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Comparison of the Flexural Strength and Elastic Modulus of Conventional, Milled and 3D-Printed Interim Restorative Materials Subjected to Different Intervals of Accelerated Aging

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Abstract

Aim: To compare the flexural strength and elastic modulus of different interim restorative materials subjected to different intervals of accelerated aging. **Materials and Method:** Three groups of interim restorative materials (N = 120) were prepared using three different manufacturing techniques: conventional PMMA resin (Jet Tooth Shade), computer-aided design/computer-aided manufacturing (CAD/CAM) milled resin blocks (Telio CAD), and three-dimensional (3D) printed resin (Crown & Bridge NextDent). The specimens from each group were subdivided into four equal subgroups (n = 10) and subjected to accelerated aging through thermocycling and brushing according to different time intervals of aging (baseline, 3 months, 6 months, and 12 months). The flexural strength and elastic modulus were measured using a three-point bending test. The data were analyzed using two-way analyses of variance (ANOVA), one-way ANOVA, and Tukey's post hoc test at a significance level of 0.05. **Results:** At baseline, the flexural strength and elastic modulus were significantly greater in the CAD/CAM milled group ($p < 0.05$) than in the conventional and 3D-printed groups. However, no significant difference in flexural strength was observed between the conventional and 3D-printed groups. However, a significant difference ($p < 0.05$) in the elastic modulus was observed between the conventional and 3D-printed groups. At all aging intervals (3, 6 and 12 months), the flexural strength and elastic modulus were significantly greater ($p < 0.05$) in the CAD/CAM milled group than in the conventional group and the 3D-printed group. Within each material tested, the baseline group had significantly greater values ($p < 0.05$) than did the other age groups.

However, there was no significant difference observed among the age intervals of 3, 6, and 12 months, except for the CAD/CAM milled group. In the 12-month aging group, a significant difference ($p < 0.05$) in the elastic modulus was found; no significant difference ($p < 0.05$) was observed between the 3 and 6-month aging groups. **Conclusion:** The CAD/CAM milled group consistently outperformed the conventional and 3D-printed groups in all age intervals. Therefore, the CAD/CAM milling technique could be recommended for long-term temporization for patients with increased occlusal forces, such as parafunctional habits, or for full-arch implant-supported interim prostheses.

Subject Areas

Dentistry

Keywords

Interim Restoration, CAD/CAM Milled, 3D-Printing, Flexural Strength, Elastic Modulus, Accelerated Aging

1. Introduction

Interim or provisional fixed restorations are used for a period during treatment until the definitive restoration is placed. They are crucial for the success of definitive restorations and essential for pulp protection, restoring aesthetics, maintaining a healthy periodontium, and providing occlusal compatibility [1]-[4]. A good quality interim restoration should have good functional load tolerance and retention [5]-[7]; moreover, it must be aesthetically and functionally adequate [2] [4].

One important aspect of interim restorations that should be considered when providing long-term interim restoration is flexural strength [6] [8]. Flexural strength is crucial for patients with parafunctional habits, long-span prostheses, and full-mouth rehabilitation and when adjustment of the vertical dimension is planned, as these types of cases require more durable restorations [3] [8] [9]. Flexural strength is defined as “the transverse strength or modulus of rupture, that is obtained by supporting a bar or beam at each end and loading it in the middle. This test is called a three-pointing bending test” [10]. Low flexural strength leads to breakage of the restoration and tooth drifting, which affects function and aesthetics [3] [9]. The elastic modulus is also an important feature for providing long-term interim restoration., and it is defined as “a measure of the stiffness of a material”. A higher modulus of elasticity indicates a stiffer material [10]. For an interim restoration to be stiffer and resistant to deformation, it is essential to resist the deflection forces produced during mastication [10] [11].

