XP Bond, Self-cure Activator, Dentsply DeTrey, 1:1 ratio, mixed for 2 s). The access cavity was filled with dual-curing composite resin core build-up material (Core-X flow, Dentsply DeTrey) starting 3 mm below the CEJ level. The composite resin was polymerized (Optilux light curing unit, Demetron

Research Corp., Danbury, USA) from the incisal, palatal, and facial aspect (20 s each site).

Group II decoronated

The crowns were cut 2 mm coronal to the most incisal point of the proximal CEJ. Access cavity was extended 3 mm below the CEJ. The dentin core was built up using the core build-up material in the respective etch-and-rinse and bonding steps as described in group I with means of a strip crown (upper central incisor, Frasaco, Tettnang, Germany). The core build-up was polymerized from each site for 20 s (Fig. 1).

Group III decoronated with post

All treatment steps were performed as in group II, but a quartz-fiber post (size 2 (red), Ø 1.25 mm, X-Post, CTS, Dentsply DeTrey) was additionally placed 8 mm within the root canal. Post space preparation was performed in one sequence as described by the manufacturer. The core build-up material was used for post cementation and core build-up (Core-X™ flow, Dentsply DeTrey). The post was shortened during crown preparation (Fig. 2).

Group VI implant restoration

Dental implants (Xive, length 11 mm, diameter 3.8 mm, Dentsply Friadent, Mannheim, Germany) were restored with prefabricated zirconia all-ceramic abutments (Hexagon driver 1.22 with a maximum torque of 24 Ncm, 22 LOT B090004782 Dentsply Friadent). Abutments were prepared in a 10° to 15° angulation palatal to the canine tooth axis (Fig. 3).

The cavities in all groups where filled in one increment. All polymerisation was done with light curing unit Astralis 5 (500 mW/cm^2, Ivoclar-Vivadent, Schaan, Liechtenstein).

Fig. 1 Specimen preparation of group "decoronated without post" (II): *left*, after decoronation; *middle*, strip crown placed for core build-up; *right*, after core build-up

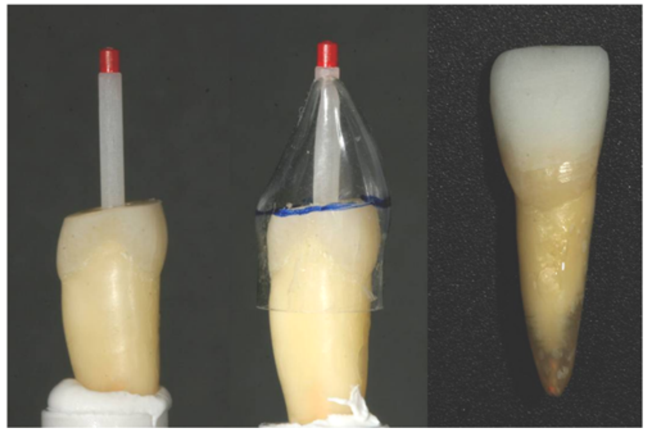

Fig. 2 Specimen preparation of group "decoronated with post" (III): *left*, after decoronation; *middle*, strip crown placed for core build-up; *right*, after core build-up

Restorations

All teeth were prepared with a circumferential 1.2-mm shoulder, a 1.5-mm incisal reduction, and 6° convergence angle to meet all-ceramic crown requirements. The margin was located 2 mm below the core build-up in dentin to ensure proper ferrule design. For the implant group, impression copings for pick-up technique (Transfer Copings for pick-up technique with transfer cap D3.8/GH5 LOT B090003992, Dentsply Friadent Germany) were fixed (Hexagon driver 1.22 mm for ratchet with a maximum torque of 24 Ncm 1.22 LOT B090004782, Dentsply Friadent). Impressions were taken from all specimens using silicon material (Aquasil Ultra Heavy as tray, Aquasil Ultra LV as wash material). Temporary crowns (Integrity, Dentsply DeTrey) were cemented on specimen teeth with a not eugenol containing provisonal cement (Integrity TempGrip, Dentsply DeTrey). The gypsum casts (Resin-Rock, typ IV

Fig. 3 Zirconia two-unit anterior cantilever-fixed partial denture fixed on prefabricated zirconia all-ceramic abutment restored implant, canine used to ensure tight proximal contact point to cantilever unit reducing rotational forces

resin-reinforced gypsum, Whip-Mix, USA) and implant abutments placed on implant laboratory analogues were scanned (Cercon Eye Scanner, software cerconart 3.0.2, DeguDent, Hanau, Germany) and zirconia frameworks milled (spacer 30 μm, frame work thickness 0.5 mm, connector size 9.5 mm^2) and veneered (Cercon Ceram Kiss; DeguDent) under standardized conditions. Liner (970 °C), two times dentin (820 and 830 °C) and glaze (800 °C) were applied and fired according to the manufacturer's instructions. Thickness of the veneering varied according to the preparation between 0.7 and 1 mm.

