Maximum Fracture Load of Interim Crowns Fabricated by Additive and Subtractive Techniques

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Purpose: To evaluate fracture load values of five types of interim CAD/CAM crowns with and without thermocycling. ***Materials and Methods:*** A complete coverage crown was designed on a mandibular first molar with a uniform 1.5-mm axial and occlusal reduction, and the STL file was exported to manufacture 100 crowns using five materials (20 crowns per material): ZCAD Temp Esthetic (SM-ZCAD; Harvest Dental); Telio CAD (SM-TCAD); P pro Crown and Bridge (AM-PPRO); E-Dent 400 C&B MHF (AM-EDENT); and DENTCA Crown & Bridge (AM-DENTCA). Each group was then divided into two subgroups: before and after thermocycling (10 cornws per subgroup). The STL file of the mandibular first molar die was used to manufacture 100 resin dies. Each die was assigned to one interim crown. Interim crowns were then luted to their assigned die using a temporary luting agent. The fracture strength of crowns was then assessed using a universal testing machine at a crosshead speed of 2 mm/minute. Two-way ANOVA followed by Tukey multiple comparations post-hoc tests were used to assess the effect of material choice and thermocycling process on the fracture strength of interim crowns (α = .05). ***Results:*** Material choice and the thermocycling process exerted a significant (P < .001) impact on the fracture strength of interim crowns. However, the interaction between these two factors did not yield a statistically significant effect (P = .176). ***Conclusions:*** Within the limitations of this study, the type of interim materials and thermocycling process have a significant impact on the fracture strength of interim crowns. *Int J Prosthodont 2024;37(suppl):s221–s226. doi: 10.11607/prd.8928*

An interim restoration serves the purpose of enhancing esthetics, stability, and function in dentistry for a predetermined duration, after which it necessitates replacement with a definitive dental prosthesis.[1] Interim restorations play a vital role, particularly in cases involving multiple teeth, where they may serve for extended periods, ensuring the preservation of tissue health, continuous stability assessment, and the facilitation of necessary adjustments.[2] Interim prostheses play a crucial role in enduring the dynamic conditions of the oral environment, especially in scenarios where complete arch rehabilitation is required. The suitability of interim materials with adequate strength and stability becomes paramount to support their functional demands. Interim restorations fabricated through subtractive or additive techniques have gained favor due to their enhanced physical and mechanical properties.[3,4]

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The subtractive manufacturing (SM) technique utilizes milling machines for crafting both external and internal surfaces of dental restorations. Milled restorations have emerged as the standard for producing long-term interim restorations, mainly due to the following attributes: high fracture resistance, minimal wear, and excellent color stability. The subtractive process has the leverage of using high-density, prepolymerized polymers, thereby enhancing the mechanical properties beyond what is achievable with chemically cured resins.[5] It is widely acknowledged that interim crowns produced through the subtractive technique exhibit superior strength compared to autopolymerized polymethyl methacrylate (PMMA) and bisacryl-based materials, regardless of the thermocycling process.[3,4,6–10] Concurrently, there are ongoing efforts to further refine the physical and mechanical properties of materials manufactured through additive techniques, reflecting a commitment to continuous improvement in this field.

In the additive manufacturing (AM) technique, various 3D-printing technologies are employed to construct dental prostheses layer by layer, allowing for the creation of 3D objects while minimizing material waste compared to SM.[11] Interim restorations produced through AM exhibit a stress resistance comparable to that of bisacryl materials.[12] However, interim restorations manufactured with AM display lower strength than PMMA-based interim crowns manufactured with SM and heat processing.[13,14] Nonetheless, there is ongoing advancement in both the AM technology and materials, aiming to enhance the physical and mechanical properties of 3D-printed materials. Among the AM techniques, direct light processing (DLP) stands as the most prevalent in dentistry for creating precise interim restorations.[15] In DLP, the polymer undergoes exposure to UV light from a projector, polymerizing the entire layer simultaneously.[16] Carbon digital light synthesis (DLS) is a recently developed 3D-printing technology that merges aspects of stereolithography and DLP.[17,18] In DLS, photosensitive resin is selectively exposed to projected UV light. During this process, a thin resin layer is positioned over an oxygen-permeable window, preventing resin adhesion due to oxygen inhibition. By controlling oxygen exposure and producing the part as a whole rather than layer by layer, DLS streamlines the 3D-printing process, yielding faster results. This innovation further results in the creation of 3D objects with a smooth surface and high resolution (featuring isotropic mechanical properties) consistent in all directions.[17–21] Additionally, interim crowns manufactured through the DLS technique have demonstrated smaller marginal gaps compared to those produced via DLP and SM.[22]

