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Original article

Partial fixed dental prostheses fabricated using fiber-reinforced composite resin supported by short and extra-short implants: A case series

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Abstract

Purpose: This study aimed to evaluate the 10-year outcomes of partial fixed dental prostheses (P-FDPs) fabricated using metal-free fiber-reinforced composite (FRC) resin frameworks veneered with composite resin and supported by short and extra-short implants.

Methods: This study included 28 patients with 38 FRC prostheses supported by 96 implants. Implant and prosthesis survival and success rates were evaluated using Kaplan-Meier analysis.

Results: The 10-year implant survival and success rate, as determined by Kaplan-Meier analysis, was 96.9%, and the prosthesis survival and success rates were 94.7% and 92.0%, respectively. None of the parameters under investigation were significantly correlated with prosthetic survival or successful outcomes, but three parameters were correlated with higher peri-implant bone levels: implant placement in the mandible as opposed to the maxilla, shorter P-FDP spans, and natural teeth on the opposing arch.

Conclusions: FRC P-FDPs supported by short and extra-short implants presented high, up to 10-year, survival and success rates, when used to restore partially edentulous arches.

Keywords: Dental implants, Dental prosthesis, Dental materials, Survival rate

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1. Introduction

Partial fixed dental prostheses (P-FDPs) supported by dental implants are cost-effective treatments for patients with partially edentulous arches. Implant-supported P-FDPs are constructed using various materials[1]. However, zirconia FDP frameworks veneered with porcelain exhibit high complication rates, specifically due to high fracture and chipping rates[2]. All-ceramic frameworks provide promising solutions; however, long-term clinical data are lacking when supported by implants[3].

As an alternative to metal and ceramic prosthetic frameworks, fiber-reinforced composite (FRC) resin frameworks can be used to construct both partial- and full-arch FDPs. The FRC resin is a metal-free material that has previously been shown to have high survival rates when used as a full-arch FDPs, with fracture and chipping rates lower than those of metal and ceramic frameworks[4,5]. The successful use of FRC resin as a framework material has been partially attributed to its high flexural strength with a flexural modulus of elasticity similar to that of cortical bone[6–9].

In addition to the properties of the restorative framework material, the success of implant-supported full-arch FDPs depends on the type of the supporting implant. Implant design and prosthetic attachment have been shown to influence the distribution of forces in the surrounding bone[10,11]. Particularly, a conical locking taper connection facilitates better load distribution. Short (≤ 10 mm, > 6 mm) and extra-short (≤ 6 mm) implants can avoid bone-grafting procedures during implant surgery[12]. A previous study on the implant system under investigation demonstrated 100% survival of FRC full-arch prostheses supported by short and extra-short implants in severely atrophic mandibles over 8 years[4].

A recently published study by the same authors evaluated the 10-year survival and success rates of 121 FRC P-FDPs and reported prosthesis survival and success rates of 95.9% and 89.8%, respectively[13]. Another study on a different implant system investigating resin-bonded FRC FDPs reported a 5-year prosthetic success rate of

WHAT IS ALREADY KNOWN ABOUT THE TOPIC?

» *Fiber-reinforced composite (FRC) resin frameworks can be used to construct both partial and full-arch fixed dental prostheses (FDPs); however, clinical data is scarce.*

WHAT THIS STUDY ADDS?

» *FRC partial-FDPs supported by short and extra-short implants presents high survival and success rates.*

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70%[14]. These results encourage the outcome evaluation of FRC FDPs supported by short and extra-short implants for the rehabilitation of partially edentulous arches. While the overall survival and success rates of FRC P-FDPs are encouraging, especially when supported by the locking taper short or extra-short implants of the system under investigation, past studies have not shown detailed analyses of marginal bone levels. Instead, by only reporting average changes in marginal bone levels, studies have obscured the distinction between early and late bone loss. Additionally, previous studies with larger cohorts did not account for the influence of specific clinically relevant variables, such as short versus extra-short implants, screwed versus cemented restorations, or clinician experience, on implant and prosthetic outcomes.

Therefore, this study aimed to evaluate the 10-year outcomes of FRC P-FDPs supported by short and extra-short implants. To explore the influence of various patient-, implant-, and prosthesis-related factors in detail, a study cohort distinct from that of the previous study was enrolled, and the patients were treated by only one clinician. The survival and success rates of the FDP prostheses and supporting implants were evaluated. The marginal bone levels surrounding the implants were recorded and analyzed in temporal detail to uncover potential trends in early and late peri-implant bone-level changes.

2. Materials and Methods

Patients were selected with the approval of the Institutional Ethics Committee (No. 018/2011). This study was designed in accordance with the Declaration of Helsinki and Good Clinical Practice guidelines. The results are reported according to the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) criteria[15].

Patients who received FRC FDP prostheses for the treatment of partially edentulous arches at the CMF Institute, Vienna, between 2012 and 2021 were included in this study. Data collection began in 2012 and continued until 2022. Only patients with prostheses supported by short or extra-short implants (Bicon LLC, Boston, USA) were included. Of the 32 patients who met the inclusion criteria, one whose prosthesis was supported by a combination of implants from different systems was excluded from the study. Three patients who did not return for follow-up visits after prosthesis insertion were also excluded. One clinician, R.E., was responsible for all the surgical and restorative procedures.

