ORIGINAL RESEARCH

Fracture Resistance of Three-unit Fixed Dental Prostheses Fabricated with Milled and 3D Printed Composite-based Materials

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Abstract

Aim: To evaluate the fracture resistance of three-unit fixed dental prosthesis (FDP) made of composite, high-density polymers (HDP), fiber-reinforced composite (FRC), and metal-ceramic (MC) using different fabrication methods.

Materials and methods: A typodont model was prepared to receive a three-unit FDP replacing a missing second maxillary premolar. The prepared model was digitally scanned using an intraoral scanner (Trios3, 3Shape, Denmark). In total, 60 FDPs were fabricated and divided into four groups ($n = 15$) according to the materials and fabrication method: the subtractive method was used for the FRC (Trilor, Bioloren, Italy) and the HDP (Ambarino, Creamed, Germany) groups; the HDP group was monolithic, whereas the FRC group was layered with a nanocomposite (G-aenial Sculpt, GC). The additive method was used for the 3D printed (3DP) nanocomposite (Irix Max, DWS, Italy) and the Cr-Co (Starbond CoS powder 30) infrastructure of the MC groups. The FDPs were adhesively seated on stereolithography (SLA) fabricated dies. All samples were subjected to thermomechanical loading and fracture testing. The data for maximum load (N) to fracture was statistically analyzed with one-way analysis of variance (ANOVA) followed by Games-Howell *post hoc* test ($\alpha = 0.05$).

Results: The MC group reported the highest fracture resistance with a statistically significant difference (2390.87 ± 166.28 N) compared to other groups. No significance was noted between 3DP and HDP groups (1360.20 ± 148.15 N and 1312.27 ± 64.40 N, respectively), while the FRC group displayed the lowest value (839.07 ± 54.30 N). The higher frequency of nonrepairable failures was observed in the MC and FRC groups, while HDP and 3DP groups reported a high frequency of repairable failures.

Conclusion: Significant differences were found in fracture resistance between the tested groups. The load-bearing capacity of the composite-based FPDs exceeded the range of maximum chewing forces.

Clinical significance: 3D printed and milled composite-based materials might offer a suitable solution for the fabrication of FPDs.

Keywords: CAD/CAM, Fiber reinforced composite, Fixed dental prosthesis, Fracture resistance, High-density polymers, 3D printing.

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Introduction

Three-unit FDP is the treatment option used to restore function, form, and esthetics in case of a missing tooth and when a single implant restoration is not indicated.[1,2] Traditionally, full metal or metal frameworks with veneering ceramic have been implemented. Recently, different metal-free systems became available allowing the clinicians to better imitate the natural tooth color, thus, avoiding the shortcomings of MC restorations.[3] Different types of ceramics were introduced, such as spinel, alumina, ceramic reinforced with lithium disilicate, and yttrium-stabilized zirconia.[4,5] Polymeric materials have also been introduced due to their lower cost in comparison with ceramics.[3] However, low-strength ceramics, such as feldspathic- and reinforced-glass ceramics, seem to be more appropriate for single crowns than for FDPs.[6,7] As for veneered zirconia, chipping of the veneering ceramic is the most observed complication for densely sintered zirconia ceramic FDPs. To solve this problem, monolithic zirconia with good mechanical properties and improved esthetics has consequently become more and more popular for the use of multiunit FDPs.[8] However, few studies are available regarding their behavior under clinical conditions. Despite the esthetic and mechanical advantages of monolithic ceramics, they still have disadvantages, such as brittleness, etch ability and bonding, repair ability, probable abrasive effect on opposing teeth, and ease of milling.[9,10]