The fracture strength of interim prostheses holds paramount importance in ensuring their long-term functionality. Numerous studies have assessed the fracture load of interim crowns produced through both SM and AM.[4,14,23] However, there remains a notable gap in the available data concerning interim crowns manufactured using DLS technology. The primary objective of this study was to conduct a comparative analysis of the fracture load among various interim crowns fabricated through AM and SM, before and after thermocycling. The first null hypothesis posited that there would be no significant difference in the fracture load of interim crowns when comparing those manufactured through SM and AM. The second null hypothesis posited that the thermocycling process would exert no substantial effect on the fracture load of these interim crowns.

MATERIALS AND METHODS

To ascertain the appropriate number of specimens for the present study, a power analysis was conducted using G*Power (version 3.1.9.7, Universität Düsseldorf). This analysis relied on data obtained from a prior study and aimed to achieve a statistical power of 0.8, with a significance level set at .05.[8] The study involved the design of a complete-coverage crown for a mandibular first molar. The crown featured a consistent 1.0-mm chamfer margin and 1.5-mm axial and occlusal reduction. Subsequently, an STL file of this design was generated and used to fabricate a total of 100 crowns, distributed across five different materials (20 crowns per material). To further explore the effects of thermocycling, each group was divided into two subgroups (10 crowns per subgroup): before and after thermocycling, allowing for a comprehensive evaluation of the impact of the thermocycling process.

Table 1 lists the specifics of the materials used, the manufacturing technology employed, the respective manufacturers, and the composition of each group. The STL file of the crown served as the basis for manufacturing (SM) the crowns using two different types of PMMA billets (ZCAD Temp Esthetic and TelioCAD, Ivoclar Vivadent) utilizing a five-axis milling machine (PrograMill PM7, Ivoclar Vivadent). Additionally, the STL file was used to 3D-print crowns (AM) using three different materials: Two materials—a microfilled hybrid material (E-Dent 400 C&B, EnvisionTEC) and a resin (P pro Crown and Bridge, Straumann)—were fabricated using DLP units (VIDA HD, EnvisionTEC; P30, Straumann; respectively), while the remaining material—a resin (Crown and Bridge, Dentca)—was produced using a DLS unit (Carbon M1, Dentca). Following the manufacturing process, all specimens underwent postprocessing procedures as detailed in Table 1.

The STL file of the mandibular first molar die served as the foundation for manufacturing 100 resin dies (P pro Master Model, Straumann) using a 3D-printing machine (P30). Following fabrication, each resin die underwent postprocessing according to the respective

