

Distribution Statement

Distribution A: Public Release.

The views presented here are those of the author and are not to be construed as official or reflecting the views of the Uniformed Services University of the Health Sciences, the Department of Defense or the U.S. Government.



UNIFORMED SERVICES UNIVERSITY OF THE HEALTH SCIENCES

POSTGRADUATE DENTAL COLLEGE
AIR FORCE POSTGRADUATE DENTAL SCHOOL
2133 PEPPERRELL ST
JBSA-LACKLAND, TEXAS 78236



THESIS APPROVAL PAGE FOR MASTER OF SCIENCE IN ORAL BIOLOGY

Title of Thesis: "Mechanical Properties of Novel 3D Printed Crown Materials"
Name of Candidate: Alexandra D. Okai, Maj, USAF, DC
Master of Science
19 May 2023

THESIS/MANUSCRIPT APPROVED:

LIEN.WEN.1
234442429

Digitally signed by
LIEN.WEN.1234442429
Date: 2023.05.22
09:35:03 -05'00'

Wen Lien, Col, USAF, DC
Director, Dental Materials Evaluation and Testing
USAF Dental Research and Consultation Service, Ft. Sam Houston, TX

RAIMONDI.CHRIST
OPHER.J.12919512
16

Digitally signed by
RAIMONDI.CHRISTOPHER.J.12
91951216
Date: 2023.05.22 09:09:21 -05'00'

Christopher J. Raimondi, Lt Col, USAF, DC
Co-Director, Dental Materials Evaluation and Testing
USAF Dental Research and Consultation Service, Ft. Sam Houston, TX

VANDEWALLE.KR
AIG.STEPHEN.113
0663733

Digitally signed by
VANDEWALLE.KRAIG.STEPHE
N.1130663733
Date: 2023.05.22 07:41:10 -05'00'

Kraig S. Vandewalle, Col (ret), USAF, DC
Director of Dental Research, Advanced Education in General Dentistry Residency
Air Force Postgraduate Dental School, JBSA-Lackland TX

Mechanical Properties of Novel 3D Printed Crown Materials

**Maj Alexandra Okai, DDS¹; Col Wen Lien, DMD, MS, MS²;
Lt Col Christopher Raimondi, DDS, MS, MS²;
Col (ret) Kraig Vandewalle, DDS, MS¹**

¹USAF Postgraduate Dental School, JBSA-Lackland, TX;

²Dental Research and Consultation Service, JBSA-Ft. Sam Houston, TX

USU Operational Gap: IV, A

Abstract

The purpose of this study was to compare the mechanical properties of 3D-printed provisional and permanent crown materials to established materials on the market. Provisional materials: VareoSmile Temp (Bego) distributed as Temporary Crown and Bridge Resin and printed with Form 3B (Formlabs), Integrity (Dentsply Sirona) hand-fabricated using a stainless-steel mold, and Telio CAD (Ivoclar Vivadent) milled from discs. Permanent materials: VareoSmile Crown Plus (Bego) distributed as Permanent Crown Resin and printed with Form 3B (Formlabs) and Enamic (VITA) sectioned from discs. Thirty (2.0 x 2.0 x 25.0 mm) beams were created for each group. After polishing, each specimen underwent 3-point bend testing using a universal testing machine. Flexural strength and flexural modulus were determined with 15 specimens per group. Flexural fatigue strength, Weibull modulus, and characteristic strength were determined with the remaining 15 specimens using the staircase method (100,000 cycles/20 Hz). Nanoindentation hardness and modulus were tested using nanoindentation with the fragmented specimens from the flexural strength test (n=5). Data were analyzed with one-way ANOVAs and Tukey's post hoc tests ($\alpha=0.05$). Significant differences were found between the groups per property ($p<0.05$). Enamic had significantly greater flexural

modulus and nanoindentation hardness/modulus than all other materials. Temporary Crown and Bridge Resin had the greatest characteristic strength, while Telio CAD had the greatest Weibull modulus. Integrity had the lowest flexural strength, Weibull modulus, and characteristic strength compared to all other materials. Telio CAD had the greatest flexural fatigue strength, but it was not significantly different from Temporary Crown and Bridge Resin and Permanent Crown Resin. In general, the novel 3D-printed crown materials performed similarly to each other, but their properties varied from the other materials based on the type of test.