After applying inclusion and exclusion criteria, 28 patients were finally included in the analysis. All the patients' prostheses were supported by only short (≤ 10 mm, > 6 mm) and extra-short (≤ 6 mm) implants, all of which had hydroxyapatite coatings (Integra-CP, Bicon LLC)[12]. The implants were placed according to the manufacturer's recommended two-stage protocol using the manufacturer's instrumentation (Surgical Kit; Bicon LLC). Mandibular implants were uncovered after at least three months of osseointegration healing time, and maxillary implants were provided for at least six months. Impressions for the prostheses were made using Polyether Impression Material (3M™ ESPE™ Impregum™ Penta™ Polyether Impression Material, 3M), using the manufacturer's impression copings (Restorative Kit, Bicon LLC). Frameworks for prostheses were milled from FRC disks or blocks (TRINIA, Bicon LLC), and veneered with either HC Disks (Shofu, Kyoto, Japan), Ceramage (Shofu), or denture teeth (Physiostar NFC+, Candulor, Switzerland; SR Phonares II, Ivoclar Vivadent, Lichtenstein). Some prostheses were finished with indirect composite resin (Ceramage, Shofu) to establish gingival aesthetics. The prostheses were attached to the abutments either by cement or screws (Fixed-Detachable Abutments, Bicon LLC.) The prostheses were adjusted with occlusal articulating films (BK01 articulating paper, Bausch) to obtain simultaneous and bilateral teeth contacts with the opposing dentition.

The following data were recorded for each patient: sex, presence of systemic and oral risk factors associated with implant failure (smoking, diabetes, cardiovascular disease, anti-resorptive drug use, severe periodontitis, etc.), and date of the most recent follow-up visit. Additionally, the date and position of the implant placements, their diameter, length, locking taper conical connection bore diameter, and surface treatment of the implant should be considered. The bone grafting procedures and presence or absence of a hemispherical abutment base were recorded for each implant. For each prosthesis, the date of insertion, location of the abutments and pontics, span of the prosthesis, presence of cantilever extensions, and material of the opposing dentition were recorded. The dates of all implant and prosthetic complications were recorded.

The marginal bone levels (MBL) surrounding each implant were measured using radiographs obtained at the time of prosthesis insertion and at the most recent follow-up visit. Panoramic radiographs, which have been shown to provide similar or even superior accuracy compared to alternatives such as periapical radiographs, were used for MBL measurement[16,17]. The measurement scale was calibrated using the length and diameter of the implant before each measurement, to adjust for possible distortions in the radiographs. Y.C. measured each implant twice, and the measurements were compared for plausibility and confirmed by R.E. MBL was defined as the vertical height from the tip of the implant shoulder to the bone level on the sides of the implant and was measured for both the mesial and distal sides and averaged (**Fig. S1**). Line charts were used to represent the bone levels around each implant to facilitate the visualization of trends in the MBL changes. Additionally, 24-month moving average statistics were used to represent average MBL trends over time.

Statistical analyses were performed using the Python software library lifelines version 0.26.0 (Python Software Foundation, Wilmington, USA). The Kaplan-Meier survival analysis was used to analyze the survival and success of the implants and prostheses. Log-rank tests were used to assess significant differences between the Kaplan-Meier survival curves. For each prosthesis, the time from prosthesis insertion to the most recent follow-up or prosthesis removal, whichever came first, was used as the time for Kaplan-Meier analysis. Two one-sided t-tests (TOST) and Mann-Whitney U tests assessed the influence of the study covariates on MBL. Multivariate Cox regression, which has been used to assess dental implant failures, was used to correlate MBL changes with the study covariates[18]. According to the PISA consensus guidelines, < 2 mm of radiographically observed crestal bone loss since the day of implant insertion was considered the outcome variable. As the PISA consensus recommends that marginal bone loss be monitored in increments of 1 mm, peri-implant bone loss of at least 1 mm since insertion was considered a secondary outcome variable[19]. To account for more than one implant placed in each patient, the regression model was clustered by patient using a robust variance estimator that accounts for potential clustering effects in some patient covariates[20].

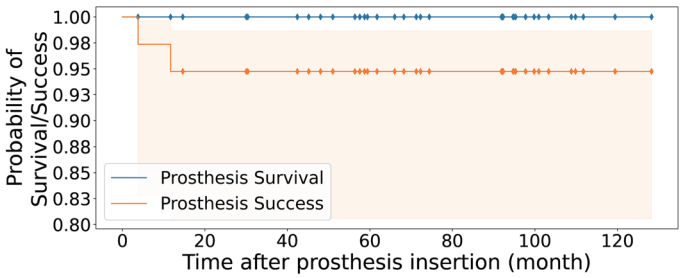

Fig. 1. Kaplan-Meier fiber-reinforced composite fixed dental prosthesis survival and success curves. Shaded areas represent 95% confidence intervals.

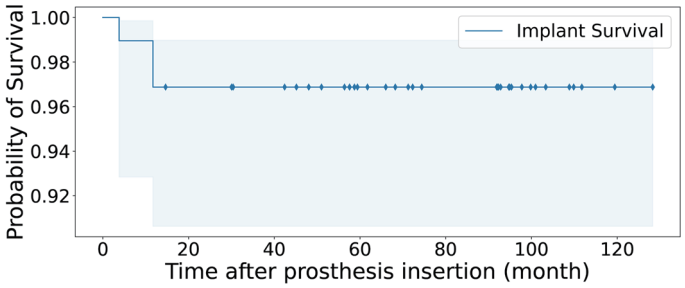

Fig. 2. Kaplan-Meier implant survival curve. Shaded areas represent 95% confidence intervals.