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With the continuing developments in CAD/CAM (computer-aided design/computer-aided manufacturing) technology, new materials as composites, FRCs, and hybrid materials were introduced for single-unit restorations.[11] CAD/CAM composites have the advantage of absorbing masticatory forces and a modulus of elasticity closer to dentin than ceramics.[12] They are also known to be less brittle with better damage tolerance resulting in smoother margins and less marginal chipping when compared to ceramics. In addition, composites exhibit more adaptability to CAD/CAM systems than ceramics in terms of bur life period and milling time.[13] Their cost is lower and no firing procedure is needed for ceramic crystallization or staining (obligatory for lithium dislocates), which makes those materials very interesting. Finally, repairing them is easier in case of failure.[14–17] *In vitro* studies[18–20] concluded high values of fracture and flexural resistance with good internal fit for single crowns made of CAD/CAM composites and HDPs in comparison with ceramics. Ahmed et al.[21] concluded a high-overall survival of FRC FDPs when used as a medium-term treatment option to replace single posterior or anterior teeth. Nevertheless, most of the clinical studies on FRC FDPs used a direct embedding of the fibers in the composite matrix. Newly introduced CAD/CAM FRCs ensure a perfect coupling between the fibers and the matrix without creation of microbubbles and warrant a minimum liquid absorption and the absence of microfractures. Till now, to the authors knowledge, CAD/CAM FRC has not been tested as FDPs.

Recently, additive manufacturing is growing as an effective technique for rapid prototyping in case of highly customized models, thus, indicated for the highly personalized prostheses obligatory in dentistry.[22] 3D printing overcomes the disadvantages of the subtractive methods like consuming excessive material and tools and the difficulty to mill undercuts and inaccessible zones to end-mills used in the production method.[23,24] Different materials have been used with additive manufacturing including metals, polymers, ceramics and more recently composites.[25] 3D printed composite crowns showed good mechanical properties when compared to milled composite crowns at different thicknesses.[2,25] A recent study conducted by Zimmermann et al.[26] concluded that CAD/CAM particle-filled composite resins showed load to fracture values in the range of ceramics when used as three-unit FDPs. Till now, data is scarce regarding the mechanical behavior of CAD/CAM composites used as materials for multiunit FDPs in comparison to MC. The aim of this study was to test the fracture resistance and failure pattern of three-unit FPs made of composite, HDPs, FRC, and MC using different fabrication methods. The null hypothesis of the study was that there are no statistical differences in fracture resistance and failure pattern between the different materials tested.

Materials and Methods

Samples Preparation

The study was conducted at the Lebanese University. A typodont model (Nissin PRO 2001, Nissin Dental Products Inc., Kyoto, Japan), with first maxillary molar and premolar (#24 and #26) and a missing second premolar (#25), was selected for this study. A standardized chamfer preparation (360°) was performed using a surveyor with a high-speed air turbine under water spray (K9 Milling Apparatus -990, Kavo, Germany). Labial, lingual, and proximal surfaces were reduced by 1.2 mm and the occlusal surface by 2 mm, with rounded transitional areas and edges. For the preparation, grit burs (235 and FG 235, Intensive, Switzerland) were used. Silicone index (Optosil, Heraeus Kulzer, Germany) of unprepared teeth was used to control axial reduction, uniformity, and depth of the prepared abutments.

Digitalization and Design

The prepared master model was digitally scanned using an intraoral scanner (Trios3, 3Shape, Denmark) to better simulate the clinical flow; the data was exported as a standard tessellation language (STL) format to a CAD software (Exocad, Germany) for the design and the fabrication of full-coverage three-unit FDP that was performed by a certified dental technician (SD).

