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Chemical Composition, Degree of Conversion and Flexural Properties of a Three-Dimensional Printed Denture Base Resin

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Research Article

Abstract

Objective: This study aimed to evaluate the chemical composition, degree of conversion (DC), and flexural properties of a commercially available 3D printing denture base resin, and to compare them with a conventional heat-cured denture base resin.

Materials and Methods: A 3D-printed denture base resin (NextDent Denture 3D+, NDD) and a conventional heat-polymerized resin (ProBase® Hot, PBH) were investigated. The chemical compositions of the unpolymerized NDD resin were characterized using Fourier-transform infrared spectroscopy (FTIR), proton nuclear magnetic resonance (^{1}H-NMR), and high-performance liquid chromatography/mass spectrometry (HPLC/MS). The DC of both materials was measured via FTIR analysis. Flexural strength, modulus, and yield stress were determined using a three-point bending test per ISO 20795-1:2013 guidelines.

Results: HPLC/MS analysis revealed that NDD primarily consists of Bis-EMA monomers with 3–7 ethylene oxide units. The PBH resin demonstrated a significantly higher DC (97.59±1.14%) than NDD (69.81±4.90%) ($p<0.001$). Flexural strength and modulus of PBH (99.40±6.56 MPa; 2812.20±54.44 MPa) were also significantly higher than NDD (88.58±8.50 MPa; 2625.40±368.42 MPa) ($p<0.001$). Despite the differences, both materials met ISO flexural property standards.

Conclusion: The 3D printing resin primarily contains Bis-EMA with varied chain extender lengths and exhibits lower DC and flexural properties compared to the heat-cured resin. Optimization of printing and post-curing parameters is necessary to improve polymerization and mechanical performance of 3D-printed denture bases.

Keywords: 3D printing/ Denture base resin/ Bis-EMA/ Degree of conversion/ Flexural strength

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Introduction

For decades, complete denture bases have been conventionally fabricated using the compression molding technique with heat curing. Although this method is widely accepted, it involves multiple laboratory steps and is prone to processing errors that can result in prosthetic distortion.[1-3] To address these limitations, computer-aided design and computer-aided manufacturing (CAD/CAM) technology has emerged as an alternative, offering improved accuracy and efficiency.[4-7] CAD/CAM systems enable fabrication through either subtractive (milling) or additive (3D printing) manufacturing techniques.[4,8] While subtractive

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methods waste excess material and are often costly,[7,9] additive manufacturing builds structures layer by layer from digital data, reducing both material consumption and production costs.[9,10]

Among various 3D printing methods, many employ photocurable liquid resins that require optimal viscosity, minimal polymerization shrinkage, and low water sorption to achieve clinically acceptable results.[11,12] A frequently used monomer in these resins is bisphenol A ethoxylated dimethacrylate (Bis-EMA),[13,14] which varies in molecular weight based on the length of its ethylene oxide chain extenders.[11-13]

Bis-EMA based resins have also been introduced commercially for fabricating 3D printed denture bases.[15] However, limited data are available regarding their chemical structure, degree of conversion (DC), and mechanical performance. Since these properties are critical to the clinical success of denture base materials, further investigation is necessary.[16-18]

Therefore, the objective of this study was to characterize the chemical composition of a commercially available 3D printing denture base resin and to evaluate its degree of conversion and flexural properties, in comparison to those of a conventional heat-cured polymethyl methacrylate (PMMA) resin. The null hypothesis tested was that there would be no significant difference in the degree of conversion and flexural properties between the 3D-printed and heat-polymerized denture base resins.

Materials and Methods

Denture Base Materials

A biocompatible Class IIa 3D printing denture base resin, NextDent Denture 3D+ (NDD; Vertex-Dental B.V., Soesterberg, Netherlands), was used as the 3D-printed material. A heat-polymerized denture base resin, ProBase® Hot (PBH; Ivoclar Vivadent AG, Schaan, Liechtenstein), served as the conventional counterpart. This in vitro study did not require Institutional Review Board (IRB) or animal ethics approval, as it did not involve human participants or animal subjects.

For NDD polymerized specimens, the specimens were digitally designed using computer-aided design (CAD) software (SOLIDWORKS 2018, Dassault Systèmes SolidWorks Corp., Waltham, MA, USA) and exported in standard triangulation language (STL) format. Specimens were printed using a digital light processing (DLP) 3D printer (Perfactory DP4 XL, EnvisionTec, Dearborn, MI, USA) (Figure 1A, 1B). Printing parameters included 0° orientation and 100 μm layer thickness. Specimens were fabricated at a 0° (horizontal) build orientation to ensure standardized geometry and reduce orientation-induced variability during mechanical testing.[19-23] After printing, supports were removed, and specimens were cleaned with isopropyl alcohol. Following air drying, they were post-cured in a UV light-curing chamber (Form Cure, Formlabs Inc., Somerville, MA, USA) at 405 nm for 30 minutes at 60°C. After post-curing, all NDD specimens were polished to remove support-related surface irregularities resulting from the 3D-printing process. Specimens were subsequently remeasured, and final dimensions were verified to ensure uniformity and dimensional equivalence with the PBH group prior to flexural strength testing. All samples were stored at room temperature prior to testing.

For PBH specimens, fabrication followed the manufacturer's instructions. The powder and liquid components were mixed at a ratio of 2.25 g/1 mL until reaching the dough stage, then packed into stainless steel molds of specified dimensions. The flask was compressed at 2 bar and heat-polymerized at 100°C for 45 minutes. After cooling to room temperature for 30 minutes, specimens were deflasked and stored at room temperature prior to testing.