Table 1. Kaplan-Meier analysis of fiber-reinforced composite fixed dental prostheses survival rates

Prostheses at risk	Time (months)						
	0	20	40	60	80	100	120
At risk	38	38	36	33	29	16	12
Censored	0	0	3	4	13	14	10
Prosthesis failed	0	2	0	0	0	0	0
Prosthesis survival probability	1	0.947	0.947	0.947	0.947	0.947	0.947

Table 2. Kaplan-Meier analysis of fiber-reinforced composite fixed dental prostheses success rates

Prostheses at risk	Time (months)						
	0	20	40	60	80	100	120
At risk	38	38	36	32	28	16	12
Censored	0	0	3	4	12	4	10
Prosthesis complication	0	2	1	0	0	0	0
Prosthesis success probability	1	0.947	0.920	0.920	0.920	0.920	0.920

Table 3. Kaplan-Meier analysis of survival of implants supporting fiber-reinforced composite fixed dental prostheses

Implants at risk	Time (months)						
	0	20	40	60	80	100	118
At risk	99	99	94	82	54	45	17
Censored	0	2	12	28	9	31	12
Implant failure	0	3	0	0	0	0	0
Implant survival probability	1	0.97	0.97	0.97	0.97	0.97	0.97

3. Results

Kaplan-Meier survival analysis revealed a prosthesis survival rate of 94.7% at 128 months after prosthesis insertion for the 38 prostheses studied (95% confidence interval [CI]: 80.6%-98.7%). Prosthesis survival was defined as the prosthesis remaining *in situ*, with or without modifications, during the observation period[21]. Prosthesis success, defined by the absence of complications, was 92.0% at 128 months after insertion (95% CI: 77.3%-97.4%). The prosthesis survival and success rates are shown in **Figure 1** and **Tables 1 and 2**.

Kaplan-Meier survival analysis was also used to test for differences in prosthesis success across different patient and prosthesis parameters, including sex, age, systemic and oral risk factors (smoking, diabetes, cardiovascular disease, antiresorptive drug use, severe periodontitis, etc.), prosthesis location (maxilla or mandible, anterior or posterior), presence of cantilever extensions, material of the opposing dentition, prosthesis abutment/pontic ratio, prosthesis span, prosthesis attachment method (cemented vs. screwed), and length of implants supporting the prosthesis. None of the analyzed parameters had significant differences in terms of prosthesis success. The results of the log-rank tests are presented in **Table S1**.

The survival rate of 96 implants supporting FRC FDPs was 96.9% (95%CI: 90.6%-99.0%) 128 months after prosthesis insertion. Implant survival was defined as the presence of implants during the observation period. Implant survival rates are presented in **Figure 2 and Table 3**.

Two instances that affected prosthesis survival were observed, both due to the failure of the supporting implants. Implant failures

were observed 4 and 12 months after prosthesis insertion, and the prostheses were subsequently refabricated. Two implants supported the same three-unit prosthesis and were explanted 12 months after prosthesis insertion. The two implants had 2.5 mm-wide locking-taper bores (MAX 2.5^{TM}, Bicon), distinct from other implants with 2 or 3 mm-wide bores by an enhanced locking-taper connection intended exclusively for single-unit maxillary anterior restorations. However, in this study, the two implants were placed in the posterior maxilla against the manufacturer's recommendations. One of the failed implants was replaced two weeks after explantation, and two additional implants were placed distally from the original prosthesis. The three newly placed implants were used to support a five-unit replacement prosthesis that was refabricated and continued to function well seven years after its insertion at the time of writing this paper. The other failed implant was explanted four months after the insertion of the prosthesis, which was also successfully replaced and loaded with a refabricated prosthesis similar to the original, which continued to function well four years after its insertion.

An additional complication that did not affect prosthesis survival was observed. The adherent crown region at the distal end of a 5-unit prosthesis broke 22 months after insertion and was repaired. For the remaining prostheses, portions made of FRC material were covered with a hybrid composite resin or acrylic; therefore, no wear or discoloration was observed in the FRC material itself. Slight wear was observed in the composite resin portions of the prostheses but did not lead to fracture, chipping, the need for adjustment, or other complications.

Kaplan-Meier survival analysis was also used to test for differences in implant survival and success across different implant parameters, including implant length, implant diameter, implant locking-taper bore diameter, bone grafting procedures, and the presence of a hemispherical abutment base. No significant differences in implant survival or success were found to correlate with any of the parameters analyzed. Results of the log-rank tests are presented in **Table S2**.

The mean MBL at the time of prosthesis insertion was 0.3 mm (SD: ±0.7 mm) below the top of the implant, and it was 0.5 mm (SD: ±0.8 mm) below the top of the implant during follow-up. The average time between initial prosthesis insertion and follow-up was 42.3 months (SD: ±22.9 months). TOST revealed that the bone level distributions upon prosthesis insertion and follow-up were equivalent within the range of ±0.5 mm (P = 0.01). A visual representation of the MBL changes around each implant is plotted in **Figure 3** along with 24-month moving average statistics. The moving average and individual lines showed that the bone levels remained stable over the follow-up period.

