ORIGINAL RESEARCH

Functional Group Delineation and Double Bond Conversion of Dental Poly(methylmethacrylate) Resin Conjugated with a Spiroacetal Cross-linker: An *In Vitro* Characterization Research

Ranganathan Ajay[1], Chandramohan Ravivarman[2], Rajkumar Daisy[3], Pradeep P Elango[4], Muthupettai V Srikanth[5], Gurunathan Deepa[6]

Received on: 27 February 2024; *Accepted on:* 30 March 2024; *Published on:* 17 May 2024

Abstract

Aim: To characterize and identify the functional groups as evidence for copolymerization (CP) and evaluate the double bond conversion (DBC) of a novel poly(methylmethacrylate) [P(MMA)] copolymer with a spiroacetal cross-linker at 10 and 20% concentrations using Fourier-transform infrared (FTIR) spectroscopy.

Materials and methods: The *in vitro* research consists of three groups—a control group G0 (without spiroacetal cross-linker) and two investigational groups G10 and G20 with spiroacetal cross-linker at 10 and 20 wt% concentration, respectively. This spiroacetal cross-linker was added to the powder-liquid mixture during manipulation at the predetermined trial concentrations. The CP and DBC% were determined and analyzed using infrared spectroscopy. The obtained DBC% values were submitted for statistical evaluation.

Results: Incorporation of the spiroacetal cross-linker in the P(MMA) resulted in a new denture base copolymer through CP which was ascertained by the appearance of new peaks between 1075 and 1190/cm in both investigational groups. Nevertheless, the new copolymer exhibited statistically greater DBC than the P(MMA). The mean DBC% of the control, G10, and G20 groups were 62.88, 69.52, and 83.00%, respectively.

Conclusion: The incorporated spiroacetal cross-linking comonomer successfully copolymerized with the denture base acrylic resulting in a new copolymer exhibiting high DBC%.

Clinical significance: Existing drawbacks concerning the physicomechanical and biological properties of denture base resin can be mitigated by the new denture base copolymer containing spiroacetal cross-linker. This would benefit the elderly patient by providing prostheses with better mechanical strength, clinical longevity, and quality of life.

Keywords: Copolymerization, Cross-link, Denture copolymer, Double bond conversion, Spiroacetal.

World Journal of Dentistry (2024): 10.5005/jp-journals-10015-2406

Introduction

Poly(methylmethacrylate) [P(MMA)] is a linear polymeric material inveterately used in dentistry for the fabrication of denture bases, dentures, obturators, orthodontic retainers, provisional restorations, and for the repair of dental prostheses. Despite its time-honored utility and supremacy, its unresolved improper double bond conversions (DBC) during radical polymerization have led to microgel agglomeration and several untoward tissue reactions.[1–4] In thermally polymerized P(MMA), there is an increased mobility of the molecules as the temperature rises resulting in high DBC.[5] However, the DBC is never complete and the resultant monomeric residuum (MR) in the polymerized material affects the properties of the P(MMA) materials.[6] The DBC and MR are two distinct variables that are inversely proportional. Varying MR quantities remain after denture bases' polymerization.[7] The unpolymerized MR leach in an aqueous medium continuously for 5 weeks post polymerization[8] which is higher in artificial saliva than distilled water.[9] Inadequate DBC or high MR release causes denture's dimensional aberrations, thereby victimizing the polymer to internal stresses that lead to the formation/propagation of cracks and eventually, denture fracture.[10,11] Therefore, increasing the DBC results in higher fracture toughness and other mechanical properties that may be ascribed to increased cross-linkage.[12] Nevertheless, the unresolved setbacks

[1]Department of Prosthodontics and Crown & Bridge, Vivekanandha Dental College for Women, Namakkal, Tamil Nadu, India

[2]Department of Conservative Dentistry and Endodontics, Dhanalakshmi Srinivasan Dental College, Perambalur, Tamil Nadu, India

[3]Department of Prosthodontics and Crown & Bridge, Dhanalakshmi Srinivasan Dental College, Perambalur, Tamil Nadu, India