The frameworks were sand blasted (Al_2O_3 50 μm, 2 bar, KaVo EWL, Biberach, Germany) at the inner surface and a thin layer silane (Calibra Silane; Dentsply Caulk, Milford, USA) was applied and allowed to set for 1 min. Provisional crowns were removed and teeth were cleaned with chlorhexidindigluconat (CHX 0.12 %, Sunstar Suisse SA, Etoy, Switzerland).

The dentin and enamel areas of the tooth were acid etched and rinsed as described for group I, composite build-ups were not treated. XP Bond and SCA were mixed in a 1:1 ratio and applied at the tooth and the inner surface of the frame work, left for 20 s, and air dried. Catalyst and base material of the composite resin cement were mixed for 30 s in a 1:1 ratio (Calibra esthetic resin cement, Catalyst Regular Viscosity/ Calibra Base Dark, Dentsply Caulk, Milford, USA) and applied into the crown. The two-unit crowns were cemented and a chemically initiated setting was allowed for 5 min (Fig. 3).

Loading protocol

TCML was performed (parameters: $2\times3{,}000$ thermal cycles, 5/55 °C, 2 min each cycle; distilled water; 1.2×10^6 mastication cycles with 50 N) to simulate 5 years of clinical service [18, 19]. The restorations were loaded under 135°, 3 mm below the incisal edge, on the palatal surface of the cantilever crown unit, i.e., lateral incisor. If no failure occurred a second sequence with identical parameters was performed. If again no failure occurred the specimens were statically loaded in a universal testing machine (Zwick 1446, Zwick, Ulm, Germany; v=1 mm/min) until failure. Failure detection was set at a 10 % loss of the maximum applied force. To reduce excessive stress concentrations, a 0.3-mm-thick tin foil was positioned between the steel piston and the palatal crown surface. A failure was judged as catastrophic when re-restoration was not possible.

Statistical analysis

Kaplan–Meier survival plots were constructed (Fig. 4). The number of cycles until failure was compared with log-rank statistics. Non-parametric Kruskal–Wallis and Mann–Whitney U test as post hoc were applied to determine differences between group median of the maximum load capability F_{max}. Differences in the frequency of the failure modes between the groups were evaluated by Fisher exact test. Data were pooled and categorized into three patterns: chipping, debonding, and chipping judged as technical failures and fracture within the root. All statistics were two-sided at α=0.05.

Results

The number of total failures during TCML varied between one (group III) and four (group I). After 1.2 Mio mechanical loadings (first TCML interval), two specimens of group I (25 %) fractured within the abutment tooth, and one specimen of group IV (12.5 %) showed chipping at the cantilever unit. During the second TCML interval (1,580,000 loadings) one debonding combined with chipping was observed in group I. After 2.4 Mio mechanical loadings, one chipping was found in groups I, II, and IV. In group I, chipping was combined again with debonding of the restoration (Table 1). Chipping areas bigger than 2 mm^2 were characterized as non-polishable. The log-rank analysis of the Kaplan–Meier survival plots (Fig. 4) revealed no statistical significant differences after 2.4 Mio loadings among the groups (p=0.08), neither at the abutment level (severely damaged teeth or zirconia abutment; p=0.085) nor restoration level (2-unit FPD; p=0.526). The number of fractures was not significantly different after TCML (p=0.157). Failed specimens were excluded from further testing and were assigned a static load of "F_{max}=0" [22].

Median fracture load varied between 176 N (group I) and 670 N (group III). The Kruskal–Wallis test revealed significantly (p=0.025) different load capabilities between the groups. The pair-wise comparison showed significant differences between groups I and III (p=0.024) as well as group III and IV (p=0.014). The comparison of the frequency of the fracture patterns revealed significant differences after linear loading (p=0.012). Table 1 provides detailed information about the type of failure. Figure 5 shows failure modes during thermo-mechanical loading and Fig. 6 a typical failure.