To assess the influence of different factors on MBL, TOST and Mann-Whitney U tests were used to evaluate MBL changes as they are related to factors such as the sex, age, presence of systemic and oral risk factors, implant location (maxilla or mandible, anterior or posterior), implant size (length and diameter), locking taper bore diameter, presence of a hemispherical abutment base, opposing dentition (implant supported or natural teeth), prosthesis span, abutment/pontic ratio, method of prosthesis attachment (cemented or screwed), and location of the implant in the prosthesis (terminal abutment, middle abutment, or adjacent to a cantilever extension). Of the fourteen factors analyzed, all but three were found by TOST equivalence testing to have no effect on MBL; variations in the covariates did not lead to changes in bone levels beyond the equivalence bounds of ±0.8 mm (**Table 4**) The three factors that failed TOST were then verified using Mann-Whitney U tests, which confirmed that they significantly influenced MBL. Specifically, peri-implant bone levels in the mandible were higher than those in the maxilla (P = 0.004), peri-implant bone levels with natural teeth on the opposing arch were higher than those opposed by implants (P = 0.007), and peri-implant bone levels in ≤ 3-unit prostheses were higher than those in 4-unit prostheses (P = 0.04), which were higher than MBL in ≥ 5-unit prostheses (P = 0.05). To better illustrate the presence and absence of the effects of these covariates on MBL, visual representations of bone-level changes in relation to different factors are plotted in **Figures 4 and 5**. The presence or absence of significant differences between MBL trends in different cohorts can be visualized by comparing the moving average trend lines of the different cohorts. The detailed results of the Mann-Whitney U tests are shown in **Table S3**.

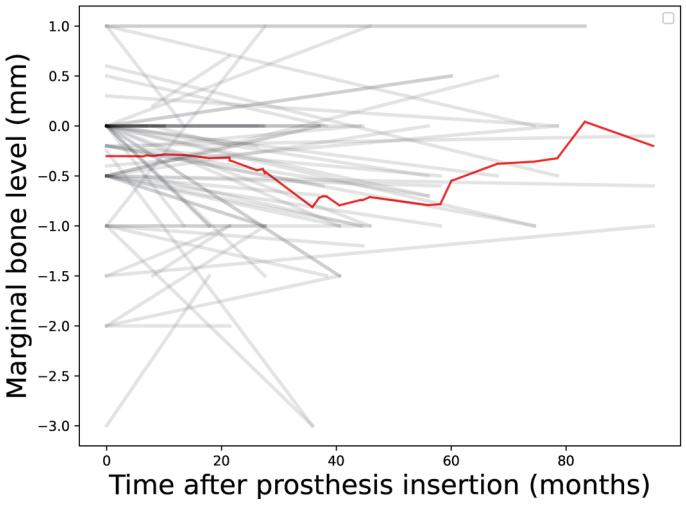

Fig. 3. Visual representation of marginal bone levels (MBL) changes between prosthesis insertion and follow-up. Each gray line represents the MBL change around an implant, and the red line represents the 24-month moving average of MBL over time.

In addition to assessing the influence of study covariates on absolute MBL values, the rate of change in MBL over time was assessed using multivariate Cox regression (**Table 5**). When Cox regression was performed using 2 mm bone loss from the time of implant insertion as the outcome variable, only three implants met the criteria for significant bone loss according to the PISA consensus guidelines on distinguishing between survival and success, resulting in high collinearity in the dataset, which resulted in the regression model failing to converge. All other implants in this study, with < 2 mm bone loss were classified as successful according to the PISA criteria. Following the PISA consensus guidelines that bone loss should be monitored at 1 mm increments, Cox regression was performed once more using 1 mm bone loss from the time of implant insertion as the outcome variable. Out of 16 covariates, only one, posterior location of the implant, was weakly correlated with reduced risk of marginal bone loss (z = -3.16, P = 0.002).

The following case report is representative of the successful use of FRC P-FDPs (**Figs. 6 and 7**). A woman taking denosumab with bilateral maxillary alveolar crestal bone resorption received three short maxillary implants at the age of 56 years (**Fig. 6**). After six months

Table 4. Assessing the effects of covariates on marginal bone levels using equivalence testing

Covariate	TOST *P*-value	Lower threshold		Upper threshold	
		Test statistic	*P*-value	Test statistic	*P*-value
Patient covariates					
Gender	0.001	3.21	0.001	-5.06	< 0.001
Age	0.002	3.02	0.002	-5.49	< 0.001
Systemic and oral risk factors	0.03	5.39	< 0.001	-1.92	0.03
Implant location					
Maxilla vs. mandible	0.11	1.24	0.11	-6.97	< 0.001
Anterior vs. posterior	0.03	3.43	0.001	-1.89	0.03
Implant diameter	< 0.001	4.81	< 0.001	-3.59	< 0.001
Implant length					
5 mm vs. 6 mm	0.006	2.58	0.006	-4.79	< 0.001
5 mm vs. 8 mm	0.01	2.37	0.01	-3.60	0.001
6 mm vs. 8 mm	0.005	3.29	0.001	-2.72	0.005
Implant locking taper bore diameter					
2 mm vs. 2.5 mm	0.003	2.86	0.003	-3.05	0.002
2 mm vs. 3 mm	0.02	2.50	0.008	-2.09	0.02
2.5 mm vs. 3 mm	< 0.001	4.49	< 0.001	-3.52	< 0.001
Hemispherical abutment base	0.004	2.70	0.004	-5.65	< 0.001
Opposing structure	0.05	1.64	0.05	-7.26	< 0.001
Prosthesis span					
≤ 3 units vs. 4 units	0.25	4.70	< 0.001	-0.69	0.25
≤ 3 units vs. ≥ 5 units	< 0.001	3.50	< 0.001	-4.39	< 0.001
4 units vs. ≥ 5 units	0.09	6.09	< 0.001	-1.38	0.09
Abutment/pontic ratio	0.02	5.02	< 0.001	-2.10	0.02
Cemented vs. screwed	< 0.001	4.69	< 0.001	-3.59	< 0.001
Location of implant in prosthesis	0.002	3.98	< 0.001	-3.02	0.002

TOST: two one-sided t-test

of healing, the implants were restored with a six-unit FRC P-FDP supported by three implants (**Figs. 7A-D**). Two years after the first bridge was inserted, the patient received three additional maxillary implants that supported another FRC, the P-FDP (**Figs. 7 E-F**). At a follow-up visit 8.5 years after the insertion of the first prosthesis, radiographic images revealed stable bone levels, with the prostheses still functioning (**Figs. 7G-I**).