[4]Department of Orthodontics and Dentofacial Orthopedics, Dhanalakshmi Srinivasan Dental College, Perambalur, Tamil Nadu, India

[5]Department of Prosthodontics and Crown & Bridge, Sathyabama Dental College and Hospital, Chennai, Tamil Nadu, India

[6]Department of Pedodontics, Saveetha Dental College & Hospital, Saveetha Institute of Medical and Technical Sciences (Deemed to be University), Chennai, Tamil Nadu, India

Corresponding Author: Chandramohan Ravivarman, Department of Conservative Dentistry and Endodontics, Dhanalakshmi Srinivasan Dental College, Perambalur, Tamil Nadu, India, Phone: +91 9841410207, e-mail: ravisham878@gmail.com

How to cite this article: Ajay R, Ravivarman C, Daisy R, *et al.* Functional Group Delineation and Double Bond Conversion of Dental Poly(methylmethacrylate) Resin Conjugated with a Spiroacetal Cross-linker: An *In Vitro* Characterization Research. World J Dent 2024;15(4):356–361.

Source of support: Nil

Conflict of interest: None

© The Author(s). 2024 Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by-nc/4.0/), which permits unrestricted use, distribution, and non-commercial reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http://creativecommons.org/publicdomain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

of P(MMA) like water sorption, solubility, and nonpalatable impact strength cause fracture of dentures under cyclic fatigue.[13,14]

The P(MMA) resins have undergone a significant number of alterations to enhance their physicomechanical characteristics and biocompatibility. These alterations can be conveniently categorized into modifications executed in prepolymeric powder and in the liquid monomer. The advances in polymer technology have produced novel polymers with improved impact strength and fatigue resistance.[15,16] Relative to prepolymeric powder's modifications, studies on monomer modifications are comparably less.[17] Recently, chemically altered monomers have been developed with excellent dimensional precision, enhanced strength, and palatable cytocompatibility.[18] The proprietary methylmethacrylate (MMA) monomer and the substituted/added comonomer ought to interact and copolymerize harmoniously to yield synergistic effects. This is because the characteristics of the resins used as denture bases are determined through the degree of copolymerization (CP).[19] The MR release after CP is predominantly governed by the DBC.[20,21] The DBC of P(MMA) polymer or its copolymers shall be determined by comparing the percentage of aliphatic carbon–carbon double bonds (C═C) present in polymerized specimens to those present in unpolymerized specimens by Fourier-transform infrared (FTIR) spectroscopy which is a commonly and widely used method to determine the DBC.[22]

3,9-*bis*(ethenyl)-2,4,8,10-tetraoxaspiro[5.5]undecane (BETU) is a bicyclic spiroacetal organic molecule with a central quaternary carbon atom (a spiro atom) to which two alicyclic rings are linked. The conjugation of the spiroacetal moiety in the polymeric structure has manifested satisfactory adhesive properties with improved flexibility and tensile strength.[23] These features are ascribed to the inherent stiffness of the spiroacetal ring which is higher than cycloaliphatic rings and lower than aromatic rings and ether-oxygen interactions, and bulkiness.[24] However, no dental literature is found on copolymerizing P(MMA) with BETU and the DBC of the resultant copolymer. Hence, this research aimed to identify the functional groups (characterization) as evidence for CP and evaluate the DBC of a new P(MMA) copolymer with BETU at 10 and 20% concentrations using FTIR spectroscopy. The null hypothesis was that there would be no evidence of CP and incorporation of BETU would not have any effect on the DBC of the resultant copolymer.

Materials and Methods

The research was executed at the Central Electrochemical Research Institute, Karaikudi. All the chemicals used in this research were procured from Sigma-Aldrich [Acme ProGen Biotech (India) Pvt. Ltd. Tamil Nadu, Table 1] and used without further processing. In P(MMA) prepolymeric powder, 0.5 wt% dibenzoyl peroxide (DBPO) initiator was added and mixed for an hour in the ball-milling machine. The filler particles were silanized using γ-methacryloxy propyltrimethoxysilane (MPTS). In 200 mL acetone, 5 gm of each Al_2O_3 and YSZ were dispensed and mixed in a magnetic stirrer for 15 minutes. Eventually, 10 wt% γ-MPTS was pipetted into the mixture and stirred for another 2 hours. Then the mixture was filtered and washed with 200 mL of acetone and dried in an oven at 80°C for 24 hours.[25] About 5 wt% of this dried silanized filler powder was added to the P(MMA)-DBPO powder mixture and mixed in the ball-milling machine for an hour.