Introduction

Digital dentistry has been expanding its capabilities with intraoral scanning (IOS) systems, computer-aided design (CAD), computer-aided manufacturing (CAM), and most recently with additive manufacturing (AM). The American Society for Testing Materials (ASTM) defines AM as “3D printing, uses computer-aided design to build objects layer by layer.”(1) AM is alluring to the dental field for many reasons. AM can fabricate products with greater sophistication due to its layer-by-layer building effect, while subtractive milling is limited by the size of the milling bur’s rotational axis to produce details. This accuracy translates to an increase in crown retention when manufactured by AM. AM reduces waste generation – up to 90% material saving – compared to the subtraction milling during fabrication.(2) AM has the ability to print with a variety of materials that can be utilized throughout multiple domains in dentistry. AM grants dental practices the opportunity to adopt this new technology with increased accuracy at a lower machinery cost.(3)

Two categories of AM that have been approved for crown fabrication are stereolithography (SLA) and digital light processing (DLP) printing. SLA was first developed in 1986 by 3D System Corp (Rockhill, SC), where it employs an ultraviolet (UV) laser to harden the photocuring resin layer by layer on a build platform.(4) Texas Instruments (Dallas, TX) began marketing DLP nineteen years later through utilization of chip technology that employs a projector to harden photocuring resin transversely throughout the platform. AM technology can fabricate a 3D product from any spatially 360 degree orientation, or build angle, when it is placed within the build platform.(4)

The world's first ceramically reinforced hybrid material that is utilized for AM fabrication single-tooth restoration was recently developed by Bego (Bremen, Germany).(5) Bego currently offers two crown materials - VareoSmile Temp and VareoSmile Crown Plus – for intraoral provisional and permanently fixed dental prosthesis, respectively. VareoSmile Temp and VareoSmile Crown Plus, albeit proprietary, are hybrid materials composed of inorganic fillers, silanized dental glass, and esterified compounds that include but are not limited to 4,4'-isopropylidiphenol, ethoxylated 2-methylprop-2enoic acid, and methyl benzoylformate, diphenyl (2, 4, 6-trimethylbenzoyl) phosphine oxide.(6) These materials are FDA 510 (k) cleared as Class II products for long term intra-oral use. Similar to all-ceramic crown guidance, the manufacturer recommends that crowns made of these materials require a minimal thickness of 1.0 mm for all axial walls and occlusal surfaces.(6)

Bego has approved VareoSmile Temp and VareoSmile Crown Plus for a variety of 3D printers, but each printer has individualized instructions for processing. For SLA

printers, both Bego products have been approved for, but not limited to, use in Formlabs (Somerville, MA) Form 3B printers. For Formlab's printers to print VareoSmile Temp and Crown Plus, Bego's products are sold from Formlabs and called Temporary Crown and Bridge Resin and Permanent Crown Resin. Bego's printing materials require processing before intraoral cementation with an isopropyl alcohol solution bath, drying with compressed air, removal of the supportive structures, air abrasion, and polishing. The manufacturer recommends cementation with a self-adhesive or an adhesive resin cement with a primer.

Limited research has been published assessing physical properties of these novel 3D-printed reinforced hybrid materials.(7) The purpose of this study was to evaluate the flexural strength, flexural fatigue behaviors, and nanindentation hardness and modulus of the 3D printed provisional material (Temporary Crown and Bridge Resin, FormLabs) and the 3D-printed permanent restorative material (Permanent Crown Resin, FormLabs) compared to traditional hand-fabricated (Integrity, Dentsply Sirona, Charlotte, NC, USA) or millable provisional materials (Telio CAD, Ivoclar Vivadent, Schaan, Liechtenstein) and a millable ceramic-polymer permanent restorative material (Enamic, VITA, Säckingen, Germany). The null hypothesis was that there would be no difference in mechanical properties based on type of material.

Materials and Methods

This study evaluated and compared the flexural strength and modulus, flexural fatigue strength, Weibull modulus, characteristic strength, and nanoindentation hardness

and modulus of the following five materials: Temporary Crown and Bridge Resin, Permanent Crown Resin, Integrity, Enamic, and Telio CAD. See table 1.

