



BASIC RESEARCH:

Fracture Resistance of CAD-CAM Interim Crowns Fabricated by Additive Versus Subtractive Manufacturing: An *In Vitro* Study

Resistencia a la fractura de coronas provisionales CAD-CAM fabricadas mediante manufactura aditiva frente a manufactura sustractiva: estudio *in vitro*

Leonard Walter Huamani Diaz¹ <https://orcid.org/0000-0002-5816-7300>

Kelly Romero² <https://orcid.org/0009-0005-3403-9493>

Ricardo Fabian Reyes Mansilla² <https://orcid.org/0009-0006-1769-8603>

Iliana Linares² <https://orcid.org/0009-0002-1432-6039>

Consuelo Marroquín-Soto³ <https://orcid.org/0000-0002-1433-6205>

César-Augusto Padilla-Avalos⁴ <https://orcid.org/0000-0002-8436-4113>

¹Division of Prosthodontics, Faculty of Dentistry, Universidad Nacional Mayor de San Marcos, Lima, Peru.

²Postgraduate Program of Prosthodontics, Faculty of Dentistry, Universidad Nacional Mayor de San Marcos, Lima, Peru.

³Associate Researcher, Research and Innovation Laboratory in Digital Dentistry, School of Dentistry, Universidad Científica del Sur, Lima, Peru.

⁴Research Professor, Research and Innovation Laboratory in Digital Dentistry, School of Dentistry, Universidad Científica del Sur, Lima, Peru.

Correspondence to: César-Augusto Padilla-Avalos, DDS, MSc, PhD - cpadillaav@cientifica.edu.pe

Received: 21-V-2026

Accepted: 19-VI-2026

ABSTRACT: Additive manufacturing has gained increasing popularity for the fabrication of interim restorations because of its efficiency, reduced material waste, and workflow flexibility. However, concerns remain regarding the mechanical reliability of additively manufactured materials compared with CAD-CAM-milled restorations. This *in vitro* study compared the fracture resistance of interim crowns fabricated by additive manufacturing and CAD-CAM milling. Twenty standardized interim crowns were digitally designed and distributed into two groups according to the manufacturing technique (n=10): additively manufactured crowns fabricated with a ceramic-filled nanohybrid resin using LCD technology, and CAD-CAM-milled crowns fabricated from prepolymerized polymethyl methacrylate (PMMA) blocks. Fracture resistance was evaluated under compressive loading using a universal testing machine at a crosshead speed of 1 mm/min until failure. Data were analyzed with the Shapiro-Wilk test and independent t test ($\alpha=.05$). CAD-CAM-milled crowns demonstrated significantly higher fracture resistance than additively manufactured crowns, with mean values of 439.1 ± 24.0 kgf (4306 ± 235 N) and 244.7 ± 34.9 kgf (2399 ± 342 N), respectively. The findings suggest that the manufacturing technique significantly influences the mechanical performance of interim restorations, with CAD-CAM-milled PMMA crowns exhibiting greater resistance to compressive loading under the conditions evaluated.

KEYWORDS: Computer-aided design; Printing, three-dimensional; Fracture resistance; Dental materials.

RESUMEN: La manufactura aditiva ha adquirido creciente popularidad para la fabricación de restauraciones provisionales debido a su eficiencia, menor desperdicio de material y flexibilidad en el flujo de trabajo. Sin embargo, persisten preocupaciones respecto a la confiabilidad mecánica de los materiales fabricados mediante manufactura aditiva en comparación con las restauraciones fresadas mediante CAD-CAM. El presente estudio *in vitro* comparó la resistencia a la fractura de coronas provisionales fabricadas mediante manufactura aditiva y fresado CAD-CAM. Veinte coronas provisionales estandarizadas fueron diseñadas digitalmente y distribuidas en dos grupos según la técnica de fabricación ($n=10$): coronas fabricadas mediante manufactura aditiva con una resina nanohíbrida rellena de cerámica utilizando tecnología LCD y coronas fresadas mediante CAD-CAM a partir de bloques prepolimerizados de polimetilmetacrilato (PMMA). La resistencia a la fractura fue evaluada bajo carga compresiva utilizando una máquina universal de ensayos a una velocidad de desplazamiento de 1 mm/min hasta la fractura. Los datos fueron analizados mediante la prueba de Shapiro-Wilk y la prueba t de Student para muestras independientes ($\alpha=.05$). Las coronas fresadas mediante CAD-CAM demostraron una resistencia a la fractura significativamente mayor que las coronas fabricadas mediante manufactura aditiva ($P<.001$), con valores promedio de 439.1 ± 24.0 kgf y 244.7 ± 34.9 kgf, respectivamente. Los hallazgos sugieren que la técnica de fabricación influye significativamente en el comportamiento mecánico de las restauraciones provisionales, mostrando las coronas de PMMA fresadas mediante CAD-CAM una mayor resistencia a la carga compresiva bajo las condiciones evaluadas.