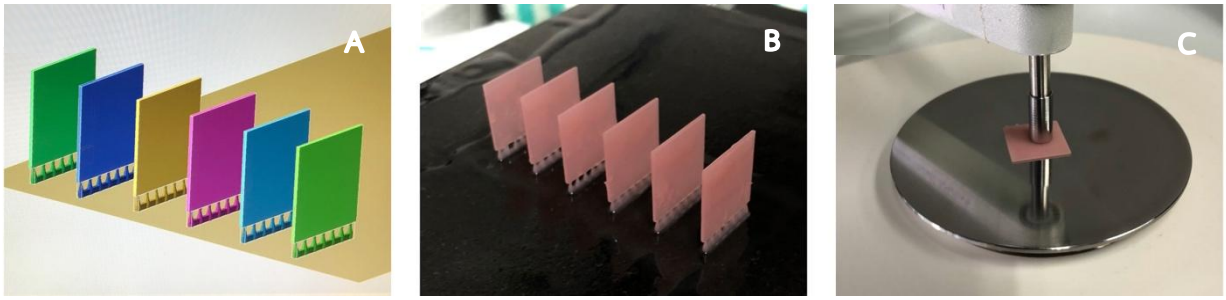


Figure 1 Fabrication of NextDent Denture 3D+ (NDD) specimens; (A) Digital designing specimen dimension using CAD software, (B) Printed specimens, (C) Measured FTIR spectra of polymerized NDD specimens.

Chemical characterizations of the unpolymerized NDD resin

Fourier transform infrared (FTIR) spectroscopy was performed using a Frontier FT-IR spectrometer (PerkinElmer, Waltham, MA, USA). Approximately 5 mg of unpolymerized NDD resin was placed on an Attenuated Total Reflectance (ATR) diamond crystal KRS-5 plate (thallium bromide/thallium iodide) and spectra were collected in absorbance mode across 400–4000 cm^{-1} at 4 cm^{-1} resolution over 16 scans. Spectral data were analyzed using Spectrum™ 10.4 software (PerkinElmer, Waltham, MA, USA).

For proton nuclear magnetic resonance (^{1}H-NMR) spectroscopy, the resin was dissolved in deuterated chloroform (CD_3 Cl; Sigma Aldrich) at a concentration of 10 mg/mL. The sample was analyzed with a 400 MHz NMR spectrometer (Bruker, Karlsruhe, Germany). The chemical shifts that appeared in the ^{1}H–NMR spectrum were assigned to plausible chemical structures corresponding to existing reference data.[24,25]

In addition, the monomer composition of the unpolymerized NDD resin was analyzed using high-performance liquid chromatography (HPLC) coupled with mass spectrometry (MS). The resin was first diluted in acetonitrile to a concentration of 10 mg/mL and centrifuged at 3000 rpm for 10 minutes to remove insoluble fillers. The supernatant was then diluted 20-fold with acetonitrile and filtered through a Teflon membrane filter (pore size: 0.4 µm).

The filtered solution was injected into the HPLC system (HPLC 600-717 Autoinjector, Waters, Milford, MA, USA) equipped with a C18 reverse-phase column (5 µm, 250 mm length) and a UV/DAD detector. An isocratic elution was performed using a mobile phase of acetonitrile/water (7:3) at a flow rate of 1 mL/min at room temperature. Seven major elution fractions were collected in amber glass vials.

Subsequently, these fractions were then subjected to liquid chromatography–mass spectrometry (LC-MS/MS; Esquire3000 Plus, Bruker Daltonics, Billerica, MA, USA). Electrospray ionization (ESI) was employed in the positive ion mode with a capillary voltage of 3 kV. The nitrogen gas pressure for nebulization was set at 60 psi, the drying gas flow at 10 L/min, and the drying gas temperature at 350°C. The mass detection range was set between 50 and 1000 m/z.

Compounds were identified by comparing the obtained mass spectra to those in the NBS spectral library, along with interpretation of fragmentation patterns. Methyl methacrylate (MMA) and bisphenol A-glycidyl methacrylate (Bis-GMA) were included as reference standards for comparative HPLC analysis.

Measurement of Degree of Conversion

The degree of conversion (DC) of both denture base resin materials was analyzed using Fourier-transform infrared (FTIR) spectroscopy by comparing the spectra of unpolymerized and

polymerized specimens (n=10). The sample size was selected based on commonly used specimen numbers in previous denture base polymer studies to ensure reproducibility and comparability of the results. For the NDD resin, the unpolymerized material was stirred on a roller mixer for 2 hours. Approximately 5 mg of resin was placed on the attenuated total reflectance (ATR) crystal surface of an FTIR spectrometer (Frontier FT-IR Spectrometer, Perkin Elmer, Waltham, MA, USA). Spectra were collected using 16 scans at a resolution of 4 cm^{-1} across the spectral range of 400–4000 cm^{-1}. Polymerized NDD specimens were digitally fabricated to dimensions of 25 mm × 25 mm × 0.5 mm, as previously described. After standardized cleaning and post-curing, ATR-FTIR spectra were collected from one flat surface of vertically printed specimens under identical acquisition parameters. Both external surfaces underwent identical processing conditions; therefore, a consistently selected surface orientation was analyzed for all samples (Figure 1C). All spectra were processed using Spectrum™ 10.4 software (Spectrum™10.4 software, PerkinElmer, Waltham, MA, USA), and absorbance peaks were quantified with Origin 2022 software (OriginLab Corp., Northampton, MA, USA). The carbonyl (C=O) stretch at 1720 cm^{-1} was used as an internal standard.[26] The DC was calculated based on the decrease in intensity of the aliphatic carbon-carbon double bond (C=C) stretch at ~1640 cm^{-1} relative to the carbonyl peak, as shown in Equation 1:

Degree of conversion (DC) =

$$\left[1 - \frac{(A_{1640}/A_{1720})_{\text{Polymerized}}}{(A_{1640}/A_{1720})_{\text{Unpolymerized}}}\right] \times 100$$

...(Equation 1)

The DC of the PBH (conventional) resin was evaluated in the same manner. To obtain a stable unpolymerized reference, the pre-polymerized PBH powder was heated at 70 °C for 30 h to reduce benzoyl peroxide (BPO) initiator activity via time-dependent thermal decomposition while minimizing the risk of PMMA degradation. After thermal treatment, the powder was mixed with the monomer liquid and immediately analyzed by ATR-FTIR at room temperature to prevent unintended free-radical polymerization prior to measurement.[27-29]

For consistency, polymerized PBH specimens were fabricated as previously described, and the cured material was ground using a sterile tungsten carbide bur to obtain powdered samples. These were analyzed via ATR-FTIR under the same conditions. DC values were calculated using Equation 1. Ten independent measurements were performed for each material.