A variety of methods, including conventional, CAD/CAM milling and 3D-printing, can be used to fabricate interim restorations. Conventional interim restorations have been used for many years because they are easily fabricated and cost effective [6] [9]. However, these methods have many disadvantages, such as polymerization shrinkage, decreased fracture resistance, exothermic reactions and color instability [12] [13]. Alternatively, new technologies (CAD/CAM milling and 3D-printing) provide interim restorations with improved physical properties [14] [15]. Moreover, CAD/CAM milled restorations have higher wear resistance, fracture resistance and microhardness [16] [17]. 3D-printed restorations also have advanced mechanical properties, excellent marginal fit, improved patient acceptance and greater accuracy [14] [18]-[20]. The main disadvantage of these new technologies is the high initial cost of implementation and maintenance [15] [21] [22]. CAD/CAM milled restorations are made by a subtractive method in which resin blocks are shaped into desired designs by cutting burs and then processed under standard parameters [11] [14] [15]. 3D-printed restorations are made by additive methods in a layer-by-layer pattern [22]. 3D-printed interim restorations are processed via several methods, including stereolithography (SLA), digital light projection (DLP), and photopolymer jetting (PolyJet) [14] [15]. Each of these printing methods has pros and cons. However, the SLA printing method yields restorations with good mechanical properties [22].

Frequent temperature variations in the oral cavity can cause interim restorations to expand or contract, increasing mechanical stress and ultimately increasing the risk of restoration fractures [23]. Accelerated aging is used to imitate the thermal and mechanical stress that dental restorations and natural teeth experience by consuming different foods and beverages and daily tooth brushing for months within a short period of time [18] [23] [24]. Interim dental restorations in the oral environment are subjected to thermal fluctuations, repetitive tooth brushing, and occlusal pressure [25] [26]. Resin-based materials undergo an aging process that includes softening, degradation, and deformation of the matrix. Consequently, cracks begin to form and expand within the porous resin regions, potentially impacting the mechanical and physical properties of the dental materials. Furthermore, teeth-brushing simulation is widely recognized as a well-established model that induces surface abrasions due to the application of brushing forces [23] [24].

Many studies have compared the flexural strength of conventional, CAD/CAM milled and 3D-printed interim restorations. Alageel *et al.* reported that after accelerated aging, the highest flexural strength was obtained for 3D-printed, CAD/CAM milled and conventional materials [27]. In addition, Ribeiro *et al.* showed that thermocycling reduced the flexural strength of interim materials, except for 3D-printed resins [28]. However, Tasin *et al.* showed that after thermocycling, the conventional PMMA group had the lowest mean flexural strength, whereas the flexural strength of the CAD/CAM milled group was similar to that of the 3D-printed group [29]. Pantea *et al.* reported that 3D-printed interim restorations have greater flexural strength and modulus of elasticity than conventional interim restorations [30]. Kawano *et al.* concluded that after thermocycling, the flexural strength of new laboratory-processed composite resin was significantly greater than that of conventional resin [31]. Furthermore, thermocycling caused a decrease in the flexural strength of most of the tested materials [31]. To the best of our knowledge, there is a lack of information about the flexural strength of newly introduced 3D-printed PMMA interim restorations when assessed for their long-term use (3 - 12 months) compared to conventional and CAD/CAM PMMA interim restorations. The aim of this study was to compare the effect of accelerated aging applied to simulate a period of 3 - 12 months of use on the flexural strength and elastic modulus of conventional, CAD/CAM milled and 3D-printed PMMA interim restorations. The null hypothesis was that there would be no difference in the mechanical properties between the tested materials after 3 - 12 months of simulation effects of the oral environment.

2. Materials and Methods

Three groups of interim restorative materials (N = 120) were tested in the form of rectangular specimens (25 × 2 × 2 mm) according to ISO10477 (**Figure 1**). Conventional autopolymerized PMMA materials (Jet Tooth ShadeTM Powder; Lang Dental Co., Chicago, IL, USA), CAD/CAM-milled prefabricated resin blocks (Telio CAD; Ivoclar Vivadent), and 3D-printed resin (Crown & Bridge NextDent®; 3D Systems, Soesterberg, Netherlands) were assessed in this study (**Figure 1**). Specimens from each group were subdivided into four equal subgroups (n = 10) according to time interval of aging at baseline, 3 months, 6 months and 12 months (**Chart 1**).