Specimen Fabrication

Temporary Crown and Bridge and Permanent Crown Resin Materials

To create Temporary Crown and Bridge and Permanent Crown Resin specimens, thirty beams from both materials were printed from Form 3B (Formlabs). The specimens were designed using DS SolidWorks software (SolidWorks, Waltham, MA) and the file was imported into the Formlabs printing software. The specimens were printed using the 50 μm thickness parameters and printed in a horizontal orientation, in which the beams were printed so that the length of the beams was parallel to the build plate. The size of the beam specimens was 2.0 mm in width, 2.0 mm in depth, and 25.0 mm in length.

The specimens (shade A2) were printed using Formlabs 3B and processed per manufacturer's instructions. Specimens were placed in a Form Wash (Formlabs) that contains isopropyl alcohol (IPA, $\geq 99\%$) for 3 minutes. Any excess resin was removed with a brush and then dried with compressed air. The specimens were then left to dry in a well-ventilated area for thirty minutes. If any uncured resin was present, isopropyl alcohol was sprayed onto the specimen and dried again for thirty minutes. Then all specimens were placed in a post-cure Form Cure (Formlabs) at 60 degrees Celsius for twenty minutes, with the support side down. The supports were then removed with a cutting wheel. The surfaces were air abraded (Basic Quattro, Renfert, Hilzingen, Germany) with sodium glass (Perlablast Micro, Bego) at a maximum of 1.5 bar. The

specimens were then placed back in the Form Cure for 20 minutes at 60 degrees Celsius in the opposite orientation as the first cure. The surfaces of each specimen were polished with 600 and 1,000 grit polishing paper (Sandblaster Pro, 3M ESPE).

Integrity Material

Thirty Integrity beam specimens were created using a 2.0 x 2.0 x 25.0 mm aluminum mold. The mold was placed on top of a clear plastic strip that had been placed on a glass slide. Integrity, shade A2, was then expressed into the mold and smoothed with a plastic instrument. A second clear plastic strip was then placed, and a glass slide was applied with finger pressure to remove extra material. The material was then allowed to set for 3 minutes and then removed from the mold. The surface of each specimen was polished as before.

Telio CAD Material

Telio CAD discs (98.5 x 20mm, shade A2) were milled to create thirty beam specimens (2.0 x 2.0 x 25.0 mm). The beams were designed using the design software as before and milled in a five-axis milling unit (imes-icore, Eitherfeld, Germany). After milling, the surface of each specimen was polished as before.

VITA Enamic Material

VITA Enamic discs (98.4 x 18 mm, shade 2M2-HT) were sectioned to create thirty beam specimens (2.0 x 2.0 x 25.0 mm) using a precision saw (IsoMet 5000, Buehler, Lake Bluff, IL). After sectioning, the surface of each specimen was polished as before.

Specimen Testing

Flexural Strength and Modulus

Flexural strength testing was completed in accordance with the international standard for ceramic materials, ISO 4049:2009 (International Organization for Standardization)(8). Fifteen beam specimens per group (n=15) were fractured in a universal testing machine (Alliance RT/5, MTS, Eden Prairie, MN, USA). Each specimen was placed on a 3-point bending test device, which was constructed with a 20.0 mm span length between the supporting rods. A central load was applied with a head diameter of 2.0 mm at a crosshead speed of 1.0 mm/minute. The flexural strength was obtained using the equation $FS = \frac{3Fl}{2bd^2}$ where F was the loading force at the fracture point, l was the length of the support span (20 mm), and b was the width and d the depth of the beam specimen. Measurements were made using electronic digital calipers as indicated previously. The flexural modulus was determined from the slope of the linear region of the load-deflection curve using analytical software (Excel, Microsoft Corp, Redmond, WA, USA).

Flexural Fatigue Strength

The flexural fatigue strength (σ_{ff}) of fifteen beams from each group (n=15) was determined for 100,000 cycles at 20 Hz per group. Each specimen was placed on the 3-point bending test device (ElectroPuls E3000, Instron, Norwood, MA, USA). The staircase method was used for the evaluation. For each group, the aforementioned flexural test has been firstly conducted to determine the starting stress level, which was 50% of the flexural

strength. The amplitude of the stress level was determined by using 1/2 of the standard deviation of the flexural strength. Tests were conducted sequentially with stress applied values increasing or decreasing by 5% of the initial starting stress value whether the previous beam resulted in failure or survival. The flexural fatigue strength and standard deviation was determined using the following equations:

$$\sigma_{ff} = X_0 + d \left(\frac{\sum in_i}{\sum n_i} \pm \frac{1}{2} \right)$$

$$SD = 1.62 d \left(\frac{\sum n_i \sum i^2 n_i - (\sum in_i)^2}{(\sum n_i)^2} + 0.029 \right)$$