Table 1 Materials Used

Material	Abbreviation	Manufacturing-postprocessing method	Composition
ZCAD Temp Esthetic, Harvest Dental	SM-ZCAD	Milling machine (PrograMill PM7, Ivoclar Vivadent)	PMMA and ester-based cross-linked polymers
Telio CAD, Ivoclar Vivadent	SM-TCAD	Milling machine (PrograMill PM7, Ivoclar Vivadent)	PMMA
P Pro Crown and Bridge, Straumann	AM-PPRO	DLP (P30, Straumann) Postprocessing with PCure (Straumann): 3:30-min cleaning in 90% isopropyl alcohol and drying; 3-min vacuuming time; 10-min curing time; 30-s pressure compensation	acrylic resin, urethane dimethacrylate, 2,2-bis (acryloyloxymethyl) butyl acrylate; trimethylolpropane triacrylate diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide
E-Dent 400 C&B, EnvisionTEC	AM-EDENT	DLP (Vida HD, EnvisionTEC) Postprocessing steps: cleaning in 90% isopropyl alcohol for 3 min to remove excess; rinse 90% isopropyl alcohol for 3 min to finalize cleaning; cure in a UV polymerization unit (PCA 100, EnvisionTEC) for 10 min	Microfilled hybrid material
Crown and Bridge, DENTCA	AM-DENTCA	DLS (Carbon M1, Dentca) Postprocessing steps: cleaning in 90% isopropyl alcohol for 3 min to remove excess; rinse 90% isopropyl alcohol for 3 min to finalize cleaning; cure in a UV polymerization unit (PCU LED N2, Derve) for 12 min while the object is placed in clear glass with vegetable glycerin	Methacrylate monomer, diurethane dimethacrylate, trimethylolpropane trimethacrylate, initiator proprietary, stabilizer proprietary, pigment

Table 2 Fracture Strength of Interim Crowns With and Without Thermocycling

Fabrication technique	Materials	Without thermocycling	With thermocycling
Subtractive manufacturing	SM-ZCAD	3,629 ± 159 N	3,059 ± 239 N
	SM-TCAD	3,622 ± 288 N	3,198 ± 196 N
Additive manufacturing	AM-PPRO	3,746 ± 529 N	3,689 ± 426 N
	AM-EDENT	3,933 ± 378 N	3,667 ± 439 N
	AM-DENTCA	2,573 ± 284 N	2,253 ± 199 N

Data are presented as mean ± SD.
SM-ZCAD = ZCAD Temp Esthetic; SM-TCAD = Telio CAD; AM-PPRO = P Pro Crown and Bridge; AM-EDENT = E-Dent 400 C&B MHF; AM-DENTCA = DENTCA Crown & Bridge

manufacturer's instructions. Each die was then paired with an interim crown, and the marginal integrity of the crowns was assessed using an explorer by one experienced practitioner (R.S.Z.). Subsequently, the specimens in thermocycling subgroups underwent 1,000 cycles alternating between temperatures of 5°C and 55°C, with a dwell time of 15 seconds. After thermocycling, the marginal integrity of the interim crowns was reevaluated on their assigned dies. Interim crowns were then luted to their corresponding dies using a temporary luting agent (TempBond NE, Kerr Dental) under a constant pressure of 450 g (Gillmore Needle Apparatus, Gilson) and left at room temperature for 24 hours. The fracture strength of the crowns was then assessed using a universal testing machine (33R4204, Instron). A stainless-steel sphere with a radius of 5 mm was positioned on the occlusal surface at the central pit. The location of the stainless-steel sphere was verified using articulating paper. Subsequently, a compressive load was applied along the long axis of the tooth at a crosshead speed of 2 mm/minutes, and the test continued until fracture occurred.

Shapiro-Wilk test was used to assess the normality assumption. Two-way ANOVA followed by Tukey multiple comparations post-hoc tests were used to assess the effect of material choice and thermocycling process on the fracture strength of CAD/CAM interim crowns. $P < .05$ was considered statistically significant. Marginal integrity of crowns was reported descriptively.

RESULTS

Table 2 presents the fracture load (N) for various materials, with and without the thermocycling process. The data met the assumption of normality ($P = .4179$). Marginal integrity of interim crowns was recorded as clinically acceptable for specimens with or without thermocycling. Two-way ANOVA (Table 3) revealed

Table 3 Two-Way ANOVA Results

	Sum of squares	df	Mean square	F	*P*
Type of material	2.44^{e7}	4	6.09^{e6}	54.40	< .001
Thermocycling process	2.68^{e6}	1	2.68^{e6}	23.91	< .001
Type of material * thermocycling process	725,293	4	181,323	1.62	.176
Residuals	1.01^{e7}	90	111,989	–	–