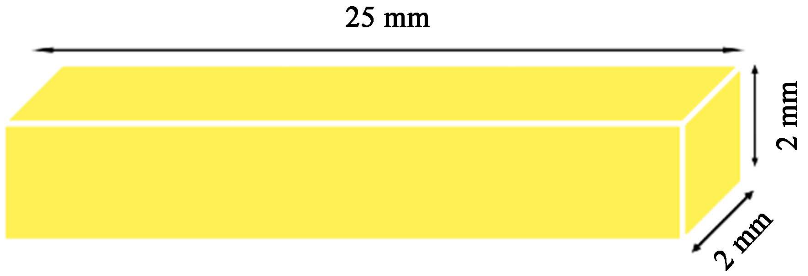
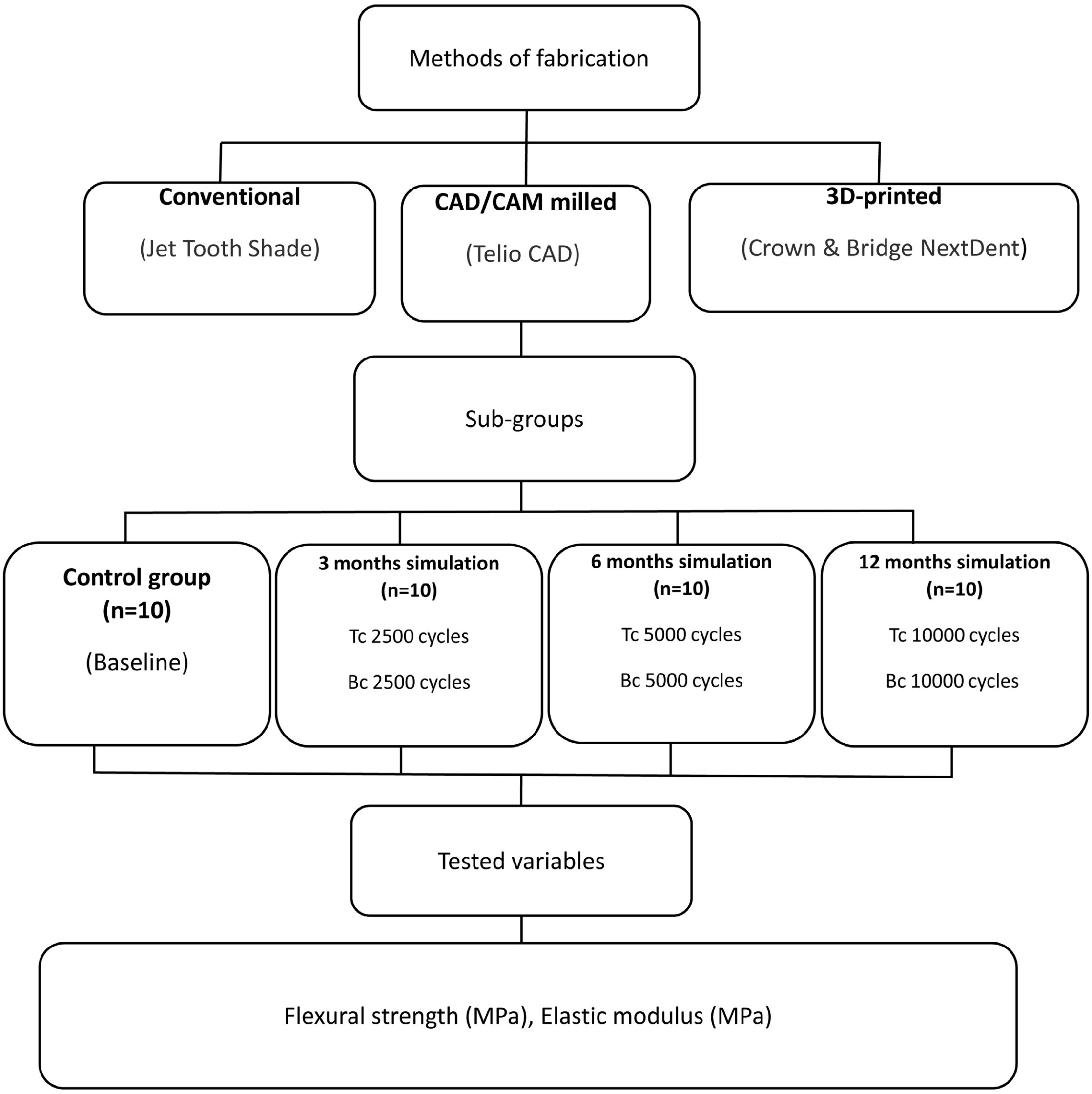


Figure 1. Schematic representation of specimen dimensions.