PALABRAS CLAVE: Restauraciones provisionales; CAD-CAM; Impresión tridimensional; Resistencia a la fractura; Polimetilmetacrilato.

INTRODUCTION

Interim crowns are essential for maintaining esthetics, function, occlusal stability, and prepared tooth protection during fixed prosthodontic treatment. Their mechanical reliability is particularly relevant in prolonged treatments, implant-supported rehabilitation, extensive restorative procedures, long-span provisionalization, and situations involving increased occlusal loading, where fracture or deformation may compromise treatment continuity and patient comfort (1-3).

Digital technologies have transformed the fabrication of interim restorations. CAD-CAM milling uses industrially prepolymerized polymethyl methacrylate (PMMA) blocks, which provide improved material homogeneity, reduced porosity, and more

consistent mechanical behavior than conventionally processed provisional polymers (1,2,4,5). In contrast, additive manufacturing fabricates restorations through layer-by-layer photopolymerization, offering reduced material waste, workflow flexibility, efficient production, and the ability to fabricate complex geometries with minimal material consumption (6,7).

Despite these advantages, concerns remain regarding the mechanical performance of additively manufactured interim restorations. Layer-by-layer fabrication may generate anisotropic behavior, interlayer discontinuities, and stress concentration areas that influence fracture resistance under functional loading (8-10). In addition, the mechanical behavior of printed restorations may be affected by resin composition, build orientation,

printing technology, layer thickness, postpolymerization protocol, marginal adaptation, and artificial aging (10-13).

Although ceramic-filled and nanohybrid printable resins have been introduced to improve the strength and clinical applicability of additively manufactured restorations, the evidence remains heterogeneous. Some studies have reported favorable mechanical performance for printed interim materials, whereas others have found higher fracture resistance for CAD-CAM-milled PMMA restorations, particularly when printing orientation, postcuring, resin formulation, thermocycling, and simulated clinical conditions are considered (5,6,14-16). Therefore, direct comparisons between additive manufacturing and CAD-CAM milling under standardized conditions remain relevant for guiding material selection in provisional prosthodontics.

Recent studies comparing milled, printed, and conventionally fabricated provisional restorations have shown that the mechanical behavior of interim crowns and fixed dental prostheses depends not only on the manufacturing technique, but also on restorative design, span length, material composition, aging protocol, and testing configuration (2,3,10,11,15,17). Therefore, this *in vitro* study compared the fracture resistance of interim crowns fabricated by additive manufacturing and CAD-CAM milling under standardized conditions. The null hypothesis was that there would be no significant difference in fracture resistance between additively manufactured and CAD-CAM-milled interim crowns.

MATERIALS AND METHODS

STUDY DESIGN AND SPECIMEN PREPARATION

An *in vitro* experimental study was conducted to compare the fracture resistance of interim crowns fabricated by additive manufacturing and CAD-CAM milling, following methodological

approaches previously used to evaluate digitally manufactured provisional restorations (2,3,15). A standardized full-contour crown was digitally designed with a 3-dimensional modeling software program (Meshmixer; Autodesk Inc), and the same design was used for all specimens (Figure 1.A,B). Twenty interim crowns were fabricated and distributed into 2 groups according to the manufacturing technique: additively manufactured crowns and CAD-CAM-milled crowns (n=10 per group). The sample size was based on previous *in vitro* studies evaluating fracture resistance of digitally fabricated interim restorations using similar group sizes.

ADDITIVE MANUFACTURING PROCEDURE

Crowns in the additive manufacturing group were fabricated with a ceramic-filled nanohybrid composite resin (Prizma Bio Crown Diamond; MakerTech Labs) using a liquid crystal display (LCD) 3D printer (Phrozen Sonic XL 4K; Phrozen Technology). All specimens were printed with a standardized layer thickness of 50 µm and a build orientation of 90 degrees (Figure 2.A), as printing orientation and layer-by-layer polymerization have been reported to influence the mechanical behavior of additively manufactured interim restorations (9,10,12). After fabrication, the specimens were washed in 99% isopropyl alcohol for 5 minutes to remove uncured resin residues, air-dried, and postpolymerized in a light-curing unit according to the manufacturer's recommendations for 10 minutes under ultraviolet light (Figure 2.B). After postpolymerization, support structures were carefully removed, and controlled mechanical polishing was performed using rubber polishers to obtain a standardized surface finish while minimizing dimensional alteration of the specimens.