Measurement of flexural strength and flexural modulus

Ten plate-shaped NDD specimens were digitally designed and fabricated as previously described, with final dimensions of 64 mm × 10 mm × 3.3 mm. The sample size of ten specimens per group was selected based on commonly used specimen numbers and ISO 20795-1:2013-based flexural testing methodology. PBH specimens were produced by compression molding using the same dimensions. After deflasking, all PBH specimens were polished using metallographic grinding paper up to P1000 grit to achieve the target dimensions.

All bar-shaped specimens were stored in distilled water at 37±1°C for 50 hours in a temperature-controlled incubator (Memmert Co., Schwabach, Germany) prior to mechanical testing. A three-point bending test was performed in accordance with ISO 20795-1:2013.[30] Mechanical testing was conducted using a universal testing machine (Instron 5566, Instron Ltd., Buckinghamshire, UK) equipped with upper and lower support anvils (4 mm in diameter), a deflectometer, and a clip-on extensometer.

The test setup used a load cell of 1 kN (Instron CAT No. EX2525-806), a support span length of 50 mm, and a crosshead speed of 5 mm/min. All tests were performed at room temperature under ambient pressure. Flexural strength and flexural modulus were calculated using the following equations:

$$\text{Flexural strength (MPa)} = 3Fl/(2bh^2) \quad \textbf{...(Equation 2)}$$

$$\text{Flexural modulus (MPa)} = F_1 l^3/4bh^3d \quad \textbf{...(Equation 3)}$$

where F (N) is the maximum load exerted on the specimen, l is the span length (50 mm), b (mm) is the specimen width, h (mm) is the specimen thickness, F_1 is the load at the proportional limit, and d is a deflection corresponding to load F_1. The 0.2% offset yield stress of each specimen was also measured.

Statistical analysis

The normality of the data distribution was assessed using the Shapiro–Wilk test. All data were expressed as means and standard deviations (SD). Levene's test was applied to evaluate the homogeneity of variances between groups. Differences in the degree of conversion and flexural properties between the NDD and PBH materials were analyzed using an independent t-test. Statistical analyses were conducted using SPSS software (version 23.0; IBM Corp., Armonk, NY, USA), and a significance level of α=0.05 was adopted for all comparisons.

Results

Chemical Composition of the Unpolymerized NDD Resin

The FTIR spectrum of the unpolymerized NDD resin showed a sharp absorbance peak at 1720 cm^{-1}, which was attributed to carbonyl (C=O) stretching. Peaks observed at 1609 cm^{-1} and 1637 cm^{-1} were assigned to the C=C stretching vibrations of aromatic and aliphatic alkenes, respectively. Additionally, a broad peak near 3400 cm^{-1} was associated with N–H or O–H stretching, suggesting the presence of amine or hydroxyl-containing compounds within the resin formulation (Figure 2)

The full ^{1}H NMR spectrum of the unpolymerized NDD resin showed a solvent peak corresponding to $CDCl_3$ at 7.25 ppm. Based on the observed chemical shifts, three major components were tentatively identified: bisphenol A-glycidyl methacrylate (Bis-GMA), bisphenol A ethoxylated dimethacrylate (Bis-EMA), and urethane dimethacrylate (UDMA). The corresponding proton chemical shifts and structural assignments of these components are summarized (Figure 3).

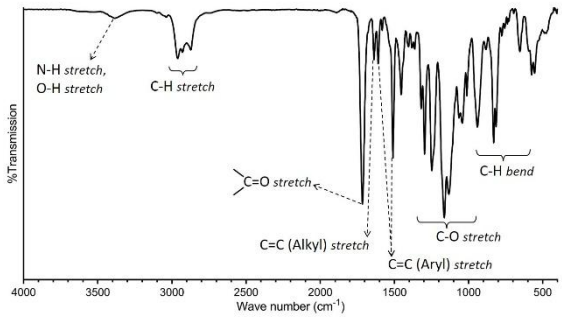


Figure 2 FTIR spectrum of the unpolymerized NextDent Denture 3D+ (NDD) resin. Tentative functional groups corresponding to the assigned peaks are indicated.

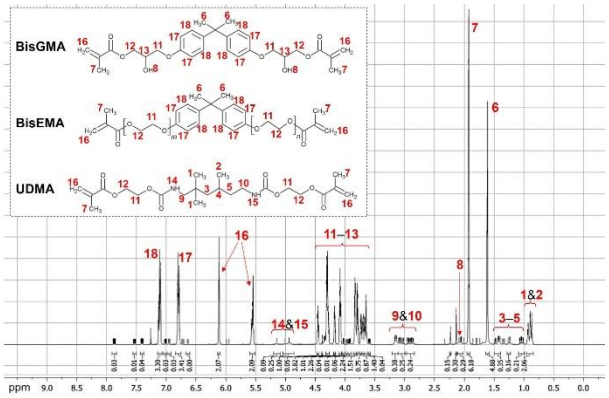


Figure 3 Proton-NMR spectrum of unpolymerized NextDent Denture 3D+ (NDD) resin in $CDCl_3$. The tentative assignment of the NMR signal corresponding to chemical structures of Bis-GMA, Bis-EMA, and UDMA was given in the inset image. Reference signal for $CDCl_3$ was detected at 7.25 ppm.

The HPLC chromatogram of the unpolymerized NDD resin was compared with those of MMA and Bis-GMA reference solutions (Figure 4). The retention times for MMA and Bis-GMA standards were 4.2 minutes and 7.8 minutes, respectively. The NDD resin exhibited seven distinct peaks corresponding to its principal monomeric components, with retention times recorded at 18.5, 20.0, 21.9, 23.6, 24.5, 26.6, and 30.1 minutes.

Seven fractions collected from HPLC were subsequently analyzed using mass spectrometry. The proposed compounds corresponding to each fraction were identified based on their fragmentation patterns (Table 1). Fractions II, IV, V, VI, and VII were identified as bisphenol A ethoxylated dimethacrylate (Bis-EMA) with varying molecular weights ranging from 496 to 672 g/mol. These monomers differed in the length of their ethylene oxide chain extenders (–O–CH2CH2–), corresponding to different degrees of ethoxylation (n+ m). It was determined that the Bis-EMA components present in the NDD resin contained between 3 and 7 ethylene oxide units. Fraction III was identified as bisphenol A dimethacrylate, while no reliable compound could be conclusively assigned to Fraction I.