4. Discussion

This study aimed to follow up the clinical outcomes of FRC P-FDPs supported by short and extra-short implants for up to 10 years after prosthesis insertion. The primary outcomes studied were implant and prosthesis survival and success rates. Kaplan-Meier survival analysis revealed that FRC P-FDPs had survival and success rates of 94.7% and 92.0%, respectively, over ten years. A previous review of all-ceramic FDPs reported a 5-year survival rate of 98.3%[21]. In comparison, this study reports a survival rate that is not only higher, but also calculated for a longer follow-up period. Additionally, compared to the complication rates of 15.1% and 50% for metal- and zirconia-ceramic FDPs, respectively, the complication rate reported in this study for FRC FDPs was only 7.9%[21]. The superior durability and biocompatibility of FRC make it an ideal candidate as a prosthetic framework. This is supported by the results of previous studies on full-arch prostheses fabricated using the same material[4,22]. These results suggest that the FRC material is not only suitable for constructing full-arch prostheses but also for fabricating FDPs.

This study also reported higher success and survival rates than a previous study on P-FDPs fabricated using the same FRC material and supported by the same implant system (10-year survival, 95.9%; success, 89.8%)[13]. While differences in patient cohorts, clinician experience, or prosthesis design may account for the differences in outcomes, it is also possible that the smaller sample size of this study led to differences in survival and success rates.

Additionally, this study analyzed the influence of patient-, implant-, and prosthesis-related parameters on prosthesis and implant outcomes. Log-rank tests on Kaplan-Meier survival curves showed no significant differences between the outcomes of implants and prostheses for any of the analyzed parameters. It is possible that an insufficient sample size prevented the discovery of meaningful correlations; however, these results echo findings similar to those of a previous FRC P-FDP study, in which neither the prosthesis span nor the abutment/pontic ratio correlated with significant differences in prosthesis survival. The results of this study suggest that FRC P-FDPs have uniformly high survival and success rates for a wide variety of prosthetic designs and clinical scenarios.

The success of FRC FDPs has been attributed to the high flexural strength and low modulus of elasticity of the FRC material, which allows for an even distribution of forces across the prosthesis and surrounding bone[6–9]. Previous studies have reported very few prosthetic complications, which were mostly the need to recement a prosthesis. The fracture rates were significantly lower than those

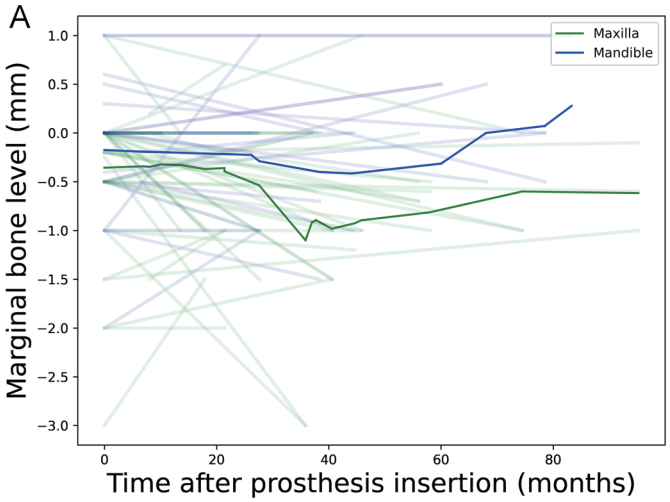

Fig. 4. Visual representations of marginal bone levels (MBL) changes in relation to factors that significantly affect peri-implant bone levels. A) MBL changes in relation to the arch in which the implant was placed. B) MBL changes in relation to prosthesis span. C) MBL changes in relation to the material on the opposing arch.

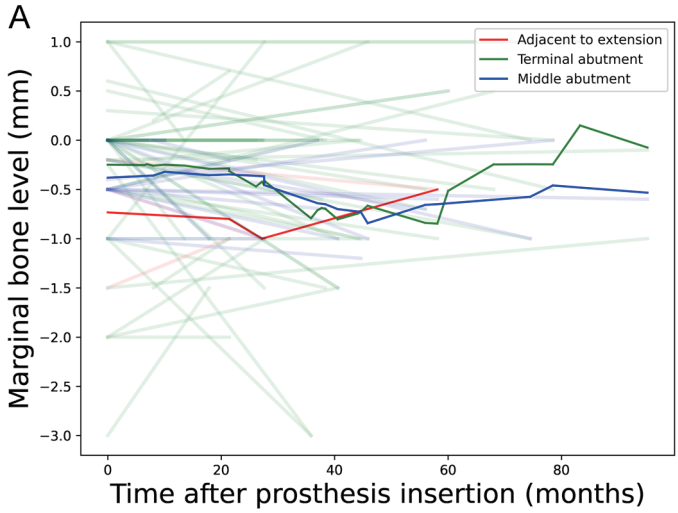

Fig. 5. Visual representations of marginal bone levels (MBL) changes in relation to factors that do not affect peri-implant bone levels. A) MBL changes in relation to the location of the implant in the prosthesis. B) MBL changes in relation to implant length. C) MBL changes in relation to the restoration being cemented versus screwed onto the abutment.