Fixed Dental Prostheses Fabrication

Fifteen FPDs ($n = 15$) were fabricated for each group according to the material and fabrication method as follows: HDP (Ambarino, Creamed, Germany); FRC (Trilor, Bioloren, Italy); MC (Starbond CoS powder 30/Super Porcelain EX3); and 3DP composite (Irix Max, DWS, Italy). The subtractive CAD/CAM fabrication method with a 5-axis milling unit (Coritec 350i, imes-icore GmbH, Germany) using CAM software (iCAM V5 smart, imes-icore GmbH, Germany) was used for groups HDP and FRC. CAM strategies including wet milling were used to fabricate the full-monolithic HDP FDPs and the FRC infrastructures according to the manufacturer's instructions. Restorations were fabricated from CAD-CAM 98.5-mm diameter blanks. The three-unit FRC infrastructures were sandblasted with 110 μ Al_2O_3 at 2 bar, cleaned with dry air, then a silane (G-Prime, GC) was applied for 2 minutes, and after evaporation a universal adhesive (G-Premio BOND, GC, Japan) was applied prior to veneering using a nanocomposite (G-aenial Sculpt, GC). The layering technique was applied using a clear template of the unprepared teeth for consistency between samples. Each 1-mm layer of composite was light cured for 40 seconds. The 3D-printing of composite FDPs was performed using a SLA-based 3D-printer (DFAB, DWS, Italy) with a nanocomposite material (Irix Max, DWS, Italy) designed for permanent restorations. The thickness of build layer was 0.05 mm and the maximum laser speed was 5000 mm/seconds. The printed specimens were cleaned with 95% ethanol for 1 minute and postcured using ultraviolet curing unit (Dcure, DWS) for 6 minutes as per the manufacturer's instructions. The MC FDPs fabrication included a 3DP Cobalt Chrome infrastructure (Starbond CoS powder 30) using a 3D printer with laser metal fusion technology (MYSINT 100, SISMA S.p.A, Italy). Then, the infrastructures were veneered with a glass ceramic (Super Porcelain EX3, Kuraray Noritake, Japan) following the manufacturer's instructions. A silicon index of the designed three-unit FDP was used for consistency between samples. In total, 60 FDPs were fabricated. All FDPs were checked under stereomicroscope (Amscope 3.5, Irvine, California, USA) for any defect and then cemented to the correspondent Stereolithographic Apparatus (SLA) fabricated dies ($n = 60$) in accordance with a standardized protocol using a self-adhesive resin cement (Theracem, Bisco, USA) and light-polymerized for 20 seconds (Elipar S10 LED curing light, 3M-ESPE).

Fatigue Simulation

All samples underwent thermocycling (THE-1100, SD Mechatronik, Germany) in distilled water for 5,000 cycles at 5°C and 55°C, with 30 seconds of dwell time and 5 seconds of transfer time. Afterward, mechanical cyclic loading was completed in a linear dual-axis chewing device (CS-4.2, Mechatronik GmbH, Germany) in a range of 5 mm of vertical movement and 0.5 mm of lateral movement, by applying axial loading force of 50 N and a frequency of 1.6 Hz in the central fossa of the pontic, with a stainless steel ball (diameter of

3 mm) for 1,200,000 cycles. The FDPs were then examined visually and under stereomicroscope. No failures, such as cracks or chipping fractures, were shown.

Fracture Resistance Test

All specimens were subjected to static loading until fracture using a universal testing machine (Treviolo, Matest Spa, Italy), with a 3-mm diameter stainless steel ball loading exactly in the central fossa of the pontic tooth element, at a cross-head speed of 0.5 mm/minutes. The maximum load to fracture value was recorded in newton (N). Afterward, all specimens were checked using a stereomicroscope (Amscope 3.5) to analyze the failure pattern that was classified as: (1) repairable (R): cracks confined in the FDP material not extending to the die or the infrastructure and (2) nonrepairable (NR): catastrophic failure or cracks extending to the die or infrastructure.

Statistical Analysis

Shapiro–Wilk's test of normality confirmed that the data was normally distributed ($p > 0.05$) when stratified into the four groups. Accordingly, the one-way ANOVA was used to compare the fracture resistance between the groups. Since the assumption of the homogeneity of variances was not met, the Welch robust ANOVA was reported, followed by Games-Howell *post hoc* test result. A confidence level of 0.05 was considered statistically significant. Data was analyzed using the Statistical Package for Social Sciences (SPSS), Version 24.0.

Results

Descriptive statistics including mean, standard deviation, minimum, and maximum values were generated for the variable in the four groups (Table 1). Mean fracture resistance levels ranged between 839.07 ± 54.3 N for the FRC group and 2390.87 ± 166.28 N for the MC group.