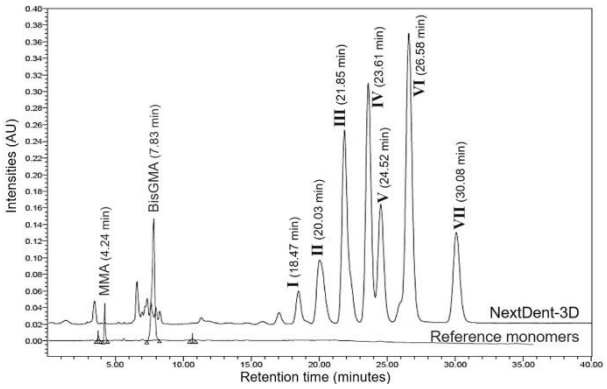


Figure 4 HPLC Chromatograms of unpolymerized NextDent Denture 3D+ (NDD) resin and reference monomers. Peaks are labeled with respective retention times in minutes for the reference MMA and Bis-GMA monomers. The seven major components of NDD were marked consecutively as I to VII.

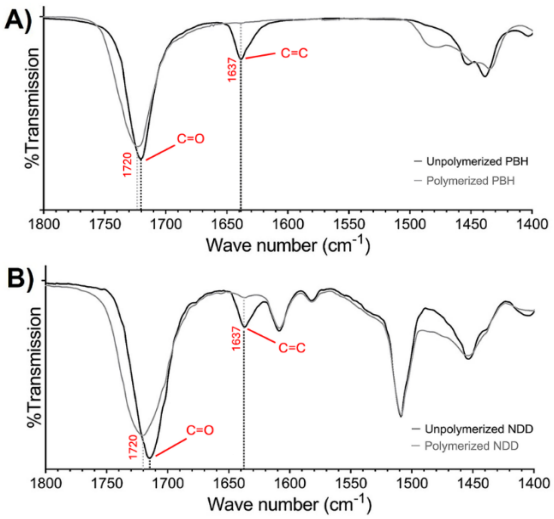


Figure 5 FTIR spectra of (A) PBH and (B) NDD, highlighting the differences between the unpolymerized (black line) and polymerized (grey line) samples. Key absorption bands altering upon polymerization were observed in the C=C aliphatic peak area at 1637 cm^{-1}.

Degree of Conversion of Denture Base Resins

As previously described, the degree of conversion (DC) for both PBH and NDD resins was determined by analyzing the peak absorbance ratio between the aliphatic carbon–carbon double bond at 1640 cm^{-1} and the carbonyl group at 1720 cm^{-1}. The vinyl (C= C) absorbance peak showed a marked reduction in polymerized specimens (Figure 5). The carbonyl peak was used as an internal reference because this functional group remains unchanged during polymerization.

The PBH resin exhibited a significantly higher degree of conversion than the NDD resin ($p<0.001$). The mean DC values were 97.59±1.14% for PBH and 69.81±4.90% for NDD (Figure 6)

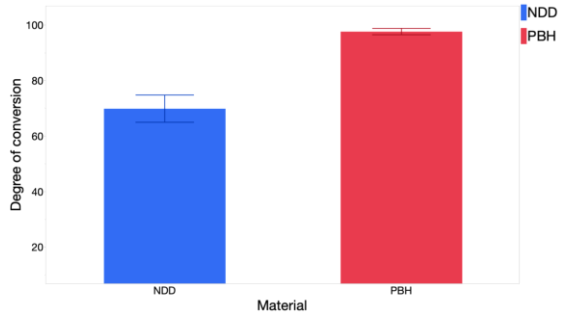


Figure 6 Degree of conversion (DC) of NextDent Denture 3D+ (NDD) and ProBase® Hot (PBH) as determined by ATR-FTIR analysis using the C=C/C=O peak ratio method. Data are presented as mean ± standard deviation (n=10). A statistically significant difference in DC was observed between the two materials ($p<0.001$).

Flexural properties of denture base resins

The flexural properties of both resins are summarized (Table 2). The NDD resin demonstrated a flexural modulus of approximately 2600 MPa, flexural strength of 89 MPa, and yield stress of 57 MPa. In contrast, the PBH resin showed higher values: a flexural modulus of 2800 MPa, flexural strength of 99 MPa, and yield stress of 64 MPa. All flexural properties of the PBH resin were significantly greater than those of the NDD resin ($p<0.001$).

Table 1 Retention times, mass-to-charge ratios, predicted molecular structures and molecular weights of different fractions from HPLC/MS. Degrees of ethoxylation of Bis-EMA were assigned as *'n + m'*.

Fraction	RT	m/z	Predicted compound	MW
I	18.47	301.0	Unidentified	Unidentified
II	20.03	519.1	Bis-EMA ($n + m = 3$)	496
III	21.85	387.0	Bisphenol A dimethacrylate	364
IV	23.61	563.1	Bis-EMA ($n + m = 4$)	540
V	24.52	607.1	Bis-EMA ($n + m = 5$)	584
VI	26.58	651.1	Bis-EMA ($n + m = 6$)	628
VII	30.08	695.2	Bis-EMA ($n + m = 7$)	672

HPLC, high-performance liquid chromatography; MS, mass spectrometer; Bis-EMA, bisphenol A ethoxylated dimethacrylate; RT, retention time in minute; m/z, mass-to-charge ratio; MW, molecular weight in g/mol.

Table 2 Flexural modulus, flexural strength, and yield stress at 0.2% offset of NDD and PBH denture base resins.