X_0 was the lowest stress level considered in the analysis and d was the fixed stress increment. To determine σ_{ff} , the analysis of the data was based on the least frequent event (failures vs survivals). The negative sign was used when the analysis was based on failures; otherwise, the positive sign was used. In the second equation, the lowest stress level considered was designated $i = 0$, the next $i = 1$, and so on, and n_i was the number of failures or survivals at the given stress level.(9, 10)

Weibull Statistical Analysis

The Weibull statistical analysis predicts the time-to-failure and probability of failure of a component. It is a way to obtain the Weibull modulus (m) and the characteristic strength (σ_0). The characteristic strength is the strength at a failure probability of 63.2%.(10,11) The Weibull modulus is used to determine the reliability (*i.e.*, the level distribution of the “defects” throughout the entire volume) of a material.(10,11) Fifteen

specimens were used for each group based on the ISO 6872:2015 (12). The Weibull's 2-parameter (σ_0 and m) distribution function is:

$$P_f = 1 - e^{-\left(\frac{\sigma}{\sigma_0}\right)^m} \quad (1)$$

where P_f is the cumulative probability of failure, σ [MPa] is the flexural strength, σ_0 [MPa] is the Weibull characteristic strength, and m is the Weibull modulus.

The two parameters, σ_0 and m , are calculated by using rank order statistics. For example, after the flexural strength for all 15 specimens was measured, the flexural strength (σ) values were ranked in ascending order and were assigned a probability of failure per each specimen based on its ranking using the following equation:

$$P_f(\sigma_i) = \frac{i-0.5}{N} \quad (2)$$

where i represents 1, 2, 3, ..., N of the i^{th} datum in ascending order of the flexural strength (σ_i), and N is the total number of specimens tested. Next, equation (1) was rearranged into the following equation:

$$\ln \left[\ln \left(\frac{1}{1-P_f} \right) \right] = m \ln \sigma_i - m \ln \sigma_0 \quad (3)$$

Then, $\ln \left[\ln \left(\frac{1}{1-P_f} \right) \right]$ was plotted on the ordinate against $\ln(\sigma_i)$ on the abscissa, from which a maximum likelihood estimation procedure was used to estimate the linear regression model. The slope and intercept of equation (3) yield m and $m \ln \sigma_0$ respectively. Then, σ_0 was solved from the intercept. When the characteristic strength is the strength value, the cumulative probability of failure, P_f , was at 63.2%. (10,11)

Nanoindentation Elastic Modulus and Hardness

Five fragmented specimens per group from the flexural strength test (n=5) were tested in a nanoindenter (iNano, Nanomechanics, Oak Ridge, TN) fitted with a 20 nm radius and 65.3° nominal angle Berkovich tip (#TB26961, Micro Star Technologies, Huntsville, TX) to measure the elastic modulus and hardness at room temperature. Thermal drift rates were reached below 0.05 nm/s threshold prior to 100 surface indentations being performed with a maximum indentation load of 5 mN. Elastic moduli were calculated by force-displacement curves for the indents using the following expression,

$$E = (1 - \nu^2) \left(\frac{1}{E_r} - \frac{1 - \nu_{\text{tip}}^2}{E_{\text{tip}}} \right)^{-1}$$

where ν and E_r (GPa) are the Poisson's ratio ($\nu = 0.3$) and reduced modulus, and ν_{tip} and E_{tip} (GPa) are the Poisson's ratio (0.07) and elastic modulus (1141 GPa) of the Berkovich indenter, respectively. The nanoindentation hardness was obtained from the indentation load divided by the projected contact area, A (nm^2): Hardness = P/A , where P (mN) was the maximum contact force exerted by the indenter onto the sample.

Statistical analysis

The mean and standard deviation were calculated for flexural strength and modulus, flexural fatigue strength, and nanoindentation hardness and modulus of each material. Data were analyzed with a one-way ANOVA and Tukey's post hoc tests per mechanical property ($\alpha=0.05$). Also, a mean was determined for Weibull modulus and characteristic strength for each material.