Discussion

To the best of our knowledge, this is the first study investigating zirconia 2U-FPDs, comparing endodontically treated teeth with moderate to large defects and implants as abutments. Specimens were exposed to a prolonged preclinical chewing simulation by TCML, which aims to simulate 10 years of clinical function. The failure rates varied from 25 to 50 % after 2.4 Mio dynamic load cycles. Teeth with

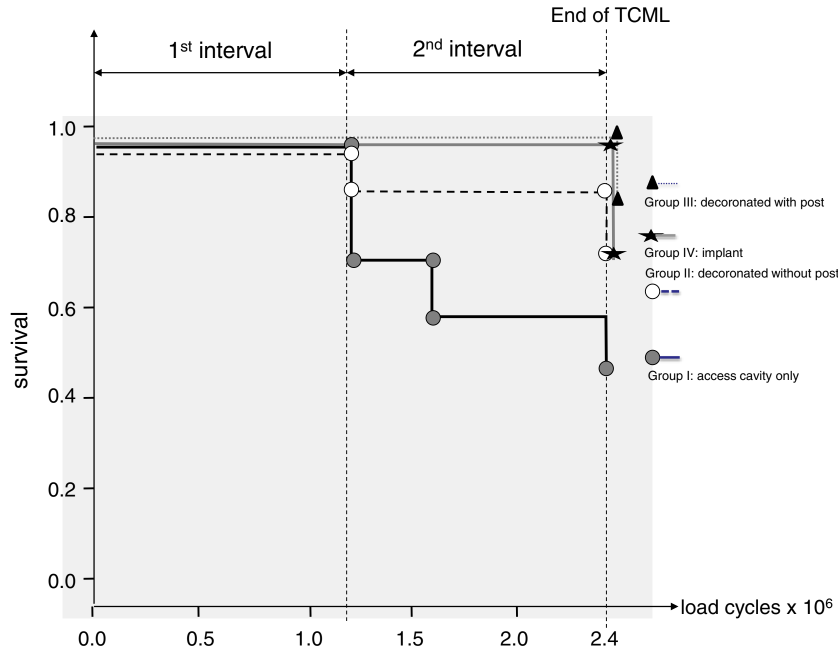

Fig. 4 Kaplan–Meier plots of the experimental groups during 5- and 10-year simulation of clinical functional forces by TCML with 1.2 and 2.4×10^6 cycles between 1 and 49 N and thermo-cycles between 5 and 55 °C in distilled water, respectively

only an access cavity restored with core build-up composite resin performed worse. The study confirmed the null hypothesis that there is no difference regarding the long-term survival of all-ceramic zirconia-framework 2U-FPD, irrespective whether damaged endodontically treated maxillary central incisors or dental implants served as abutments.

Artificial aging, which combines TCML [23], provides a sufficient prognosis of probable clinical failure [18], and was already successfully applied for post-and-core restoration [20, 24] and anterior resin-bonded FPDs [25, 26]. Limitations of this *in vitro* test assay for clinical conclusions should be expected due to the limited number of specimens and the small number of appearing complications at abutment level.

A prolonged TCML includes fatigue phenomena and is of utmost importance to increase the predictive power of *in vitro* data in terms of clinical survival of a restoration [27]. It may also help to exclude catastrophic clinical failure [18]. The bonding, core build-up, and post materials which were used perform well under *in vitro* conditions [28], [29]. Also,

Table 1 Number of preliminary failures and cycles until failure during TCML, failure type and mean values for the load capability in [Newtons] of load testing after TCML, and number of catastrophic fractures

Group	*n*	Distance CEJ[a]—apex (min/max) [mm]	Total length (min/max) [mm]	Preliminary TCML failure [*n*]	Cycles until failure	Failure type after TCML	Median (min/max) F_{max} [N]	Failure type after linear loading [*n*]
Access cavity only	8	17 (16/19)	24 (23/26)	4	2×1,200,000	Crashed within tooth[b]	176	4× chipping
					1×1,580,000	Debonding + chipping	(0/556)	
					1×2,400,000	Debonding + chipping		
Decoronated	8	17 (16/18)	19 (18/25)	2	2×2,400,000	Chipping	311	2× chipping
						Chipping[b]	(0/892)	3× build-up fracture[b]
								1× tooth fracture[b]
Decoronated with post	8	17 (16/17)	19 (18/19)	1	1×2,400,000	Chipping	670	5× chipping
							(0/997)	1× debonding
								1× tooth fracture[b]
Implant	8	–	11	2	1×1,200,000	Chipping	324	1× chipping
					1×2,400,000	Chipping	(0/755)	3× debonding + chipping
								2× abutment fracture[b]