Material	Flexural modulus (MPa)	Flexural strength (MPa)	Yield stress (MPa)
NDD	2625.40 (368.42)[b]	88.58 (8.50)[b]	57.47 (6.78)[b]
PBH	2812.20 (54.44)[a]	99.40 (6.56)[a]	63.73 (3.06)[a]

NDD, NextDent Denture 3D+; PBH, ProBase®Hot; SD, standard deviation; MPa, megapascal. Values are expressed as Mean (SD) in MPa unit. Different superscript letters (a, b) within the same column indicate statistically significant differences between groups according to independent t-tests ($p<0.001$)

Discussion

The primary objective of this study was to analyze the main chemical constituents of the 3D-printed denture base resin material. Based on the FTIR spectroscopy results in Figure 2, the major compounds in the NDD resin were identified as bisphenol A derivatives, as indicated by characteristic absorbance peaks corresponding to C=C, C=O, C–O, and aromatic carbon groups.[31] Furthermore, the ^{1}H NMR spectrum revealed signals consistent with two bisphenol A-based monomers, namely Bis-GMA and Bis-EMA in Figure 3.[32] Additional NMR signals were also observed, suggesting the presence of urethane dimethacrylate (UDMA).

HPLC analysis indicated that Bis-GMA was not a major component of the NDD resin, as demonstrated by only a minor peak appearing at a retention time of 7.83 minutes in Figure 4. In contrast, mass spectrometry (MS) analysis identified five out of seven main fractions in the NDD resin as Bis-EMA monomers. These Bis-EMA derivatives varied in their degrees of ethoxylation, containing three to seven ethylene oxide units (Table 1).[33]

Among various monomers, Bis-GMA is widely utilized in photo-curable dental composites.[34] However, Bis-GMA exhibits notably high viscosity compared to other dimethacrylate monomers,

primarily due to strong hydrogen bonding interactions from its hydroxyl groups.[34] This high viscosity can impede the 3D printing process—particularly in digital light processing (DLP) techniques, which rely on precise, layer-by-layer polymerization.[35] Therefore, Bis-GMA is typically not included as a major component in 3D printing resin formulations, where lower-viscosity monomers such as Bis-EMA are favored.

Moreover, Bis-EMA is more commonly used in 3D printing applications.[35,36] Unlike Bis-GMA, Bis-EMA exhibits lower viscosity due to the absence of hydroxyl functional groups.[34,35] Additionally, the presence of ethylene oxide units (–O–CH_2CH_2–) in its molecular structure enhances flowability.[11] However, variations in the length of these chain extenders can influence the physical and mechanical properties of the material.[11,13]

In the present study, Bis-EMA monomers with 3 to 7 ethylene oxide units were identified as the principal monomeric species in the NDD resin.[33] However, the HPLC/MS analysis enabled qualitative identification of Bis-EMA homologues with varying degrees of ethoxylation; quantitative determination of the relative abundance of individual homologues was not performed in the present study, as this would require dedicated quantitative chromatographic methods. This limitation is acknowledged, and future studies employing quantitative LC–MS techniques are warranted to determine the compositional ratios of individual Bis-EMA homologues.

Taken together, these compositional findings provide a structural basis for interpreting the polymerization behavior and mechanical performance observed in this study. Previous research has shown that Bis-EMA resins with shorter chain extenders (n + m ≈ 3–4) yield more rigid products with lower water sorption. In contrast, an excessive number of ethylene oxide units results in a relatively softer or rubber-like material with increased water sorption.[11,13] A formulation that combines Bis-EMA monomers with varying chain extender lengths may optimize the balance between mechanical strength and processing characteristics.[13]

FTIR spectroscopy was employed not only for structural analysis of chemical compounds but also for the quantitative measurement of the degree of conversion. The degree of conversion (DC) is a critical parameter that directly influences the clinical performance of dental materials. In general, a higher DC results in a polymer with greater molecular weight, thereby enhancing mechanical properties.[35] Conversely, the presence of unreacted monomers can compromise both the physical integrity and biocompatibility of the material.[37,38]

In terms of DC, the PBH resin exhibited a DC greater than 95%, while the NDD resin achieved a DC of only approximately 70%. According to previous research, the chemical structure and composition of photo-curable resins significantly affect polymerization behavior.[11,13,34-36] Bis-EMA resins with shorter ethylene oxide chains tend to achieve lower DC compared to those with longer chain extenders.[11,13] The inclusion of co-monomers such as UDMA may also influence the polymerization process and influence DC values.[35]

Moreover, the DC can also be influenced by several printing parameters, such as specimens layer thickness[16], distance between the light source and the cured material[39], exposure duration[40], and the characteristics of the light-curing unit.[40,41] Furthermore, the post-curing process has a considerable impact on the completeness of polymerization of 3D–printing polymers.[35,42-44]

Although alternative post-curing systems, such as nitrogen-atmosphere curing or high-intensity flash-curing units, have been reported to further enhance polymer conversion, the post-curing protocol applied in the present study was performed in accordance with the manufacturer's Instructions for Use (IFU) for NextDent Denture 3D+. Specifically, post-

curing was conducted at the recommended temperature and duration, thereby reflecting a clinically relevant processing condition. Therefore, the reported DC values represent performance under standardized clinical processing rather than experimentally optimized curing conditions. Future investigations may explore optimized post-curing strategies to further improve polymer conversion and mechanical performance.

Flexural properties of the 3D-printed denture base resin (NDD) were compared with those of the conventional heat-cured denture base resin (PBH). Although dimethacrylate-based resins are generally expected to yield stronger materials, the NDD specimens demonstrated lower flexural properties than the conventional PMMA-based PBH resin. This result aligns with previous findings reporting that the flexural strength of 3D printing resins is lower than that of heat-cured acrylic resins.[38]

The high standard deviation observed in the flexural modulus of the NDD group likely reflects structural anisotropy and microstructural heterogeneity inherent to the DLP additive manufacturing process. In contrast to the uniform polymer mass achieved through conventional heat-polymerization (PBH), 3D-printed resins are fabricated in discrete 100 μm layers, where subtle variations in light intensity, curing depth, and interlayer bonding can influence mechanical stiffness. This interpretation is further supported by FTIR analysis, which demonstrated that NDD achieved a significantly lower DC (69.81%) than PBH (97.59%). The resulting polymer network in NDD therefore contains a higher fraction of residual Bis-EMA monomer and a less densely cross-linked structure, contributing to less uniform mechanical behavior.

Although the present study included ten specimens per group, which was consistent with the specimen number commonly used in ISO 20795-1:2013-based flexural testing protocols, future investigations with larger sample sizes may help further mitigate the influence of manufacturing-related variability on flexural properties.