Conventional specimens were prepared using PMMA (Jet Tooth ShadeTM self-Curing acrylic resin, 6/1 Kit-Lang Dental Manufacturing Co., Inc., Illinois, IL, USA). A 2:1 powder/liquid mixing ratio was prepared using a metal mold under a load of 3 kg and then finished using wet silicon carbide paper (600 grit). The CAD/CAM milled groups were prepared using PMMA resin blocks (Telio CAD; Ivoclar Vivadent). Specimens were designed using a 3-Shape Dental System™ CAD solution and then milled using a VHF CAM 5-S1 milling machine (VHF camfacture AG, Ammerbuch, Germany) with bur diameters of 1 mm and 3 mm. Design and milling were performed using standard parameters. Specimen finishing was performed according to the manufacturer's instructions. The 3D-printed specimens were fabricated using an SLA printer (028D; DWS, Italy)



Tc = thermocycling, Bc=Brushing cycle

Chart 1. Study methodology.

in PMMA resin (Crown & Bridge NextDent®; 3D Systems, Soesterberg, The Netherlands). The thickness of the build layer was 50 μ with a 0˚ orientation. The specimens were soaked in 95% ethanol alcohol and then polymerized for 30 minutes using a postcuring unit (according to the manufacturer's instructions).

Thermocycling and brushing were utilized to represent accelerated aging processes, where every 2500 cycles of brushing and thermocycling simulated 3 months of oral use [29] [32] [33]. All the specimens were subjected to 2500 or 5000 or 10,000 cycles (5˚C - 55˚C), with a dwell time of 30 sec and a transfer time of 10 sec. The tested specimens underwent simulated brushing following thermocycling. Each specimen was fixed on a customized putty mold to stabilize it and subjected to 2500, 5000, or 10,000 brushing cycles of 15 mm traveling length and a speed of 35 mm/sec under a vertical load of 250 g and 1.5 Hz. The brushing cycles consisted of horizontal back-and-forth strokes of soft nylon toothbrush (TARA) in a 1:1 water/dentifrice slurry (Colgate). At baseline and after 3, 6 and 12 months of accelerated aging, the flexural strength and modulus of elasticity were tested using a three-point bending test with a universal testing machine (Instron Corp., Canton, MA, USA) with a 500 N load cell and a vertical load applied on the center of the specimens with a 20 mm support span and a 4 mm/min crosshead speed (**Figure 2**). The load was continuously applied until the specimens broke, and the breaking loads were recorded separately. Flexural strength was measured from the registered breaking load using the following equation:

Figure 2. Sample placed in universal testing machine (Instron) and subjected to a three-point bending test.

$$\sigma = 3FL/2bd^2;$$

where

σ = Flexural strength, F = load (force) at the fracture point, L = length of the support span, b = width of specimen, d = thickness of the specimen.

The elastic modulus (E) was measured using the following equation:

$$E = FL^3/4bh^3d;$$

where, L = length of the support span, b = the width of the specimen at the failure site, h is the thickness of the specimen at the failure site, and d is the deflection at load F.

3. Results

Data were normally distributed according to the Shapiro-Wilk test. Intergroup comparisons were performed using two-way (ANOVA) or one-way (ANOVA), and pairwise comparisons were performed using Tukey's post hoc test. All the statistical analyses were conducted using SPSS version 26 (Chicago, IL, USA). The mean and standard deviation of the flexural strength and elastic modulus of each specimen are presented in **Table 1**.

Table 1. The results of One-way ANOVA and Tukey's post hoc test.