Table 5. Multivariate Cox regression between study covariates and marginal bone level changes

Covariate	Coefficient	Lower 95% CI	Upper 95% CI	z	*P*
Anterior location: 1 vs. posterior location: 0	-3.78	-6.12	-1.43	-3.16	0.002
Abutment/pontic ratio	-2.24	-4.69	0.21	-1.79	0.07
Hemispherical base	-1.50	-3.39	0.39	-1.56	0.12
Systemic and oral risk factors	-0.90	-2.26	0.47	-1.29	0.20
Implant length	-0.71	-1.78	0.37	-1.29	0.20
Implant locking taper bore diameter	-2.32	-6.06	1.43	-1.21	0.23
Prosthesis span	-2.43	-7.05	2.18	-1.03	0.30
Terminal abutment	-0.22	-0.73	0.30	-0.83	0.41
Cemented abutment: 1 vs. screwed abutment: 0	-0.27	-2.02	1.47	-0.31	0.76
Age	0.44	-3.89	4.78	0.20	0.84
Abutment adjacent to cantilever extension	0.24	-1.24	1.72	0.32	0.75
Middle abutment	0.19	-0.47	0.84	0.57	0.57
Opposing implant: 1 vs. natural teeth: 0	0.42	-0.80	1.65	0.68	0.50
Male: 1 vs. Female: 0	1.22	-0.45	2.89	1.43	0.15
Implant diameter	4.90	-1.78	11.58	1.44	0.15
Maxillary location: 1 vs. mandibular location: 0	2.17	-0.43	4.78	1.63	0.10

The outcome variable was peri-implant bone loss > 1 mm from the top of the implant. The highlighted columns represent significant ($P \leq 0.05$) covariates.
CI: confidence interval.

reported for metal or all-ceramic frameworks[4,5]. Similarly, only one prosthesis developed complications in the current study. In another FRC P-FDP study, prosthesis loosening was the major reported complication. The use of screw-retained prostheses could potentially explain the lack of the required recementation[13]. The slight wear that was observed in the resin portions of the prostheses, especially on the occlusal surfaces, did not lead to complications affecting the normal structure, function, or aesthetics of the prostheses.

The versatility of the FRC P-FDPs can also be observed in the marginal bone levels surrounding the supporting implants. Overall bone levels, on average, were stably maintained at the top of the implant during the entire study. Additionally, key covariates of prosthesis design did not influence MBL, as demonstrated by TOST equivalence testing. In particular, the location of an implant in a prosthesis did not affect the bone levels surrounding the implant (**Fig. 5A**). Whether the implant was at one terminus of the prosthesis, in the middle, or adjacent to a distal extension, had no effect on MBL. This suggests that when designing an implant-supported FRC P-FDP, the clinician can safely arrange abutments and pontics in a way that best suits the clinical situation without being concerned about the prosthesis design affecting implant outcomes.

In addition, this study enabled a direct comparison between screw-retained and cemented prostheses. While the previous FRC P-FDP study only assessed cemented prostheses, this study demonstrated that screw-retained prostheses not only have similar success and survival rates as cemented prostheses but also have equivalent peri-implant bone levels (**Fig. 5C**).

The short and extra-short implants used to support the FDPs in this study demonstrated high survival and success rates. This corroborates previous reports that short and extra-short implants are suitable for use in rehabilitating patients with partially or completely edentulous arches[4,10,23]. Specifically, the implant length did not significantly affect prosthesis survival or success. Moreover, the bone levels surrounding the short and extra-short implants were similar over the course of 10 years, as assessed by TOST equivalence testing (**Fig. 5B**). These findings demonstrate that short and extra-short implants are similarly suitable for supporting FRC FDPs. The high success rate of this combination of FRC FDPs with short and extra-short implants can be attributed to the fact that both the prosthetic framework material and the implant system facilitate an even distribution of forces throughout the bone, promoting the maintenance of the peri-implant bone[24–26]. A recent photoelastic study has also demonstrated that the combination of the implant system under investigation with FRC prostheses led to the distribution of occlusal forces in patterns that are conducive of bone maintenance[27].

Factors that significantly correlated with differences in MBL included the maxillary or mandibular arch, span of the prosthesis, and structure of the opposing dentition. Of these three factors, the correlation of opposing natural teeth with a higher MBL (**Fig. 4C**) has been previously demonstrated to be true for the implant system under investigation[28]. The bone gain associated with mandibular implants in this study (**Fig. 4A**) was not reported in prior analyses and could possibly be unique to implant-supported FRC P-FDPs[23,28,29]. Lastly, in this study, a shorter prosthesis span with three units or less was correlated with bone gain, while longer spans were correlated with the maintenance of peri-implant bone levels (**Fig. 4B**). It is important to mention that although the three factors are indeed correlated with differences in bone-level outcomes, they are not linked to significant differences in implant or prosthesis survival or success. This is partly due to the nature of the implant system used, which can successfully support prostheses under conditions of marginal bone loss[30].

Beyond evaluating the influence of study covariates on absolute MBL values, multivariate Cox regression was used to evaluate whether the covariates correlated with changes in MBL over time. The high implant success rate coupled with the relatively small sample size resulted in an insufficient number of implants that met the PISA consensus-recommended criteria for 2 mm bone loss. When a secondary outcome of 1 mm bone loss was used instead, only one