Table 4 Fracture Strength of Interim Crowns for Studied Materials

Fabrication technique	Materials	Sample size, n	Mean ± SD	95% CI	Median	IQR
Subtractive manufacturing	SM-ZCAD	20	3,344 ± 353A N	3,195; 3,493	3,432 N	530
	SM-TCAD	20	3,410 ± 324A n	3,261; 3,558	3,349 N	608
Additive manufacturing	AM-PPRO	20	3,718 ± 468B N	3,569; 3,866	3,793 N	629
	AM-EDENT	20	3,800 ± 421B N	3,651; 3,949	3,813 N	460
	AM-DENTCA	20	2,413 ± 289C N	2,264; 2,562	2,375 N	282

IQR = interquartile range.
95% CI values are presented as lower and upper limits. Same uppercase letters represent no significant difference (*P* > .05).

Table 5 Fracture Strength of Interim Crowns With and Without Thermocycling

Treatment	Sample size, n	Mean ± SD	95% CI	Median	IQR
With thermocycling	50	3,173 ± 611 N	3,079; 3,267	3178 N	593
Without thermocycling	50	3,501 ± 587 N	3,406; 3,595	3624 N	702

95% CI values are presented as lower and upper limits.

that both the material choice and thermocycling process exerted a significant (*P* < .001) impact on the fracture strength of interim crowns. However, the interaction between these two factors did not yield a statistically significant effect (*P* = .176), indicating that their combined influence on fracture strength was not significant.

Further investigation into the influence of material choice indicated a significant effect (*P* < .001) on the fracture load of interim crowns. Subsequent Tukey post hoc tests (Table 4) revealed that the AM-DENTCA group exhibited significantly (*P* < .001) lower fracture strength than all other groups. Conversely, the AM-PPRO and AM-EDENT groups displayed significantly (*P* < .05) higher fracture strength than other groups. Notably, there was no statistically significant difference observed between the SM-ZCAD and SM-TCAD groups (*P* = .97) or between the AM-PPRO and AM-EDENT groups (*P* = .94). Additionally, Tukey post hoc tests (Table 5) revealed that the thermocycling process significantly (*P* < .05) reduced the fracture load of interim crowns. However, due to the lack of a significant interaction between material type and the thermocycling process (*P* = .176), further pair-wise comparisons between specific groups were not possible.

DISCUSSION

This study assessed the fracture load of CAD/CAM interim crowns, considering various materials, both with and without the thermocycling process. The null hypothesis was that the fracture strength of interim crowns would remain unaffected by the choice of material and the thermocycling procedure. However, the findings rejected the null hypothesis, as it was discovered that both the material selection and the thermocycling process exerted a significant (*P* < .001) impact on the fracture strength of CAD/CAM interim crowns.

Interim prostheses play a crucial role in enduring the dynamic conditions of the oral environment.[24] The present study employed the thermocycling process as a means to simulate the fatigue that interim crowns might experience in the oral cavity over an extended period. This process allowed the interim crowns and their sustainability as long-term interim prostheses to be evaluated. Furthermore, previous studies utilized nonrigid dies characterized by an elastic modulus similar to that of natural teeth to replicate the clinical environment.[14,25,26] In alignment with this practice, the present study also used nonrigid dies to create a more realistic and clinically relevant testing environment.

The present study recorded interim crown fracture load values ranging between 2413 N and 3,800 N. Notably, these values significantly surpass the fracture loads reported in previous studies for CAD/CAM interim crowns, which typically fell within the range of 953 N to 1,289 N.[3,4,8] These variations in fracture load values between the present and previous studies may be attributed to several factors,[3,4,8] including differences in the type of die material used (previous studies used epoxy resin or metal alloy dies) and variations in the amount of axial wall reduction (set at 1 mm in previous studies). However, the present fracture load values align closely with those reported by Bjorge,[14] which ranged from 2,334 N to 2,702 N. This similarity might be attributed to a common factor in the present study and Bjorge's research: the use of 3D-printed dies.

The present study evaluated the influence of thermocycling on the fracture load of interim crowns. The findings revealed a significant decrease in fracture load following thermocycling ($P < .001$). While no prior study has specifically examined the effect of thermocycling on interim crown fracture load, this aging process has been utilized as a means to assess interim materials. Previous research has indicated that thermocycling adversely impacts the mechanical properties of CAD/CAM interim materials.[7,27] This effect may be attributed to residual stresses induced by water uptake and temperature fluctuations during the thermocycling process. These stresses have the potential to initiate crack formation, ultimately leading to long-term structural failure.