The liquid monomer was prepared in a 500 mL conical flask containing MMA. About 10 wt% ethylene glycol dimethacrylate (EGDMA) and 10 wt% *n*-butyl methacrylate (*n*-BMA) were pipetted and stirred with the magnetic stirrer for 15 minutes. The groups were divided according to the BETU's concentration and composition in the cured specimens (Table 2). The present *in vitro* research consists of three groups—a control group G0 (without BETU) and two investigational groups G10 and G20 with BETU comonomer at 10 and 20 wt% concentration, respectively. The powder and liquid compositions were uniform for all the groups except for the BETU's incorporation. The cured samples (≈200 μm thick; n = 10/group) were prepared by the glass-slide technique as described by Rodriguez et al.[26] and heat-cured by a long polymerizing cycle with terminal boiling for half an hour in an acrylizer. The uncured samples (n = 10/group) were formulated without an initiator to avoid untimely polymerization reactions.

The CP and DBC were ascertained by FTIR spectroscopy in attenuated total reflection (ATR) mode (FTIR-ATR) (Tensor 27 model; Bruker Optik, GmbH, Germany). All the spectra were obtained from 64 scans and normalized at 4/cm spectral resolution. Two absorption (Abs) peaks appeared for aliphatic unsaturated C═C and esterified carbonyl (C═O) stretches. A congruous baseline was fitted and the Abs peaks were parted into two Lorentzian curves. The absorption potency was deduced by computing the peaks' areas. The DBC was equated by the following formula:

$$\mathrm{DBC\%} = \left[1 - \left(\frac{\frac{\mathrm{C{=}C}}{\mathrm{C{=}C}}\{\mathrm{Cured}\}}{\frac{\mathrm{C{=}C}}{\mathrm{C{=}O}}\{\mathrm{Uncured}\}}\right)\right] \times 100.$$

The investigator was blinded about the BETU's concentration in the monomer and also the groups comprising the polymerized

Table 1: Chemicals used in the research and their functions

Chemical	*Function*
P(MMA) powder (molecular weight ~ 350,000 gm/mol)	The main component in the powder
DBPO	Initiator
Alumina (Al_2O_3)	Filler
Yttrium-stabilized zirconia (YSZ)	Filler
γ-MPTS	Coupling agent
MMA with ≤30 ppm mequinol as an inhibitor	The main component in the liquid
EGDMA	Cross-linker
n-BMA	Intrinsic-reactive plasticizer
BETU	Spiroacetal cross-linker

Table 2: Study groups and their composition in polymerized specimens

Group	*Powder*	*Liquid*	*BETU*
G0	94.5 wt% P(MMA) prepolymeric powder, 0.5 wt% DBPO, 5 wt% Al_2O_3-YSZ (1:1)	MMA with ≤30 ppm mequinol as an inhibitor, 10% *n*-BMA as a plasticizer, and 10% tricyclodecane dimethanol diacrylate as a cross-linker	Absent
G10			10 wt%
G20			20 wt%

For a 3:1 powder–liquid ratio, the BETU was added to the powder-liquid mixture finally

specimens by labeling them with opaque stickers with random numbers on them. The operator and statistician were also blinded about the same.

Statistical Analysis

The acquired data were analyzed for statistically significant differences by employing Statistical Package for the Social Sciences (SPSS) software version 29.0. The data normality was checked by the Kolmogorov–Smirnov test and was normally distributed ($p > 0.05$). Descriptive statistical tests were performed. The mean, standard deviation (SD), standard error, upper bound, and lower bound were calculated. One-way analysis of variance (ANOVA) and *post hoc* Tukey–Kramer multiple comparison tests were exercised concerning DBC to compare among and between the groups, respectively. A probability value <0.05 was taken into account for statistical significance.