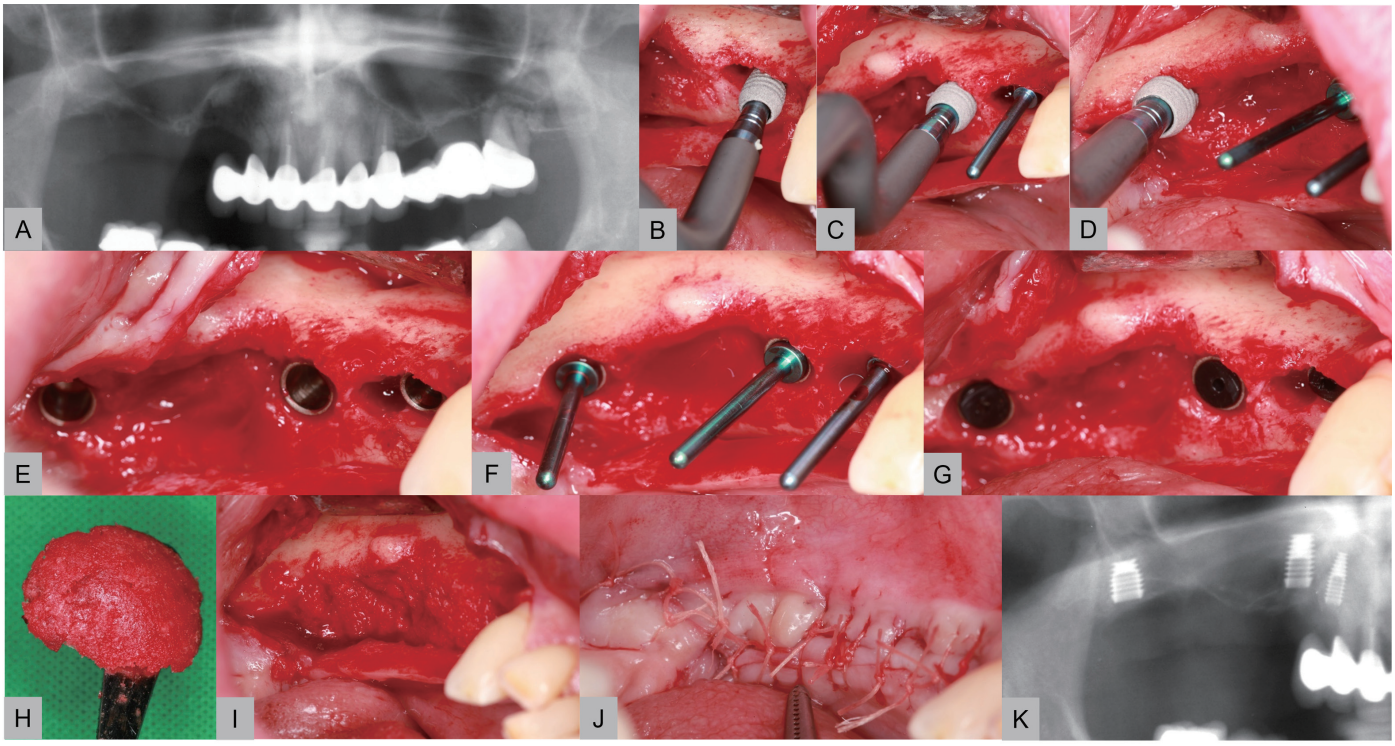

Fig. 6. Representative clinical case of implant surgery for a fiber-reinforced composite fixed dental prosthesis supported by short implants. A) Panoramic radiograph of a 53-year-old female patient with missing teeth 1 to 6, poorly conditioned bridge from teeth 11 to 15, severe alveolar crest bone resorption bilaterally, and very large pneumatized maxillary sinuses. The patient has been under denosumab medication for 10 years. B) Insertion of a 3.0 × 8.0 mm Bicon Integra-CP implant with a Threaded Offset Handle in region 6. C) Insertion of a 4.0 × 8.0 mm Bicon Integra-CP implant with a Threaded Offset Handle in region 5. D) Insertion of a 4.5 × 6.0 mm Bicon Integra-CP implant with a Threaded Offset Handle in region 1. E) Intraoperative view after inserting the two short and an extra-short implant. Note the small bony defect distal to implant region 6. F) Intraoperative view after inserting the three guide pins for final position control and contingently correction. G) Intraoperative view after inserting the three shortened black healing plugs. H) Molded harvested autogenous bone chips collected during the irrigation free drilling of the osteotomies for the implant beds. I) Intraoperative site after covering the seated implants as well as the little bony defect distal to implant region 6 with the autogenous bone chips. J) Primary sutures with 5/0 resorbable suture material. K) Panoramic radiograph after implant insertion.

covariate, the posterior location of the implant, was weakly correlated with a reduced risk of marginal bone loss, a correlation that has not been reported in the literature.

More importantly, the changes in MBL over time did not occur at a uniform rate[23,29,31,32]. Rather, changes in MBL follow an established pattern of early implant bone loss, followed by the stable maintenance of bone levels[33–35]. Therefore, changes in MBL over time may not be as informative about long-term implant performance as compared to absolute MBL. Notably, none of the covariates were excluded from the Cox regression analysis. Although the sample size was not sufficient to reach the traditional rule-of-thumb benchmark of 10 events per variable (EPV), studies have shown that for Cox analyses with 5-9 EPV, such as this one, only a minor degree of extra caution is warranted[36].

The limitations of this study include its retrospective design, lack of a control cohort, and small sample size. The lack of standardization in implant parameters makes extrapolation of survival and success rates difficult but also illustrates the versatility of FRC prostheses, which can be used to restore implants with different dimensions and surrounding bone conditions. The lack of data on the specific materials used for veneering prostheses makes it difficult to compare different veneering materials. Additionally, the large number of TOST statistical tests performed while testing for MBL equivalence increased the likelihood of Type 1 error occurrence. Therefore, the supporting literature must be carefully considered when interpreting MBL data, and further prospective studies are needed to elucidate the causal relationship between prosthesis design and P-FDP outcomes. Despite these limitations, the results of this study showed that FRC P-FDPs supported by short and extra-short implants presented high survival and success rates as well as stable MBL for up to 10 years when used to reconstruct partially edentulous arches.