Research investigating the comparative performance of interim crowns fabricated through SM vs AM techniques has yielded varying results.[4,14,23] Previous studies have reported that interim crowns fabricated through SM exhibited either comparable or higher fracture loads than their AM counterparts.[4,14,23] Bjorge's study[14] reported that interim crowns fabricated through SM had higher fracture loads compared to ones manufactured through AM. However, the present study reports somewhat different findings: Two AM groups (AM-PPRO and AT-EDENT) demonstrated significantly ($P < .05$) higher fracture loads than their SM counterparts. Conversely, the AM-DENTCA group exhibited significantly ($P < .05$) lower fracture loads than the SM groups. The difference between the current study and Bjorge's study might be due to the utilization of various materials and technology. Bjorge used a different 3D-printing resin and stereolithography (SLA) technology for the interim crowns fabricated through AM, while the present study employed DLP and DLS technologies with three different 3D-printing resins. Similarly, Al-Wahadni et al's study[23] exhibited differences from the present findings. Those authors[23] found that interim crowns fabricated through DLP technology had significantly lower fracture loads than ones manufactured through the SM technique, while the present data indicated that two DLP-fabricated groups (AM) had significantly ($P < .05$) higher fracture loads than the SM groups. This discrepancy may be attributed to variations in the choice of 3D-printing resins, PMMA billets, and postprocessing protocols used in the two studies. Finally, Reeponmaha et al[4] reported that interim crowns fabricated via AM were similar in fracture load to those produced via SM, which differs from the present findings. Once again, it is important to note that Reeponmaha et al[4] employed a different 3D-printing technology, resin, and PMMA billet than those used in the present study, potentially accounting for these differences in outcomes.

The present study assessed the fracture load of interim crowns fabricated with DLS technology. A prior study by Al-Wahadni et al[23] highlighted the influence of 3D-printing technology on the fracture load of interim crowns. Al-Wahadni et al's research[23] found that interim crowns fabricated with SLA technology exhibited higher fracture loads than those fabricated through DLP technology. The outcome of the present study similarly showed that interim crowns fabricated through DLP technology (AM-PPRO and AT-EDENT) had significantly ($P < .05$) higher fracture loads than those produced using DLS technology (AM-DENTCA).

Postpolymerization conditions play a crucial role in determining the flexural and fracture strengths of 3D-printing resin.[28,29] The current findings align with existing research, as postpolymerization in glycerin has been shown to reduce the mechanical properties of interim 3D-printing resins, and curing in a dry condition provided the best outcomes.[28] The differences in postprocessing steps and materials used may have contributed to the variations in fracture loads observed in the present study. The AM-DENTCA group underwent postpolymerization in glycerin, potentially impacting their lower fracture load compared to DLP-fabricated interim crowns, which were postpolymerized in dry conditions. Additionally, it is important to note that AM-DENTCA employs a PMMA-based material, while AM-PPRO and AM-EDENT utilize resin-based materials, which may have further contributed to the observed differences in fracture loads.

The present study has several limitations, including being confined to a limited selection of interim dental materials, which may not represent the full spectrum of recently developed CAD/CAM interim crowns. Further, the study focused on a restricted set of mechanical properties, leaving other potentially relevant factors unexplored. Additionally, the impact of fatigue load on fracture strength and fractography were not assessed, which could be important considerations in future studies. Moreover, postprocessing steps were followed per the manufacturers' instructions, and they were not standardized.

CONCLUSIONS

The present study investigated the fracture strength of interim crowns and explored the impact of various factors, including type of technology and thermocycling process. Significant differences in fracture loads were found between interim crowns fabricated through SM and AM, showing the importance of technology choice and material considerations in dental prosthesis manufacturing. Moreover, it was found that thermocycling significantly reduced the fracture load of interim crowns.

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