Variable	Material	Aging							
		Baseline		3 months		6 months		12 months	
		mean ± sd	F p-value	mean ± sd	F p-value	mean ± sd	F p-value	mean ± sd	F p-value
Flexural strength (MPa)	Conventional	84.35 ± 11.47^{Ba}	0.00	69.38 ± 10.28^{Ab}	0.00	72.38 ± 8.87^{Ab}	0.00	68.27 ± 5.73^{Ab}	0.00
	CAD/CAM milled	148.85 ± 6.21^{Bb}		118.59 ± 10.57^{Ac}		116.77 ± 13.54^{Ac}		115.47 ± 15.41^{Ac}	
	3D-printed	80.62 ± 8.25^{Ba}		46.96 ± 7.40^{Aa}		47.34 ± 8.69^{Aa}		38.36 ± 8.33^{Aa}	
Elastic modulus (MPa)	Conventional	2813.43 ± 202.49^{Bb}	0.00	2303.76 ± 294.13^{Ab}	0.00	2321.23 ± 129.12^{Ab}	0.00	2439.14 ± 126.80^{Ab}	0.00
	CAD/CAM milled	3581.63 ± 90.84^{Cc}		3049.54 ± 193.48^{Ac}		2987.81 ± 198.47^{Ac}		3337.98 ± 219.55^{Bc}	
	3D-printed	1761.94 ± 250.02^{Ba}		1146.55 ± 195.69^{Aa}		1260.71 ± 95.12^{Aa}		1281.15 ± 181.67^{Aa}	

Different uppercase letters denote statistical difference among the aging intervals for the same material. Different lowercase letters denote statistical difference among the tested material for each tested variable. Significant difference at $p \le 0.05$.

Among the baseline and all aging interval groups, the CAD/CAM milled group had significantly greater flexural strength and elastic modulus ($p < 0.05$) than did the conventional and 3D-printed groups (**Table 1**).

At baseline, no significant difference in flexural strength was observed between the conventional and 3D-printed groups (**Figure 3**). However, a significant difference ($p < 0.05$) in the elastic modulus was observed between the two groups (**Figure 4**).

Within each tested material, the baseline group had significantly greater values ($p < 0.05$) than did the other aging intervals. However, there was no significant difference observed among the aging intervals of 3, 6, and 12 months, except for the CAD/CAM milled group. In the 12-month aging group, a significant difference ($p < 0.05$) was found in the elastic modulus. No significant difference ($p < 0.05$) was observed between the 3- and 6-month aging groups.

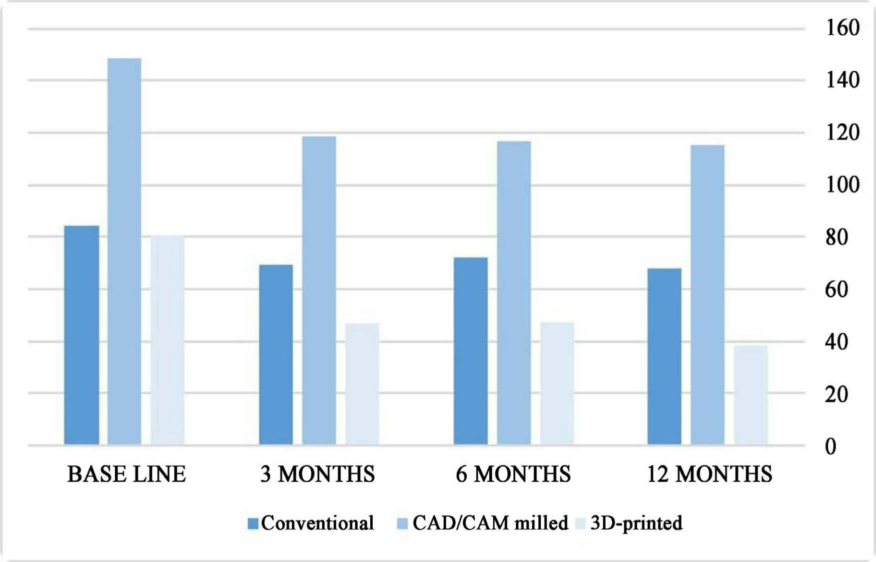


Figure 3. The mean values of Flexural strength (MPa) of different interim restorations through different accelerated aging intervals.