[a] Cemento–enamel junction

[b] Catastrophic failure (chipping>2 mm^2 ; not to polish)

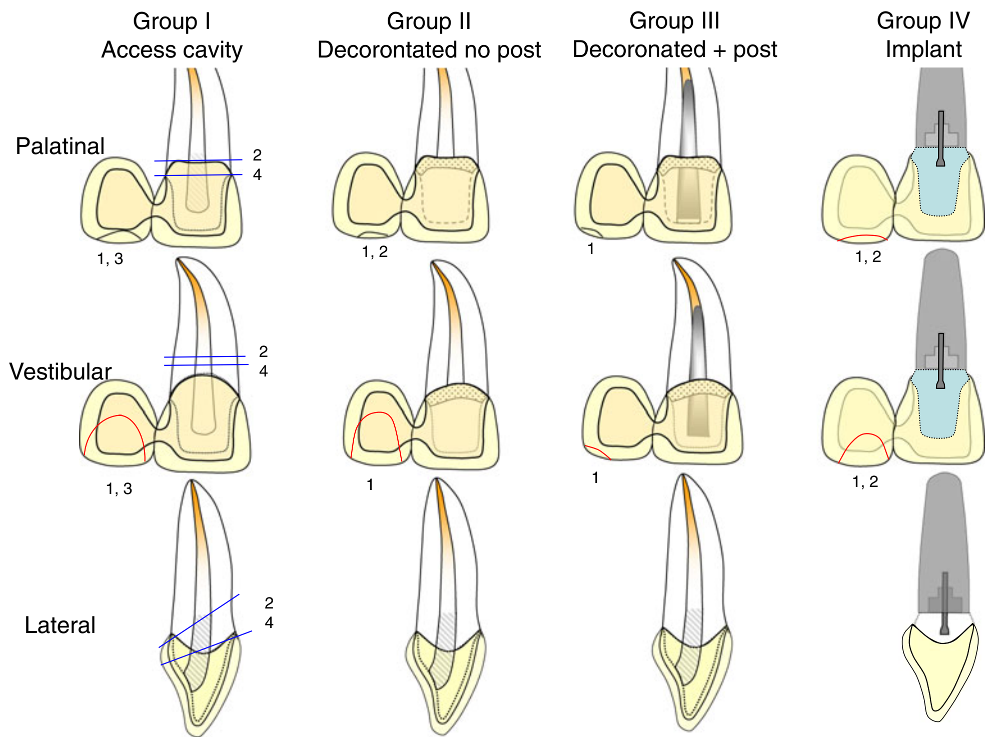

Fig. 5 Failure modes per group during chewing simulation (TCML), *red line* represent chipping, *blue line* level of tooth fracture (number of failure)

the dual-curing composite resin shows good performance *in vitro* and *in vivo* [30–33]. The approach to use core build-up resins for cementation already provided promising results [34, 35]. The data show that composite core build-ups provide good experimental and *in vivo* experience and might therefore be sufficient for a cantilever FPDs.

Due to the lack of *in vivo* and *in vitro* data, we are not able to compare the results directly to existing scientific literature. Thus, analogies must be drawn to single-crown restoration data in the anterior region or data of conventional cantilever FPDs in the molar region. *In vitro* and *in vivo* investigations show that anterior resin-bonded cantilever-fixed prostheses made of all-ceramic seem to be an alternative to two-retainer restorations or FPDs [25, 26, 36]. Ohlmann et al. state that the *in vitro* fracture strength of cantilevered FPDs may not be sufficient for a molar clinical application [37]. Nevertheless,