Two primary material-related factors may further explain the lower flexural properties observed in the NDD group: (1) the molecular structure of Bis-EMA monomers, and (2) the overall degree of conversion. Bis-EMA contains flexible ethylene oxide linkages, which contribute to a softer and more pliable polymer network. Consequently, the flexural modulus and yield stress of the NDD resin were lower than those of the PBH resin.[11,31]

In addition to structural flexibility, the significantly lower degree of conversion (DC) in the NDD resin indicates incomplete polymerization, resulting in reduced molecular weight and increased residual monomer content—both of which can negatively impact mechanical strength. [35,37,38] Despite these differences, both materials fulfilled the minimum flexural strength (65 MPa) and flexural modulus (2000 MPa) requirements specified in ISO 20795-1:2013.[30]

Beyond intrinsic material composition, it is important to recognize that the mechanical properties of 3D-printed resins are strongly influenced by printing parameters and post-processing conditions. Printing orientation is a primary factor governing the layer-by-layer architecture and mechanical behavior of additively manufactured resins.[20] Although a 0° (horizontal) orientation was selected in this study to enhance structural homogeneity and dimensional accuracy, other orientations (e.g., 30° or 45°) have been reported to improve flexural strength by altering layer alignment relative to the loading direction.[45]

Post-curing is also critical for achieving adequate polymerization, as printed resins often remain partially cured following fabrication. Previous studies have shown that flexural properties are significantly affected by post-curing parameters such

as polymerization time and temperature.[46] The lower degree of conversion observed in the NDD group (69.81%) compared with PBH (97.59%) suggests that the selected parameters may not have fully optimized the polymer network. Incomplete polymerization results in residual monomers that act as plasticizers, thereby reducing mechanical stiffness.[21] In addition, printing direction and layer thickness have been shown to significantly influence the mechanical behavior of DLP-printed resins.[19] Accordingly, the findings of this study should be interpreted with caution, and future investigations should explore the combined effects of build orientation and post-curing conditions to further optimize the mechanical performance of 3D-printed denture base materials.

Nevertheless, continued refinement of 3D printing parameters and post-curing protocols is essential to improve conversion rates and elevate the overall mechanical performance of 3D-printed denture base materials.

Conclusion

Within the limitations of this study, it can be concluded that the 3D printing denture base resin (NDD) primarily consists of Bis-EMA monomers with chain extender lengths ranging from 3 to 7 ethylene oxide units. The degree of conversion of the conventional heat-cured denture base resin was significantly higher than that of the 3D-printed resin. As a result, the flexural properties of the heat-polymerized material were superior to those of the 3D-printed counterpart. Nevertheless, both materials demonstrated acceptable flexural strength and modulus in accordance with ISO 20795-1:2013 standards.

Ethics

Ethics approval was not required because this was an in vitro study involving no human participants, human-derived specimens, or animals.

Conflict of Interest

The authors declare no conflict of interest.

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References

1. Janeva NM, Kovacevska G, Elencevski S, Panchevska S, Mijoska A, Lazarevska B. Advantages of CAD/ CAM versus conventional complete dentures: a review. Maced J Med Sci. 2018;6(8):1498-1502.
2. Lee S, Hong SJ, Paek J, Pae A, Kwon KR, Noh K. Comparing accuracy of denture bases fabricated by injection molding, CAD/CAM milling, and rapid prototyping method. J Adv Prosthodont. 2019;11(1):55-64.
3. Arakawa I, Al- Haj Husain N, Srinivasan M, Maniewicz S, Abou-Ayash S, Schimmel M. Clinical outcomes and costs of conventional and digital complete dentures in a university clinic: a retrospective study. J Prosthet Dent. 2022;128(3):390-5.
4. Davidowitz G, Kotick PG. The use of CAD/CAM in dentistry. Dent Clin North Am. 2011;55(3):559-70.
5. Kattadiyil MT, Jekki R, Goodacre CJ, Baba NZ. Comparison of treatment outcomes in digital and conventional complete removable dental prosthesis fabrications in a predoctoral setting. J Prosthet Dent. 2015;114(6):818-25.
6. Ligon SC, Liska R, Stampfl J, Gurr M, Mülhaupt R. Polymers for 3D printing and customized additive manufacturing. Chem Rev. 2017;117(15):10212-90.