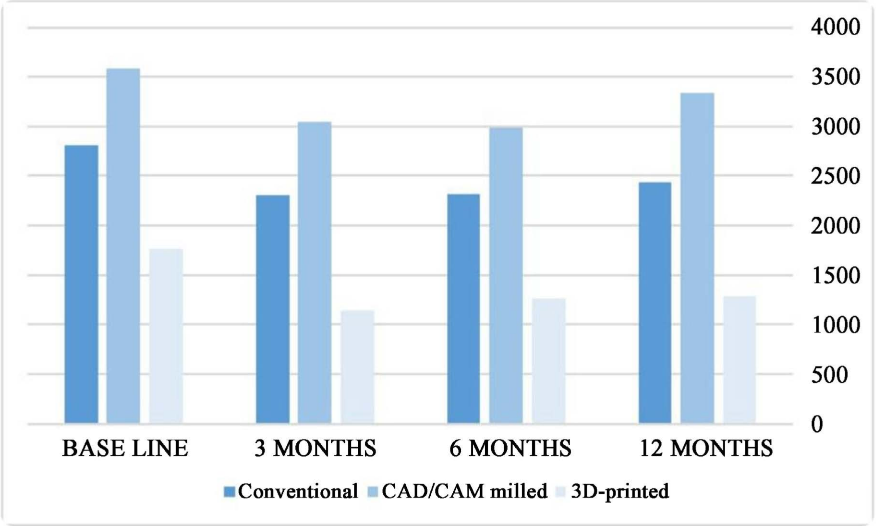


Figure 4. The mean values of Elastic modulus (MPa) of different interim restorations through different accelerated aging intervals.

4. Discussion

The aim of this *in vitro* study was to compare three different interim restorative materials prepared using different manufacturing techniques and subjected to accelerated aging. The null hypothesis was rejected because significant differences were found in the flexural strength and the elastic modulus between the tested groups.

Several studies have used different accelerated aging techniques to simulate the effects of the oral environment on interim restorations. Ellakany *et al.* tested the effect of 50,000 thermocycles on conventional, CAD/CAM milled and 3D-printed PMMA interim restorations [34]. Yao *et al.* compared the flexural strength and marginal accuracy of conventional and CAD/CAM milled materials before and after 5000 thermal cycles [35]. Atay *et al.* investigated the physical characteristics of CAD/CAM milled interim restorations after being subjected to various storage conditions, such as storage in a dry environment, immersion in distilled water at 37˚C for one week and water immersion for one week, followed by 10,000 thermal cycles [23]. In the present study, the accelerated aging protocol involved subjecting the specimens to 2500, 5000 and 10,000 thermal cycles followed by toothbrushing to simulate 3, 6 and 12 months of exposure to the oral environment. The results of the present study are consistent with those of earlier studies, indicating that the mechanical properties of interim restorations are impacted by accelerated aging. The results showed a significant reduction in the flexural strength and elastic modulus at all aging intervals compared to those at baseline. However, there was no significant difference observed among the age intervals of 3, 6, and 12 months, except for the CAD/CAM milled group. In the 12-month aging group, a significant difference was found in the elastic modulus compared to that of the 3 and 6 months aging groups; this was consistent with the findings of Ellakany *et al.*, who discovered that the milled group had the highest elastic modulus [34].

In the present study, the CAD/CAM milled restorations had the highest flexural strength and elastic modulus, followed by the conventional and 3D-printed interim restorations at baseline and at all aging intervals. This finding could be attributed to the highly cross-linked structure of CAD/CAM milled restorations and the decreased manufacturing errors as these restorations are produced under strict conditions, which effectively minimizes flaws during restoration milling [9] [11] [14] [16] [23] [35] [36]. These results are consistent with those of a systematic review conducted by Al-Humood *et al.*, which concluded that the mechanical properties of CAD/CAM milled interim restorations are significantly stronger than those of 3D-printed and conventional restorations [37]; this could be attributed to the reduced porosity or enhanced structural characteristics [11] [16].