Significant statistical differences in fracture resistance were concluded between the different composite-based materials used for FDP fabrication and the MC group. The MC group displayed the highest fracture resistance with a statistically significant difference of 1030.66 ± 57.5 N when compared to the 3DP group ($p < 0.001$), 1078.6 ± 46.04 N compared to the HDP group ($p < 0.001$), and 1551.8 ± 45.16 N compared to the FRC group ($p < 0.001$). On the contrary, FRC group had the lowest fracture resistance mean among the four groups ($p < 0.001$) and performed statistically significant difference with the 3DP and the HDP groups. No statistically significant difference was observed between the 3DP and the HDP groups in relation to their fracture resistance values ($p = 0.665$) (Table 2).

The mode of failure of the different specimens was evaluated in repairable (R) and nonrepairable (NR) fractures and presented in Table 3. The higher frequency of nonrepairable failures was observed in the MC group (14 NR/1 R), followed by the FRC group (11 NR/4 R). While HDP and 3DP groups reported a high frequency of repairable failures (HDP: 11 R/4 NR and 3DP: 12 R). Regarding the failure pattern, repairable fractures confined in the material not extending to the die or the infrastructure were considered repairable (Figs 1A and B), whereas catastrophic failures or cracks extending to the die or infrastructure were considered nonrepairable (Figs 2A and B).

Table 1: Fracture resistance across the four tested groups ($n = 60$)

Group	*n*	*Mean*	*SD*	*Minimum*	*Maximum*
3DP	15	1360.20	148.15	1070	1684
MC (control)	15	2390.87	166.28	2118	2720
HDP	15	1312.27	64.40	1175	1391
FRC	15	839.07	54.30	740	927

Variable recorded in N; SD: standard deviation

Discussion

According to the results of this study, significant statistical differences in fracture resistance were concluded between the different composite-based materials used for FDP fabrication and the MC group; therefore, the tested null hypothesis was rejected. The different elements included in the study influenced the results attained to different levels. In fact, the characteristics of different tested materials, the failure pattern parameters, the fabrication technique, the abutment die material, and the adhesion system used must be considered.[27]

Currently, the CAD/CAM technology helped in increasing the general efficiency of the treatments by reducing the costs and the time of treatments.[28,29] Also, esthetic is improved when compared to MC restorations[30] and the possible intraoral repair in case of chipping.[31] In the present study, the fracture resistance of three composite-based CAD/CAM materials was studied in comparison to MC in three-unit bridge restoration; as the MC is considered as the standard optimal material for the manufacture of multiple-unit FDPs.[32–34]

CAD/CAM composite-based materials (HDP and 3DP) are formed of ceramic-based filler particles embedded in a composite resin polymer matrix. The composition and percentage of fillers are different for each particular material and might be the main cause for the unlike material characteristics.[11,19,35] In general, CAD/CAM composite materials exhibit a quite high-flexural strength with a quite low-flexural modulus.[36,37] Therefore, they are able to endure more elastic deformation before failure resulting in increased load-bearing capacity. Also, these materials have low brittleness, increased flexibility, and the property of absorbing the stress induced by increased load. According to Zimmerman et al., [26] the fillers can stop the crack propagation through crack deflection and bridging effects resulting in an increase of the

Table 2: Results of one-way ANOVA test

	3DP		*MC*		*HDP*		*FRC*		*One-way ANOVA*	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*F*	*p*
Fracture resistance	1360.20[b]	148.15	2390.87[a]	166.28	1312.27[b]	64.40	839.07[c]	54.30	461.99	<0.001[*]

[*]Statistically significant at $p < 0.01$; the values of fracture resistance are represented by mean ± SD; alphabetic superscripts denote significantly different means at $p < 0.05$ (*post hoc* Games-Howell test)

flexural strength of these materials. In the present study, although significant differences in load-bearing capacity were concluded between composite-based materials and MC, the results found are promising where all the tested materials had values higher than 600 N which is considered as the highest occlusal loading force occurring during mastication in the posterior area for adult men.[38,39]