7. Baba NZ, Goodacre BJ, Goodacre CJ, Müller F, Wagner S. CAD/CAM complete denture systems and physical properties: a review of the literature. J Prosthodont. 2021;30(2):113-24.
8. Javaid M, Haleem A. Current status and applications of additive manufacturing in dentistry: a literature-based review. J Oral Biol Craniofac Res. 2019;9(3):179-85.
9. Alharbi N, Wismeijer D, Osman RB. Additive manufacturing techniques in prosthodontics: where do we currently stand? A critical review. Int J Prosthodont. 2017;30(5):474-84.
10. Goodacre BJ, Goodacre CJ. Additive manufacturing for complete denture fabrication: a narrative review. J Prosthodont. 2022;31(1):47-51.
11. Ogliari FA, Ely C, Zanchi CH, Fortes CB, Samul SMW, Demarco FF, et al. Influence of chain extender length of aromatic dimethacrylates on polymer network development. Dent Mater. 2008;24(2):165-71.
12. Pratap B, Gupta RK, Bhardwaj B, Nag M. Resin-based restorative dental materials: characteristics and future perspectives. Jpn Dent Sci Rev. 2019;55(1):126-38.
13. Wada J, Heponiemi P, Wada K, Garoushi S, Wakabayashi N, Iwamoto T, et al. Effect of ethylene oxide unit number in bis-EMA on the physical properties of additive- manufactured occlusal splint material. J Prosthodont Res. 2024;68(4):558-67.
14. Gajewski VE, Pfeifer CS, Froes-Salgado NR, Boaro LC, Braga RR. Monomers used in resin composites: degree of conversion, mechanical properties and water sorption/ solubility. Braz Dent J. 2012;23(5):508-14.
15. Lin WS, Harris BT, Pellerito J, Morton D. Fabrication of an interim complete removable dental prosthesis with an in-office digital light processing three-dimensional printer: a proof-of-concept technique. J Prosthet Dent. 2018;120(3):331-4.
16. Kunjan C, N J, Chandrasekhar U. Influence of layer thickness on mechanical properties in stereolithography. Rapid Prototyp J. 2006;12(2):106-13.
17. Ferracane JL. Hygroscopic and hydrolytic effects in dental polymer networks. Dent Mater. 2006;22(3):211-22.
18. Palin WM, Fleming GJP, Trevor Burke FJ, Marquis PM, Randall RC. Monomer conversion versus flexure strength of a novel dental composite. J Dent. 2003;31(5):341-51.
19. Farkas AZ, Galatanu SV, Nagib R. The influence of printing layer thickness and orientation on the mechanical properties of DLP 3D-printed dental resin. Polymers (Basel). 2023;15(5):1113.
20. Jafarpour D, El- Amier N, Tahboub K, Zimmermann E, Pero AC, de Souza R. Effects of DLP printing orientation and postprocessing regimes on the properties of 3D printed denture bases. J Prosthet Dent. 2025;134(1) : 239. e1-239.e9.
21. Tahayeri A, Morgan M, Fugolin AP, Bompolaki D, Athirasala A, Pfeifer CS, et al. 3D printed versus conventionally cured provisional crown and bridge dental materials. Dent Mater. 2018;34(2):192-200.
22. AlGhamdi MA, Gad MM. Impact of printing orientation on the accuracy of additively fabricated denture base materials: a systematic review. Dent J (Basel). 2024;12(8):230.
23. Mudhaffer S, Althagafi R, Haider J, Satterthwaite J, Silikas N. Effects of printing orientation and artificial ageing on martens hardness and indentation modulus of 3D printed restorative resin materials. Dent Mater. 2024;40(7):1003-14.
24. Asmussen E. NMR analysis of monomers in restorative resins. Acta Odontol Scand. 1975;33(3):129-34.

25. Vankerckhoven H, Lambrechts P, van Beylen M, Vanherle G. Characterization of composite resins by NMR and TEM. J Dent Res. 1981;60(12):1957-65.
26. Dizon JRC, Espera AH, Chen Q, Advincula RC. Mechanical characterization of 3D- printed polymers. Addit Manuf. 2018;20:44-67.
27. Leão RS, de Moraes SLD, Aquino KADS, Isolan CP, Casado BGDS, Montes MAJR. Effect of pressure, post-pressing time, and polymerization cycle on the degree of conversion of thermoactivated acrylic resin. Int J Dent. 2018;2018:5743840.
28. Shen Y, Zhu W, Papadaki M, Mannan MS, Mashuga CV, Cheng Z. Thermal decomposition of solid benzoyl peroxide using advanced reactive system screening tool: effect of concentration, confinement, and selected acids and bases. J Loss Prev Process Ind. 2019;60:28-34.
29. Nozaki K, Bartlett PD. The kinetics of decomposition of benzoyl peroxide in solvents. J Am Chem Soc. 1946;68(9):1686-92.
30. ISO 20795-1:2013. Dentistry—base polymers—part 1: denture base polymers. Geneva: ISO; 2013.
31. Khan AS, Khalid H, Sarfraz Z, Khan AF, Iqbal J, Muhammad N, et al. Vibrational spectroscopy of selective dental restorative materials. Appl Spectrosc Rev. 2016;52(6):507-40.
32. Fujisawa S. Nuclear magnetic resonance spectra of Bis-GMA and Iso-bis-GMA. Dent Mater J. 1994;13(2):251-5.
33. Durner J, Schrickel K, Watts DC, Ilie N. Determination of homologous distributions of bisEMA dimethacrylates in bulk-fill resin-composites by GC-MS. Dent Mater. 2015;31(4):473-80.
34. Gonçalves F, Kawano Y, Pfeifer C, Stansbury JW, Braga RR. Influence of BisGMA, TEGDMA, and BisEMA contents on viscosity, conversion, and flexural strength of experimental resins and composites. Eur J Oral Sci. 2009;117(4):442-6.
35. Perea-Lowery L, Gibreel M, Vallittu PK, Lassila L. Evaluation of the mechanical properties and degree of conversion of 3D-printed splint material. J Mech Behav Biomed Mater. 2021;115:104254.
36. Lin CH, Lin YM, Lai YL, Lee SY. Mechanical properties, accuracy, and cytotoxicity of UV-polymerized 3D printing resins composed of Bis-EMA, UDMA, and TEGDMA. J Prosthet Dent. 2020;123(2):349-54.
37. Aati S, Akram Z, Shrestha B, Patel J, Shi B, Shearston K, et al. Effect of post-curing light exposure time on the physico-mechanical properties and cytotoxicity of 3D-printed denture base material. Dent Mater. 2022;38(1):57-67.
38. Chhabra M, Nanditha Kumar M, Raghavendra Swamy KN, Thippeswamy HM. Flexural strength and impact strength of heat-cured acrylic and 3D-printed denture base resins: a comparative in vitro study. J Oral Biol Craniofac Res. 2022;12(1):1-3.
39. Dionysopoulos D, Papadopoulos C, Koliniotou-Koumpia E. Effect of temperature, curing time, and filler composition on surface microhardness of composite resins. J Conserv Dent. 2015;18(2):114-8.
40. Choudhary S, Suprabha B. Effectiveness of light emitting diode and halogen light curing units for curing microhybrid and nanocomposites. J Conserv Dent. 2013;16(3):233-7.
41. Torno V, Soares P, Martin JM, Mazur RF, Souza EM, Vieira S. Effects of irradiance, wavelength, and thermal emission of different light curing units on the Knoop and Vickers hardness of a composite resin. J Biomed Mater Res B Appl Biomater. 2008;85(1):166-71.
42. Reymus M, Lümkemann N, Stawarczyk B. 3D-printed material for temporary restorations: impact of print layer thickness and post-curing method on degree of conversion. Int J Comput Dent. 2019;22(3):231-7.