SUBTRACTIVE MANUFACTURING PROCEDURE

Crowns in the subtractive manufacturing group were milled from prepolymerized polymethyl methacrylate (PMMA) blocks (Aidite Monochroma-

tic PMMA; Aidite) using a 5-axis milling machine (UP3D; UP3D Tech Co) (Figure 3.A,B). All specimens were fabricated using the same milling strategy and bur configuration under standardized dry-milling conditions according to the manufacturer's recommendations. After milling, the restorations were cleaned with compressed air to remove residual particles and inspected according to the manufacturer's recommendations. No additional polishing procedures were performed to avoid alterations in surface characteristics and specimen dimensions. All specimens were fabricated by the same operator under standardized conditions within each manufacturing workflow to ensure procedural consistency.

MECHANICAL TESTING

All specimens were visually inspected before testing for surface defects or manufacturing irregularities. Each crown was positioned on a standardized supporting structure to simulate

clinical seating conditions. The operator responsible for mechanical testing was blinded to the manufacturing group allocation of the specimens during fracture resistance evaluation. Fracture resistance was evaluated with a previously calibrated universal testing machine (WEW-300B; Jinan Testing Equipment Co) (Figure 3.C). A vertical compressive load was applied to the occlusal surface at a crosshead speed of 1 mm/min until failure, consistent with previous *in vitro* studies evaluating fracture resistance of digitally fabricated interim crowns and fixed dental prostheses (3,5,15). The maximum load at fracture was recorded in kilograms-force (kgf).

STATISTICAL ANALYSIS

Data were analyzed with a statistical software program (SPSS, version 26; IBM Corp). Data normality was assessed with the Shapiro-Wilk test. Fracture resistance values between groups were compared with an independent t test ($\alpha=.05$).

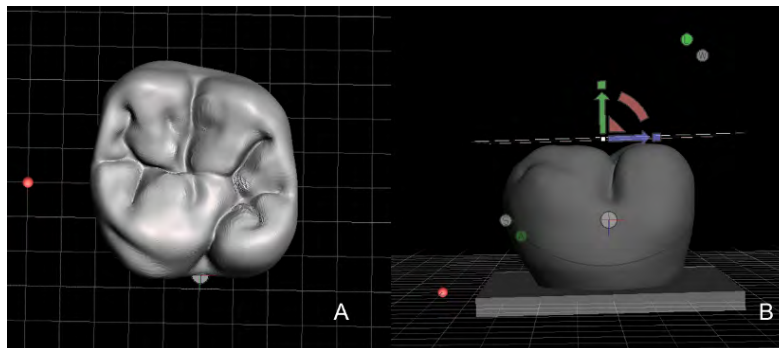


Figure 1. Standardized digital design of the interim crown. (a) Occlusal view. (b) Frontal view on the manufacturing platform.

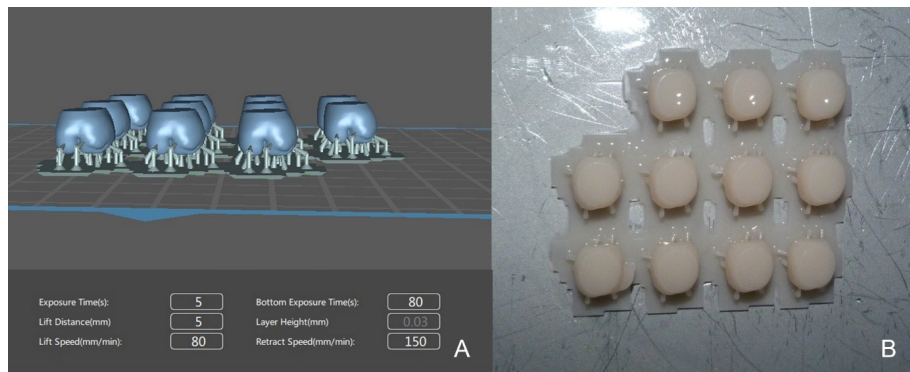


Figure 2. Specimen fabrication procedures. (a) Standardized 3D-printing parameters and build orientation. (b) Additively manufactured interim crown specimens.