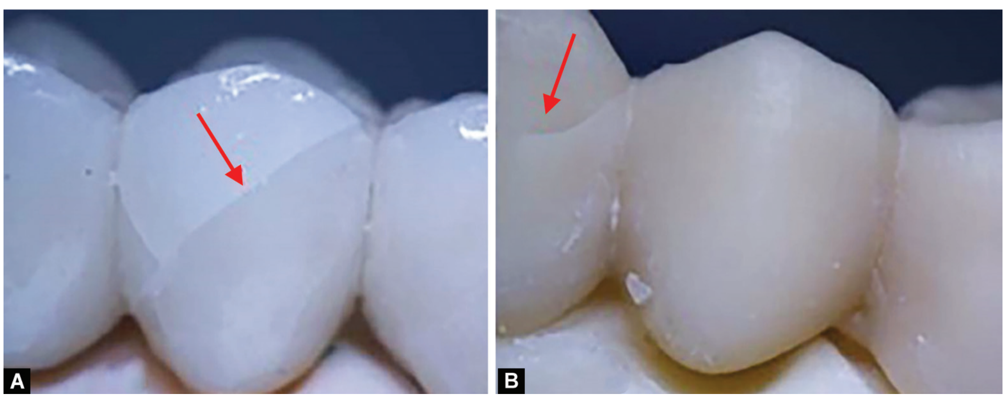
Significant differences in fracture resistance values were also concluded between the tested materials, where HDP and 3DP had better fracture resistance compared to the FRC group. This difference is mainly attributed to the layered structure of the FRC bridges formed of FRC frameworks veneered with resin composite, where all the observed failures were the fracture of the veneering composite. These conclusions are consistent with previous literature regarding FRC FDPs. Ahmed et al.[21] and Kolbeck et al.[40] reported fracture and/or debonding of the veneering resin composite as the most common mode of failure. No discernable damage to the framework fibers was observed. In fact, high stresses evolve in the framework/veneer interfaces, resulting in a principal area for fracture.[41,42] The use of monolithic FRC FDPs might enhance the fracture resistance of these materials. Hence, the esthetics and aging of such restorations are yet to be studied.

Table 3: Fracture pattern of specimens in different tested groups

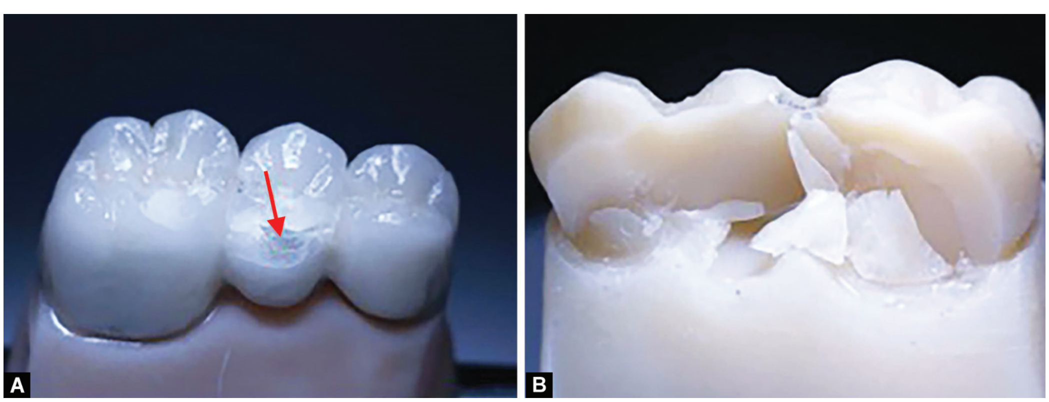
Group	*Nonrepairable (NR)*	*Repairable (R)*
3DP	3	12
MC	14	1
HDP	4	11
FRC	11	4

Regarding the HDP and 3DP groups, all the failures occurred within the connector starting at the gingival interdental embrasure which corroborates with the findings of other *in vitro* studies.[26,40,43] According to Taskonak et al.[44] "for fixed partial dental prosthesis, the connector gingival area is subjected to high-tensile stresses during occlusal loading and represents a potential location for failure."