5. Conclusions

P-FDPs fabricated using milled FRC frameworks and supported by short and extra-short implants demonstrated high survival and success rates and stable bone levels over a period of up to 10 years. The treatment outcomes of these prostheses were similarly favorable across a variety of prosthetic designs, highlighting the versatility of FRC materials for use in P-FDP frameworks.

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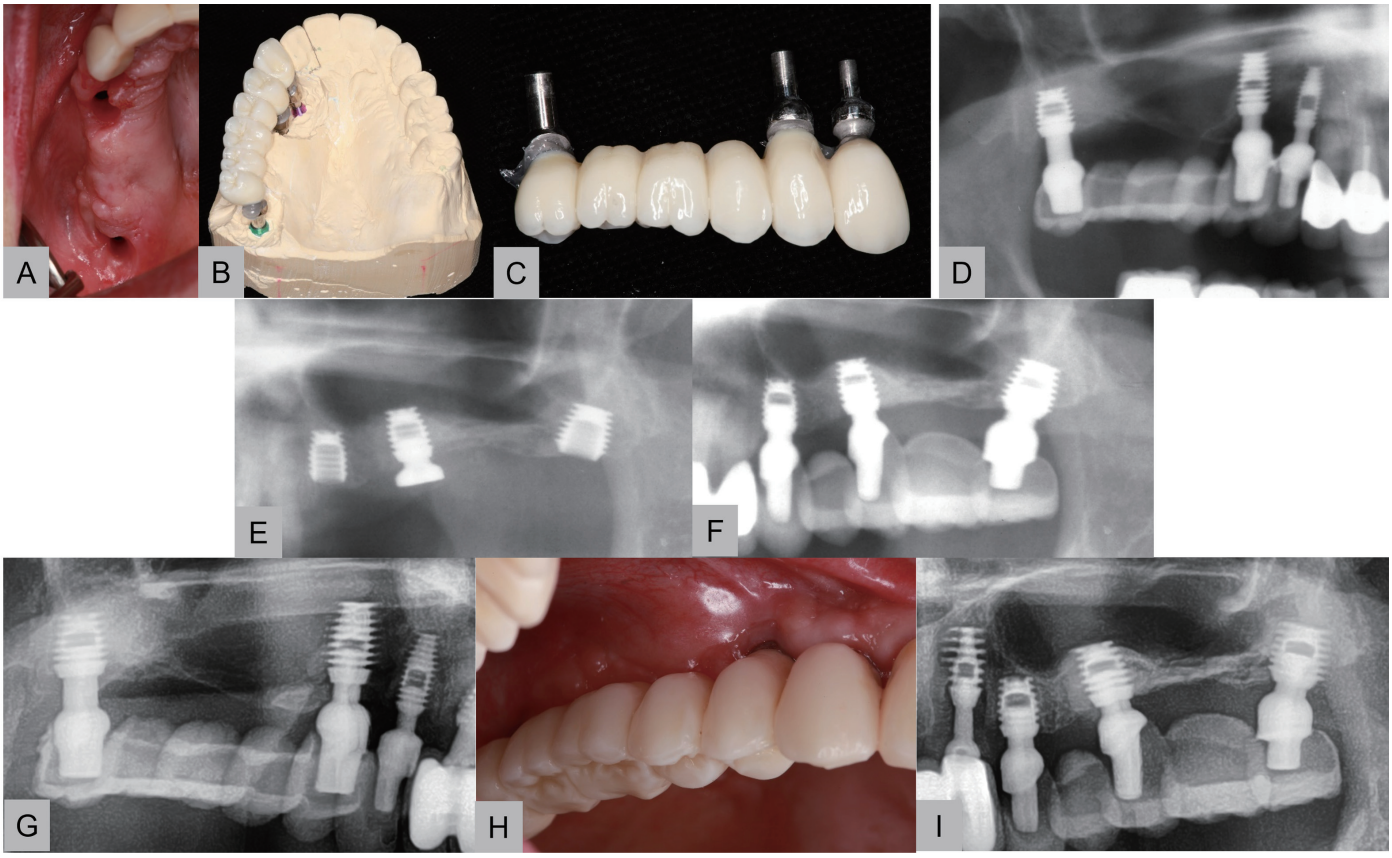

Fig. 7. Representative clinical case of restorative procedures for fiber-reinforced composite fixed dental prostheses supported by short implants. A) Intraoperative site after uncovering the three implants six months later and ten days after removal of the temporary abutments before inserting the TRINIA™ bridge on the right side of the maxilla. B) Finalized TRINIA™ bridge with six teeth on stone model. C) Lateral view of the TRINIA™ bridge with six teeth. D) Panoramic radiograph at initial loading of the three short and extra-short Bicon implants. E) Panoramic radiograph after inserting three additional implants on the left side of the maxilla. In region 11 a 4.5 × 6.0 mm, in region 13 a 4.5 × 6.0 mm, and in region 16 a 4.0 × 6.0 mm Integra-CP Bicon implant. F) Panoramic radiograph at initial loading of the three extra-short Bicon implants. G) Panoramic radiograph of the right maxilla at recall after 8.5 years loading of the six teeth TRINIA™ bridge with three short and extra-short Bicon implants. H) Intraoral view of the six teeth TRINIA™ bridge of the right maxilla at recall after 8.5 years loading. I) Panoramic radiograph of the left maxilla at recall after 4.9 years loading of the five teeth TRINIA™ bridge with three extra-short Bicon implants.

Conflict of interest statement

The authors declare that they have no conflicts of interest.

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