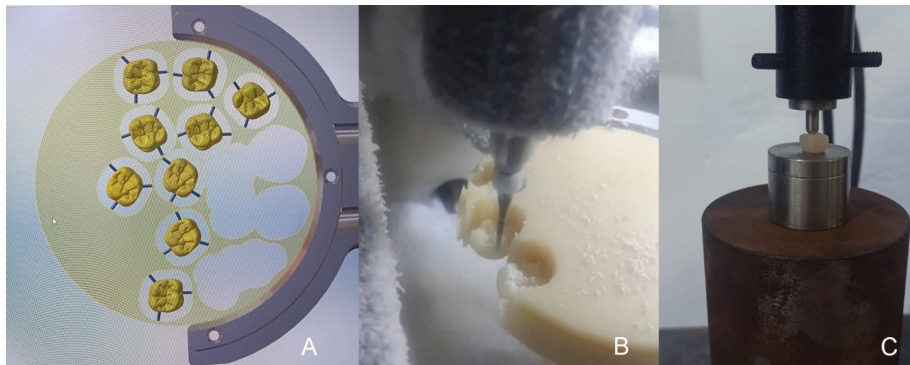


Figure 3. CAD-CAM milling and mechanical testing procedures. (a) Digital positioning of the crown specimens before milling. (b) Milling of PMMA interim crowns. (c) Fracture resistance testing with a universal testing machine.

RESULTS

Fracture resistance values are summarized in Table 1. CAD-CAM-milled interim crowns showed higher fracture resistance than additively manufactured crowns, with mean values of 439.1 ± 24.0 kgf (4306 ± 235 N) and 244.7 ± 34.9 kgf (2399 ± 342 N), respectively. Fracture resistance ranged from 389.5 to 471.1 kgf in the

CAD-CAM-milled group and from 193.8 to 311.0 kgf in the additively manufactured group.

The difference between manufacturing techniques was statistically significant, with CAD-CAM-milled crowns showing a higher mean fracture resistance than additively manufactured crowns (mean difference: 194.4 kgf [1906 N]; 95% CI: 166.0-222.7 kgf [1628-2184 N]; $P < .001$) (Table 1).

Table 1. Fracture resistance of interim crowns according to manufacturing technique and statistical comparison between groups.

Manufacturing technique	n	Mean $\pm$ SD, kgf (N)	Minimum, kgf	Maximum, kgf	Mean difference, kgf (N)	95% CI, kgf (N)	P value
CAD-CAM-milled	10	439.1 $\pm$ 24.0 (4306 $\pm$ 235)	389.5	471.1	194.4 (1906)	166.0-222.7 (1628-2184)	<.001
Additively manufactured	10	244.7 $\pm$ 34.9 (2399 $\pm$ 342)	193.8	311.0	-	-	-

SD, standard deviation; CI, confidence interval. Newton values were calculated using the conversion factor 1 kgf=9.80665 N. The mean difference was calculated as CAD-CAM-milled minus additively manufactured crowns. P value was calculated using the independent samples t test.

DISCUSSION

The present study demonstrated significantly higher fracture resistance for CAD-CAM-milled interim crowns than for additively manufactured crowns, leading to rejection of the null hypothesis. This finding agrees with previous *in vitro* studies reporting higher fracture resistance or failure load values for CAD-CAM-milled interim restorations than for additively manufactured restorations (2,3,5,15). Similar investigations on provisional crowns, fixed dental prostheses, and resin-based CAD-CAM materials have also shown that manufacturing technique can affect fracture behavior and mechanical reliability (4,17,18).

The superior performance of CAD-CAM-milled crowns may be explained by the structural characteristics of industrially prepolymerized PMMA blocks, which provide a dense and homogeneous polymer network with reduced porosity and improved structural integrity. These features may allow more uniform stress distribution during compressive loading and increase fracture resistance (2,7,19). In contrast, additively manufactured crowns are produced through layer-by-layer photopolymerization, which may generate anisotropic behavior and interfacial discontinuities, facilitating stress concentration and crack propagation under loading (8-10). Although ceramic-filled and

nanohybrid resins have improved the mechanical performance of printed materials, fracture resistance may still be affected by resin composition, printing orientation, layer thickness, postpolymerization protocol, marginal adaptation, and aging conditions (6,10-13).