Results

Significant differences between materials ($p < 0.05$) were found for each mechanical property based on the results of the one-way ANOVA. See table 2. Temporary Crown and Bridge Resin had the greatest flexural strength (151.6 ± 11.1 MPa), but it was not significantly different ($p = 0.074$) from Telio CAD (141.5 ± 4.9 MPa). The flexural strength of Bego Temporary Crown & Bridge (151.6 ± 11.1 MPa) was significantly higher than Bego Permanent Crown Resin (135.9 ± 14.5 MPa) with $p = 0.0013$. Permanent Crown Resin (135.9 ± 14.5 MPa) and Enamic (132.0 ± 10.5 MPa) performed more moderately and were not significantly different ($p = 0.863$) from each other or Telio CAD ($p > 0.116$). The flexural strength of Integrity (86.8 ± 10.0 MPa) was significantly lower than all the other materials ($p < 0.001$). The flexural modulus of Enamic (24.2 ± 3.1 GPa) was significantly greater than all the other materials ($p < 0.001$). Temporary Crown and Bridge Resin (4.6 ± 0.2 GPa) and Permanent Crown Resin (4.7 ± 0.2 GPa) performed more moderately and were not significantly different from each other ($p = 0.998$). Telio CAD (2.6 ± 0.5 GPa) and Integrity (3.1 ± 0.4 GPa) had the lowest flexural moduli and were significantly less than all the other materials ($p < 0.027$), but not each other ($p = 0.875$).

Telio CAD had the greatest flexural fatigue strength (104.2 ± 9.4 MPa), but it was not significantly different from Temporary Crown and Bridge Resin (101.2 ± 27.8 MPa) and Permanent Crown Resin (97.1 ± 21.5 MPa) with $p = 0.994$ and $p = 0.875$ respectively. Integrity had the lowest flexural fatigue strength (77.4 ± 13.4 MPa), but it was not significantly different ($p = 0.072$) than Permanent Crown Resin (97.1 ± 21.5 MPa) or

Enamic (81.0 ± 24.1 MPa). Telio CAD had the greatest Weibull modulus (33.7), which was greater than all the other materials (range: 10.4 – 16.1). Temporary Crown and Bridge Resin had the greatest characteristic strength (156.6), which was greater than all the other materials (range 91.0 – 143.8).

Enamic had the greatest nanoindentation hardness (4.854 ± 0.116 GPa), which was significantly greater ($p < 0.001$) than all the other materials. Telio CAD had the lowest nanoindentation hardness (0.435 ± 0.004 GPa), but it was not significantly different from Temporary Crown and Bridge Resin (0.532 ± 0.006 GPa) and Permanent Crown Resin (0.522 ± 0.011 GPa) with $p = 0.062$ and $p = 0.111$ respectively. Enamic had the greatest nanoindentation modulus (42.51 ± 0.76 GPa) and it was significantly greater than ($p < 0.001$) than all other materials. Telio CAD had the lowest nanoindentation modulus (5.76 ± 0.03 GPa) and it was significantly lower ($p < 0.017$) than all other materials. Temporary Crown and Bridge Resin (6.70 ± 0.05 GPa) and Permanent Crown Resin (6.94 ± 0.09) performed more moderately and were not significantly different from each other ($p = 0.892$).

Discussion

The null hypothesis was rejected, there was a difference in mechanical properties based on type of material. Limited research is available evaluating the mechanical properties of new 3D-printed provisional and permanent crown materials. The manufacturer's published VarseoSmile Temporary material to have a flexural strength of ≥ 100 MPa and VarseoSmile Crown Plus' flexural strength to be 116-150 MPa. This study validated both of these flexural strength values. (13)

Atrai et al (2022) evaluated the mechanical properties of 3D-printed resins, which included Temporary Crown and Bridge Resin.(7) The authors found that Temporary Crown and Bridge Resin had a characteristic strength of 187.73 MPa, which was greater than the 156.6 MPa characteristic strength found in this study.(7)