43. Aromaa MK, Vallittu PK. Delayed post-curing stage and oxygen inhibition of free-radical polymerization of dimethacrylate resin. Dent Mater. 2018;34(9):1247-52.
44. Kim D, Shim JS, Lee D, Shin SH, Nam NE, Park KH, et al. Effects of post-curing time on the mechanical and color properties of three-dimensional printed crown and bridge materials. Polymers (Basel). 2020;12(11):2762.
45. Park SM, Park JM, Kim SK, Heo SJ, Koak JY. Flexural strength of 3D-printing resin materials for provisional fixed dental prostheses. Materials (Basel). 2020;13(18):3970.
46. Gad MM, Fouda SM. Factors affecting flexural strength of 3D-printed resins: a systematic review. J Prosthodont. 2023;32(2):96-110.

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KDJ Khon Kaen University Dental Journal

องค์ประกอบทางเคมี ระดับการเปลี่ยนเป็นพอลิเมอร์ และคุณสมบัติการดัดงอของวัสดุเรซินฐานฟันเทียมที่ขึ้นรูปด้วยการพิมพ์สามมิติ

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บทความวิจัย

บทคัดย่อ

วัตถุประสงค์: การศึกษานี้มีวัตถุประสงค์เพื่อประเมินองค์ประกอบทางเคมี ระดับการเปลี่ยนเป็นพอลิเมอร์ และคุณสมบัติการดัดงอของวัสดุเรซินฐานฟันเทียมที่ขึ้นรูปด้วยการพิมพ์สามมิติที่มีจำหน่ายในเชิงพาณิชย์ และเพื่อเปรียบเทียบกับวัสดุเรซินฐานฟันเทียมที่ขึ้นรูปด้วยการบ่มด้วยความร้อนแบบดั้งเดิม

วัสดุอุปกรณ์และวิธีการ: ศึกษาองค์ประกอบทางเคมีของเรซินฐานฟันเทียมที่ขึ้นรูปด้วยการพิมพ์สามมิติ ที่ยังไม่ผ่านการพอลิเมอร์ไรซ์ด้วยการวิเคราะห์โดยใช้เทคนิคฟูเรียร์ทรานส์ฟอร์มอินฟราเรดสเปกโตรสโคปี โปรตอนนิวเคลียร์แมกเนติกเรโซแนนซ์สเปกโตรสโคปี และโครมาโทกราฟีของเหลวสมรรถนะสูง/ แมสสเปกโตรมิเตอร์ และเปรียบเทียบระดับการเปลี่ยนเป็นพอลิเมอร์ ของวัสดุดังกล่าวกับวัสดุเรซินฐานฟันเทียมที่ขึ้นรูปด้วยการบ่มด้วยความร้อนแบบดั้งเดิม โดยใช้เทคนิคฟูเรียร์ทรานส์ฟอร์มอินฟราเรดสเปกโตรสโคปี และทดสอบคุณสมบัติการดัดงอแบบสามจุดตามแนวทางของ ISO 20795-1:2013 เพื่อวิเคราะห์คุณสมบัติความแข็งแกร่งแรงดัดมอดูลัสการดัดงอ และความเค้นคราก

ผล: การวิเคราะห์ด้วยโครมาโทกราฟีของเหลวสมรรถนะสูง/ แมสสเปกโตรมิเตอร์ พบว่าวัสดุเรซินฐานฟันเทียมที่ขึ้นรูปด้วยการพิมพ์สามมิติ ประกอบด้วยมอนอเมอร์หลักคือ บิสฟีนอลเอ อีทอกซิเลต ไดเมทาคริเลต (BisEMA) ที่มีความยาวหน่วยเอทิลีนออกไซด์ 3-7 หน่วย โดยพบว่าระดับการเปลี่ยนเป็นพอลิเมอร์ของวัสดุเรซินฐานฟันเทียมที่ขึ้นรูปด้วยการบ่มด้วยความร้อนแบบดั้งเดิม สูงกว่าเรซินฐานฟันเทียมที่ขึ้นรูปด้วยการพิมพ์สามมิติอย่างมีนัยสำคัญ (97.59±1.14% และ 69.81±4.90% ตามลำดับ) ($p<0.001$) นอกจากนั้นวัสดุเรซินฐานฟันเทียมที่ขึ้นรูปด้วยการบ่มด้วยความร้อนแบบดั้งเดิม มีค่าความแข็งแกร่งแรงดัด 99.40±6.56 MPa และมอดูลัสการดัดงอ 2812.20±54.44 MPa ซึ่งสูงกว่าวัสดุเรซินฐานฟันเทียมที่ขึ้นรูปด้วยการพิมพ์สามมิติอย่างมีนัยสำคัญเช่นกัน ($p<0.001$) ที่มีค่าความแข็งแกร่งแรงดัด 88.58±8.50 MPa และมอดูลัสการดัดงอ 2625.40±368.42 MPa อย่างไรก็ตามวัสดุทั้งสองชนิดมีคุณสมบัติการดัดงอตามมาตรฐานของ ISO 20795-1:2013

บทสรุป: วัสดุเรซินฐานฟันเทียมที่ขึ้นรูปด้วยการพิมพ์สามมิติ ประกอบด้วยมอนอเมอร์ บิสฟีนอลเอ อีทอกซิเลต ไดเมทาคริเลต ที่มีความยาวของสายโซ่ที่หลากหลาย โดยมีระดับการเปลี่ยนเป็นพอลิเมอร์ และคุณสมบัติการดัดงอที่ต่ำกว่าวัสดุเรซินฐานฟันเทียมที่ขึ้นรูปด้วยการบ่มด้วยความร้อนแบบดั้งเดิม ดังนั้นการปรับปรุงปัจจัยต่าง ๆ ที่เกี่ยวข้องกับการขึ้นรูปด้วยการพิมพ์สามมิติและการบ่มหลังการพิมพ์สามมิติ เป็นสิ่งจำเป็นเพื่อทำให้การเกิดพอลิเมอร์สูงขึ้นและมีประสิทธิภาพเชิงกลที่ดีขึ้น

คำไขรหัส: การพิมพ์สามมิติ/ วัสดุเรซินฐานฟันเทียม/ บิสฟีนอลเอ อีทอกซิเลต ไดเมทาคริเลต/ ระดับการเปลี่ยนเป็นพอลิเมอร์/ ความแข็งแกร่งแรงดัด

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