Overall, these results support previous evidence showing superior mechanical properties for CAD-CAM-milled interim materials, including greater fracture resistance, higher homogeneity, reduced porosity, and improved flexural strength (2,3,5,15). However, the evidence remains heterogeneous. Some studies have reported that 3D-printed provisional materials may approach or even exceed milled PMMA when resin formulation, build orientation, postcuring, and simulated clinical conditions are optimized (6,14,16,20). Therefore, the mechanical behavior of printed interim restorations should not be interpreted only by manufacturing category, but also by the specific processing parameters used.

Clinically, CAD-CAM-milled interim crowns may be preferable when greater mechanical reliability is required, such as in patients with increased occlusal loading, extended provisionalization, implant-supported restorations, or long-span provisional prostheses (1,3,13). Additively manufactured restorations may remain appropriate for short-term

or low-load indications because of their efficiency, reduced material waste, workflow flexibility, and rapid fabrication (6,7). The present study is limited by its *in vitro* design, which did not reproduce thermal fluctuations, cyclic fatigue, humidity, salivary exposure, or artificial aging conditions that may affect fracture behavior in digitally fabricated provisional restorations (5,8-10). In addition, only one printed material and one printing technology were evaluated. Future studies should include fatigue loading, aging protocols, different additive manufacturing systems, resin formulations, and standardized testing configurations to better assess the mechanical performance of interim restorative materials.

CONCLUSIONS

CAD-CAM-milled PMMA interim crowns demonstrated significantly higher fracture resistance than additively manufactured ceramic-filled nanohybrid resin crowns under compressive loading. Within the limitations of this *in vitro* study, manufacturing technique influenced the fracture behavior of interim restorations, suggesting that milled PMMA may be preferable when greater mechanical reliability is required.

CONFLICTS OF INTEREST: The authors declare no conflict of interest.

FUNDING STATEMENT: This research did not receive any specific grant from public, commercial, or not-for-profit funding agencies.

AUTHOR CONTRIBUTION STATEMENT: Conceptualization and Design, L.W.H.D.; Investigation and Data Collection, K.R., R.F.R.M. and I.L.; Formal Analysis, Data Interpretation, and Visualization, C.M.S. and C.A.P.A.; Writing – Original Draft Preparation, C.M.S. and C.A.P.A.; Writing – Review and Editing, C.A.P.A.; Supervision and Project Administration, L.W.H.D. All authors have read and agreed to the published version of the manuscript.

REFERENCES

1. Herdocia-Lluberes C.S., Chardon-Narvaez A., Jana-Hernández Z., Lopez-Santiago J.G., Guo K., Blanco-Plard A., et al. Fracture resistance of analog and CAD-CAM long-span fixed provisional restorations: An *in vitro* experimental study. *J Prosthodont Res.* 2025. doi:10.1111/jopr.14021
2. Henderson J.Y., Koriath T.V.P., Tantbirojn D., Versluis A. Failure load of milled, 3D-printed, and conventional chairside-dispensed interim 3-unit fixed dental prostheses. *J Prosthet Dent.* 2022; 127: 275.e1-7. doi:10.1016/j.prosdent.2021.11.005
3. Martín-Ortega N., Sallorenzo A., Casajús J., Cervera A., Revilla-León M., Gómez-Polo M. Fracture resistance of additive manufactured and milled implant-supported interim crowns. *J Prosthet Dent.* 2022;127: 267-74. doi:10.1016/j.prosdent.2020.11.017
4. Legaz J., Sailer I., Mojon P., Lee H., Karasan D. Mechanical properties of additively manufactured and milled interim 3-unit fixed dental prostheses. *J Prosthodont Res.* 2023; 32: 234-43. doi:10.1111/jopr.13524
5. Yildirim M., Aykent F., Özdoğan M.S. Comparison of fracture strength, surface hardness, and color stain of conventionally fabricated, 3D printed, and CAD-CAM milled interim prosthodontic materials after thermocycling. *J Adv Prosthodont.* 2024; 16: 115-25. doi:10.4047/jap.2024.16.2.115
6. Jain S., Sayed M.E., Shetty M., Alqahtani S.M., Al Wadei M.H.D., Gupta S.G., et al. Physical and mechanical properties of 3D-printed provisional crowns and fixed dental prosthesis resins compared to CAD/CAM milled and conventional provisional resins: A systematic review and meta-analysis. *Polymers (Basel).* 2022; 14: 2691. doi:10.3390/polym14132691
7. Revilla-León M., Meyers M.J., Zandinejad A., Özcan M. A review on chemical compo-