Myagmar et al. (2021) compared the wear resistance and surface roughness among interim resin materials fabricated via printing, milling, and hand fabrication.(14) They found that a 3D-printed resin provisional material (NextDent C&B, NextDent, Soesterberg, Netherlands) had greater wear resistance and a smoother surface than a self-curing resin provisional material (Jet, Lang Dental Manufacturing, Wheeling, IL) in vitro.(14) In a separate in vitro study, the internal fit and marginal adaptation of a 3D-printed provisional methacrylate material (Dima Print Denture Teeth, Kulzer North America, South Bend, IN) was compared to a hand-fabricated resin-based composite (LuxaCrown, DMG America, Ridgefield Park, NJ) and a millable ceramic polymer (Lava Ultimate, 3M ESPE, St. Paul, MN).(15) That study demonstrated comparable results among all three materials. However, the hand-fabricated resin-based composite presented with a better internal fit and lower absolute marginal discrepancy than the millable ceramic polymer and 3D-printed provisional material.(15)

The Weibull modulus was used to evaluate the distribution of strengths and weaknesses of the materials. (10, 11) Telio CAD, a cross-linked polymethyl methacrylate material, demonstrated the highest Weibull modulus, which was likely due to more uniformly distributed defects. Therefore, it may be more predictably reliable. Of the provisional materials, the Weibull modulus for Telio CAD was 52.2% and 63.2% greater

than Integrity and Temporary Crown and Bridge Resin, respectively. Curiously, the Weibull modulus of the Temporary Crown and Bridge Resin was 32.9% greater than Permanent Crown Resin. Of the permanent materials, the Weibull modulus of the Permanent Crown Resin was 9.2% less than Enamic.

Integrity had the lowest flexural strength, endurance limit, reliability, and characteristic strength properties. The hand mixing of the methacrylic ester-based material and the subsequent incorporation of air and porosities likely contributed to the lower properties. Enamic, a feldspar ceramic methacrylate polymer, had significantly greater nanoindentation hardness (4.85 GPa vs. range: 0.435 – 0.564 GPa) and modulus (42.51 GPa vs. range 5.76 – 8.81 GPa) compared to all the other materials. The higher hardness and modulus may contribute to a significantly greater wear resistance of the material clinically.

Interestingly, some of the properties such as flexural strength, flexural fatigue strength, Weibull modulus, and characteristic strength were greater with Temporary Crown and Bridge Resin compared to the Permanent Crown Resin. Flexural modulus and nanoindentation hardness were very similar between the two materials. Bego markets both materials as a hybrid material composed of inorganic fillers, silanized dental glass, and esterified compounds.(6). The minor differences in mechanical properties demonstrated by this study could suggest that perhaps the materials have the same or similar formulation. Perhaps, future clinical studies may be able to tease out differences in performance and survival between Temporary Crown and Bridge Resin and Permanent Crown Resin. Using a provisional cement, Temporary Crown and Bridge

Resin is advertised for up to 12 months of intraoral use. With a self-adhesive or adhesive resin cement, Permanent Crown Resin is marketed as a long-term permanent restorative material.(6)

Limitations of this study include: 1) it is an in vitro study, and 2) mechanical properties of 3D-printed resin could vary with the use of different 3D printers (SLA vs DLP), build angles during 3D printing, and post-processing procedures. Ultimately, in vivo studies are necessary to determine the clinical success of these new 3D-printable crown materials.

Conclusions

Within the limitations of this study, the novel 3D-printed crown materials performed similarly to each other, but their properties varied from each other based on the type of mechanical property tests. Clinicians should be mindful of the properties of these materials when they are selecting a material for an interim or permanent indirect restoration.

Disclaimer

The views expressed in this article are those of the authors and do not reflect the official policy of the Uniformed Services University, Department of Defense, or other departments of the United States Government. The authors do not have any financial interest in the companies whose materials are discussed in this manuscript.

References

1. International Additive Manufacturing Overview, West Conshohocken, PA2021 [updated 2021. Available from: <https://www.astm.org/industry/additive-manufacturing-overview.html>.
2. Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations: current systems and future possibilities. J Am Dent Assoc. 2006;137(9):1289-96.
3. Shaikh SS, Nahar P, Shaikh SY, Sayed Aj, Mohammed Ali H. Current perspectives of 3d printing in dental applications. Brazilian Dental Science. 2021.
4. Quan H, Zhang T, Xu H, Luo S, Nie J, Zhu X. Photo-curing 3D printing technique and its challenges. Bioact Mater. 2020;5(1):110-5.
5. Schweiger J, Edelhoff D, Güth J-F. 3D Printing in Digital Prosthetic Dentistry: An Overview of Recent Developments in Additive Manufacturing. Journal of Clinical Medicine. 2021;10(9):2010.
6. KG BBGWHGC. Bego VarseoSmile CrF(own Plus [Available from: <https://www.bego.com/3d-printing/materials/varseosmile-crown-plus/>.
7. Atria PJ, Bordin D, Marti F, et al. 3D-printed resins for provisional dental restorations: Comparison of mechanical and biological properties. J Esthet Restor Dent. 2022;34(5):804-815. doi:10.1111/jerd.12888