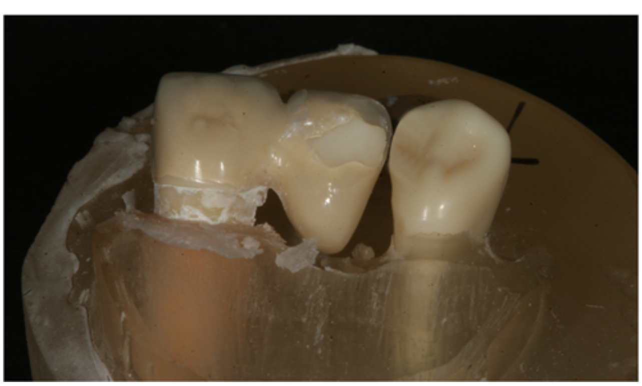

Fig. 6 Failure after TCML (example group III)

the success of cantilever zirconia restorations seems to depend on fabrication technique and the loading situations [38]. Promising clinical results for zirconia FPDs with end abutment or cantilever design show only marginal differences between these groups after 4-years clinical application [39]. During the simulation, most failures in all groups were chipping of the veneering ceramic. This is an actually discussed problem with ceramic-veneered zirconia restorations [40], which might be related to the design, material quality, or fabrication process of the veneering material, but not to the type of restoration or abutment as such. Small differences were found between tooth- or implant-supported restorations. Both show low numbers of catastrophic failures, but high rate of complications, especially chipping, under clinical conditions [41]. However, it can be stated that chipping might in most cases not lead to a re-restoration. After polishing of the damaged ceramic surface the restoration will remain in function.

The worse performance in group I might be explained by effects of the high polymerization shrinkage stresses [42, 43] within the root canal and access cavity itself, which might be due to the large configuration factor [44]. Only in the group with access cavity, half of the specimens failed. As half of the chippings were combined with debonding, the assumption that shrinkage or adhesive problems may influence the performance seems proximate. An explanation of the results might be found in the rigidity of the whole restorative complex “tooth rebuilt with composite resin” (group I) compared to “teeth rebuilt with (group III) or without (group II) endodontic post-and-composite resin", which might lead to a higher stress on the cement interface. Different modulus of core and dentin and the individual share of both materials influence the stability of the whole system. Bonding between cement and dentin or between cement and composite is strictly different, which might influence the stability of the whole system: Fracture results of the surviving restorations indicate clear differences between the three types of restorations, supporting the worse performances of group I. However, this would mean that a core build-up material alone as in group II seems stiffer than a combination of core build-up and dentin tissue. There is no external evidence to support this assumption. Thus, more research on this surprising finding is needed.

Based on clinical data, we know that crowned glass-fiber post-restored maxillary incisors with three or four remaining cavity walls, i.e., an access cavity, show survival rates >98 % after a mean observation period of 5.3 years [45]. Serious catastrophic tooth fractures were found in 25 % of the specimens. The loading on the cantilever during the simulation process might have caused a strong tilting and torsion moment on the restoration. These oblique, non-axial forces due to the loading at the cantilever unit, were highlighted as risk factor for fatigue fracture of brittle tooth material [46, 47], and may explain the tooth fractures of the present investigation. In terms of defect extension [44], the decoronated teeth of groups II and III seemed to be more jeopardized. Lower failure rates might be attributed to improved adhesive and mechanical properties of the core materials, and the use of the post. Although not significant, the high failure rate suggests that incisors with only an access cavity may be less reliable over 10-year clinical function. Whether an additional post placement in such cases would be advantageous should be investigated in future studies.

Fracture load testing demonstrated lowest fracture resistance for group I with access cavity, which might confirm the low survival rate during TCML. A supporting post effect in group III compared to group II could not be demonstrated. However, the fracture results of group III with post were higher in comparison to the implant group IV and access cavity group I. It should be kept in mind that load capacity tests do not show a direct clinical relevance, but they may allow for the detection of premature subcritical damages during the simulation process and further on a differentiation between the individual groups.

Other laboratory [20] and clinical [48] studies confirmed that post placement seemed beneficial for single-tooth restorations, when no cavity wall remained. Implant-based restorations were not superior to restorations on decoronated, severely damaged teeth, which were long-term preclinically loaded by TCML.

Conclusion

Within the limitations of an *in vitro* study, it can be concluded that zirconia-framework 2U-FPDs on decoronated teeth with/without post showed comparable *in vitro* reliability as restorations on implants. The results indicated that restorations on teeth with only access cavity perform worse in survival and linear loading.

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

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