- sition, mechanical properties, and manufacturing work flow of additively manufactured current polymers for interim dental restorations. *J Esthet Restor Dent*. 2019; 31: 51-7. doi:10.1111/jerd.12438
8. Alkhateeb R.I., Algaoud H.S., Aldamant-hori R.B., Alshubaili R.R., Alalawi H., Gad M.M. Fracture load of 3D-printed interim three-unit fixed dental prostheses: Impact of printing orientation and post-curing time. *Polymers (Basel)*. 2023; 15: 1737. doi:10.3390/polym15071737
 9. Diken Turksayar A.A., Donmez M.B., Olcay E.O., Demirel M., Demir E. Effect of printing orientation on the fracture strength of additively manufactured 3-unit interim fixed dental prostheses after aging. *J Dent*. 2022; 124: 104155. doi:10.1016/j.jdent.2022.104155
 10. Reymus M., Fabritius R., Keßler A., Hickel R., Edelhoff D., Stawarczyk B. Fracture load of 3D-printed fixed dental prostheses compared with milled and conventionally fabricated ones: The impact of resin material, build direction, post-curing, and artificial aging—an in vitro study. *Clin Oral Investig*. 2020; 24: 701-10. doi:10.1007/s00784-019-02952-7
 11. Abdulkareem M.A., Al-Shamma A.M.W. Marginal adaptation and fracture resistance of 3D-printed and CAD/CAM-milled definitive resin matrix ceramic crowns. *Int J Comput Dent*. 2024; 27: 355-63. doi:10.3290/j.ijcd.b4494301
 12. Aljehani A., Nabalawi A., Hefni A., Alsefri Z., Fakhry O., Al Zaibak W., et al. Effect of build orientation on the fracture resistance and marginal quality of 3D-printed anatomic provisional crowns: An in-vitro study. *Saudi Dent J*. 2024; 36: 584-90. doi:10.1016/j.sdentj.2024.01.004
 13. Elsareef S.S., Azer A.S., Morsy N. Evaluation of fracture resistance and marginal fit of implant-supported interim crowns fabricated by conventional, additive and subtractive methods. *BMC Oral Health*. 2024; 24: 852. doi:10.1186/s12903-024-04597-9
 14. Gul B.C., Demirci F., Baki N., Bahce E., Özcan M. Mechanical analysis of 3D printed dental restorations manufactured using different resins and validation with FEM analysis. *BMC Oral Health*. 2025; 25: 131. doi:10.1186/s12903-024-05384-2
 15. Othman A., Sandmair M., Alevizakos V., von See C. The fracture resistance of 3D-printed versus milled provisional crowns: An in vitro study. *PLoS One*. 2023; 18: e0285760. doi: 10.1371/journal.pone.0285760
 16. Schulz A.C., Othman A., Ströbele D.A., Wagner J., Mosch R., von See C. Fracture strength test of digitally produced ceramic-filled and unfilled dental resin restorations via 3D printing: An in vitro study. *J Clin Exp Dent*. 2023; 15: e118-24. doi:10.4317/jced.60173
 17. Güney B., Nalbant A.D., Bankoğlu Güngör M. Comparison of the fracture resistance of provisional crowns and fixed partial dentures manufactured with conventional, milling, and 3D-printing techniques. *Appl Sci (Basel)*. 2025; 15: 6539. doi:10.3390/app15126539
 18. Abad-Coronel C., Bravo M., Tello S., Cornejo E., Paredes Y., Paltan C.A., et al. Fracture resistance comparative analysis of milled-derived vs. 3D-printed CAD/CAM materials for single-unit restorations. *Polymers (Basel)*. 2023; 15: 3773. doi:10.3390/polym15183773
 19. Prpić V., Schauerperl Z., Čatić A., Dulčić N., Čimić S. Comparison of mechanical properties of 3D-printed, CAD/CAM, and conventional denture base materials. *J Prosthodont Res*. 2020; 29: 524-8. doi:10.1111/jopr.13175
 20. Zarate-Maquera A.D., Sánchez-Tito M., Tozo-Burgos J.G. Mechanical performance of 3D-printed resins versus CAD/CAM PMMA for provisional crowns: New evidence under simulated clinical conditions. *J Clin Exp Dent*. 2025; 17: e1235-40. doi:10.4317/jced.63128