8. ISO Standard 4049, Dentistry - Polymer-based restorative materials 2009.
9. Holman CD, Lien W, Gallardo FF, Vandewalle KS. Assessing Flexural Strength Degradation of New Cubic Containing Zirconia Materials. *J Contemp Dent Pract.* 2020;21(2):114-119.
10. Belli R, Petschelt A, Hofner B, Hajt6 J, Scherrer SS, Lohbauer U. Fracture Rates and Lifetime Estimations of CAD/CAM All-ceramic Restorations. *J Dent Res.* 2016;95(1):67-73.
11. Zucuni CP, Guilardi LF, Rippe MP, Pereira GKR, Valandro LF. Polishing of Ground Y-TZP Ceramic is Mandatory for Improving the Mechanical Behavior. *Braz Dent J.* 2018;29(5):483-91.
12. ISO Standard 6872, Dentistry - Cermaic Materials 2015.
13. "Bego 3D Printing Solution." from <https://www.bego.com/3d-printing/materials/varseosmile-crown-plus/>.
14. Myagmar G, Lee JH, Ahn JS, Yeo IL, Yoon HI, Han JS. Wear of 3D printed and CAD/CAM milled interim resin materials after chewing simulation. *J Adv Prosthodont.* 2021;13(3):144-51.
15. Wu J, Xie H, Sadr A, Chung K-H. Evaluation of Internal Fit and Marginal Adaptation of Provisional Crowns Fabricated with Three Different Techniques. *Sensors.* 2021;21(3):740.

Material	Manufacturer	Indications	Composition	Fabrication Method
Temporary Crown and Bridge Resin	FormLabs, Somerville, MA	Provisional	hybrid materials composed of inorganic fillers, silanized dental glass, and esterified compounds	CAD/3D Printing
Permanent Crown Resin	FormLabs, Somerville, MA	Permanent	hybrid materials composed of inorganic fillers, silanized dental glass, and esterified compounds	CAD/3D Printing
Integrity	Dentsply Sirona, Charlotte, NC	Provisional	multi-functional methacrylic ester-based material	Automix
Enamic	VITA Zahnfabrik, Bad Säckingen, Germany	Permanent	feldspar ceramic methacrylate polymer	CAD/CAM
Telio CAD	Ivoclar Vivadent, Schaan, Liechtenstein	Provisional	cross-linked polymethyl methacrylate material	CAD/CAM

Table 1: Indications, composition, and fabrication method of the materials tested in this study.

Group	Flexural Strength (MPa)	SD	Flexural Modulus (GPa)	SD	Flexural Fatigue Strength (MPa)	SD	Weibull Modulus	Characteristic Strength (MPa)	Nanoindentation Hardness (GPa)	SD	Nanoindentation Modulus (GPa)	SD
Integrity	86.8	10.0 C	3.1	0.4 C	77.4	13.4 C	10.4	91.0	0.564	0.023 B	8.81	0.57 B
Telio CAD	141.5	4.9 AB	2.6	0.5 C	104.2	9.4 A	33.7	143.8	0.435	0.004 C	5.76	0.03 D
Temporary Crown & Bridge Resin	151.6	11.1 A	4.6	0.2 B	101.2	27.8 AB	16.1	156.6	0.532	0.006 BC	6.70	0.05 C
Permanent Crown Resin	135.9	14.5 B	4.7	0.2 B	97.1	21.5 ABC	10.8	142.4	0.522	0.011 BC	6.94	0.09 C
Enamic	132.0	10.5 B	24.2	3.1 A	81.0	24.1 BC	11.9	135.9	4.854	0.116 A	42.51	0.76 A

Groups with the same letter per column are not significantly different ($p > 0.05$)

Table 2. The mechanical properties of the tested materials