Conventional interim restoration material had a lower flexural strength and elastic modulus than did CAD/CAM milled. It is possible that conventional autopolymerized resin could entrap some air during manual mixing of PMMA resins, which leads to more porous material and crack initiation, resulting in reduced mechanical strength [27] [38] [39]. The strength of conventional interim restoration can be significantly affected by water absorption resulting from storage in water or artificial saliva, as well as thermocycling, because conventionally fabricated interim restorations tend to absorb water, which leads to deterioration of the polymeric chains through hydrolysis of the monomer. Consequently, the mechanical properties of the resin degrade [16] [21] [36] [37].

In this study, the group with interim restoration using 3D-printing showed the lowest flexural strength and elastic modulus and the least durability for long-term usage. These findings were confirmed in another study conducted by Digholdar *et al.*, who compared the flexural strength of interim restoration fabricated using different methods [9]. They found that the CAD/CAM milled interim restoration had the highest flexural strength compared to the conventional, and the 3D-printed interim restoration had the lowest flexural strength. A similar result was reported by Berli *et al.*, who showed that 3D-printed interim restoration exhibited lower resistance to stress and aging than conventional, or CAD/CAM milled interim restorations [19]. In addition, the 3D-printed group was more affected by accelerated aging [19]. This is possibly due to the different manufacturing parameters such as curing speed, printed layer thickness, printing direction and post-curing techniques. These factors were identified to have an impact directly or indirectly on the mechanical properties of 3D-printed resin material [9] [19] [40]-[42]. This impact was proven by Piedra-Cascón *et al.*, who found that printing a 3D-printed prosthesis in a vertical direction would pose significantly higher compressive strength than a 3D-printed prosthesis in a horizontal direction [43]. In addition, Väyrynen *et al.*, and Hwangbo *et al.*, reported that the utilization of isopropyl alcohol for resin monomer removal after printing leads to a substantial decline in mechanical properties [44] [45].

Moreover, conflicting results have been reported by Alqahtani *et al.*, Alageel *et al.*, and Tasin *et al.*, who all agreed that CAD/CAM milled, and 3D-printed resins have similar flexural strength values [21] [27] [29]. The discrepancy in the results for this study and the study by Alqahtani *et al.*, could be attributed to the difference in materials used and the absence of using the accelerated aging [21]. Further, the discrepancy in the results from Alageel *et al.*, may be due to the different fabrication methods and parameters used in the DLP printing method [27]. On the other hand, Tasin *et al.* compared PMMA CAD/CAM milled and 3D-printed composite resin materials [29]. Furthermore, Sadek *et al.*, found that 3D-printed PMMA interim materials have greater flexural strength and increased durability against chemical and mechanical aging compared to conventional and CAD/CAM PMMA interim materials. They used different accelerated aging regimen by utilizing 60,000 cycles of chewing simulation and different storage media (artificial saliva, mouthwash and coffee) [46]. Pantea *et al.*, reported that 3D-printed interim resins have a higher flexural strength and modulus of elasticity than conventional interim resin materials. This may be attributed to the use of different printing methods (DLP and LCD) and the absence of accelerated aging [30].

There are several limitations on the current study. Due to the fact that this study was conducted *in vitro* with flat specimens that did not accurately replicate *in vivo* settings. Furthermore, since the study tested the 3D-printed material from one manufacturer, the results may not apply to other brands or varieties of 3D-printing resin. Given that 3D-printed interim resin restorations can be fabricated with modified characteristics due to variations in composition, polymerization duration, and printing techniques, future investigations should compare different 3D-printed resin materials and printing methods. Although *in vitro* studies provide valuable preliminary data, clinical studies are essential to validate and confirm these findings in oral environment.

5. Conclusion

The CAD/CAM milled interim restorations demonstrated better mechanical properties when compared to conventional, and 3D-printed interim restorations. CAD/CAM milled interim restorations could be recommended for long-term temporization, long-span prosthesis, full arch implant-supported interim prosthesis or for patients with increased occlusal forces, such as parafunctional habits or hard food consumption.

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Conflicts of Interest

The authors declare no conflicts of interest.

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