Subtractive manufacturing is similar to additive manufacturing in terms of the impression technique and the reduction of different fabrication steps.[45] However, additive manufacturing decreases the waste of materials, consumes less energy, and produces complex details at a predictable cost. The final product is reached with fewer steps, and the human intervention is reduced resulting in less errors. Therefore, the introduction of 3D printing as an alternative to the subtractive method is an interesting option for the manufacturing of dental restorations. The tested 3DP composite in this study recorded an acceptable fracture load of a mean of 1360 N, therefore, joining the advantages of the additive manufacturing in relation to the reduced cost, the good esthetic, and the intraoral repairability. 3D printed Cr-Co frameworks were also used for the control group, as they are less expensive than the precious alloys, they have a good bonding characteristic with porcelain,[46] a higher hardness and Young's modulus, and a good resistance to corrosion



Figs 1A and B: Repairable failure mode with fracture confined in the material not extending to the die or the infrastructure. (A) MC group; and (B) 3DP group



Figs 2A and B: Nonrepairable failure mode with catastrophic failure or cracks extending to the die or infrastructure. (A) MC group; and (B) 3DP group in comparison to other metals used in prosthetic infrastructures.[47] These properties enhance their tolerance to load in longer-span prostheses and their stability in the oral cavity over time.

The results of the present study align with the recent literature on CAD/CAM composite FDPs by Zimmermann et al.[26] who compared the fracture resistance of CAD/CAM particle-filled composite FDPs made with subtractive and additive manufacturing to ceramics and concluded acceptable values of load to fracture. To the author's knowledge, this is the first study to compare CAD/CAM composite-based FDPs to MC. On the contrary, according to the literature,[21,48,49] FRCs seem to offer a cost-efficient, minimally invasive, and esthetic alternative to restore three-unit bridges with good clinical performance.

In regard to the fatigue test, the thermal fatigue caused by thermal stress is generally more important than the fatigue caused by pure mechanical stress. Therefore, in this study, the thermal stress was performed before mechanical (dynamic) loading of the samples since withstanding its effects is of a significant importance for the survival of a material. Furthermore, in the present study, a resin-based material die was used to simulate the abutment teeth since the elastic modulus of the supporting dies might have a substantial effect on the capability of the model to reflect accurately the clinical conditions. Materials with a lower modulus of elasticity can serve as supporting dies for fracture resistance tests to better simulate the clinical conditions.[50] When natural teeth are used for *in vitro* studies, some restrictions might exist in term of reproducibility and comparability between natural teeth specimens.[51]

In regard to cementation, a self-adhesive resin cement was used in this study since adhesive cements have higher mechanical properties and a better adhesion at the interfaces between core, cement, and abutment when compared to conventional cements leading to an increase in fracture load of the crowns.[52] In fact, no debonding on the abutment die was observed neither after fatigue nor after fracture resistance test. Despite the aforementioned advantages of the resin die material, the absence of natural extracted abutment teeth highlights the limitations of the present *in vitro* study in mimicking oral conditions.

An *in vitro* model cannot simulate the extensive diversity of clinical factors that could influence the fracture load of restorations. Therefore, root morphology and periodontal support cannot be fully addressed in an *in vitro* model. Additionally, parameters like wear resistance and color stability of these composite materials are yet to be studied. However, the conclusions of the current study are important to reflect when designing clinical studies.

Conclusion

Three-unit FPDs made with monolithic materials, such as 3DP composite and HDPs, showed better fracture resistance in comparison to the layered CAD/CAM FRC FPDs, where chipping was the most common type of failure. 3D printed and milled composite-based materials might offer a suitable solution for the fabrication of FDPs.

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