Results

The investigational (G10, G20) and the control (G0) groups were characterized by six spectral differences (zones I–V; Fig. 1). The peaks at 2922–2920/cm and 2851–2850/cm in the investigational groups evinced the CP of BETU with P(MMA) resulting in a new P(MMA-*Co*-BETU) copolymer (zone I; orange band). The appearance of the strong new peaks in zone III (pink band) in the G10 and G20 is suggestive of BETU's inclusion in the polymer. Weak peaks at 842–807/cm in G10 suggest the presence of unreacted BETU (zone V; lavender band). In the same zone, the presence of a new peak at 721–720/cm in the investigational groups attributable to -$(CH_2)_n$- methylene rocking suggests CP. Table 3 shows the attributions of functional groups with zonal differences between the groups. Zones II (yellow band; 1632/cm) and IV (blue band; 949/cm) show the presence of unsaturated C=C bonds concerning unreacted MMA in G0 and were absent in the investigational groups.

The mean (SD) DBC% of G0, G10, and G20 were 62.88 (0.60), 69.52 (0.96), and 83.00 (0.57), respectively. A significant difference ($p = 0.000$) was evident among the groups (Table 4). Nevertheless, significant differences ($p = 0.000$) were observed between the groups by multiple comparisons (Table 5). The DBC of the control was lesser than that of the investigational groups. Between the investigational groups, G20 exhibited superior DBC than G10. Figure 2 shows the IR graphs of all the groups showing the variations in the absorbance peak intensities between cured and uncured specimens.

Discussion

In the present research, BETU successfully copolymerized with MMA to form a new denture base copolymer P(MMA-*Co*-BETU) with high DBC% when compared to P(MMA). Five IR spectral distinctions appeared among the groups that were named zones I–V. In zone I, the appearance of new peaks in the investigational groups G10 and G20 are attributable to the -ĊH-CH_2- symmetric stretch, where

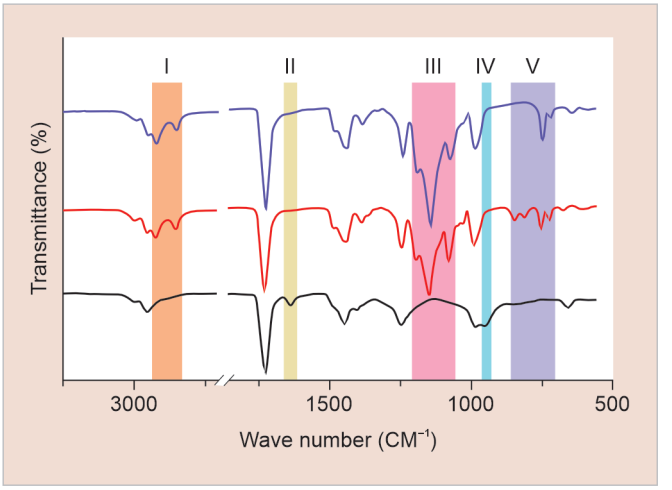


Fig. 1: Fourier-transform infrared spectra of the groups with the zones of differences

Table 3: Fourier-transform infrared peaks of the polymerized resins

Wavenumber, cm^{-1}	*Attribution*	*Group*	*Zone*
2993–2992	CH_3 stretch (C–H)	G0, G10, G20	
2950	Aliphatic chain =C–CH_2–stretch (νC–H)	G0, G10, G20	
2922–2920	-ĊH-CH_2- symmetric stretch (νC–H) (polymerization)	**G10, G20**	**I**
2851–2850		**G10, G20**	
1724–1722	C=O carbonyl	G0, G10, G20	
1632	Carbon–carbon stretch (C=C)	**G0**	**II**
1443–1437	CH_3 asymmetric bending (νC–H); CH_3 umbrella deformation	G0, G10, G20	
1400–1382	CH_3 α-methyl bend (C–CH_3)	G0, G10, G20	
1241–1240	C–O–CH_3 stretch	G0, G10, G20	
1190–1189	Cyclic ether linkage I stretch of spiroacetal moiety (–CH–O–CH_2–)	**G10, G20**	**III**
1144		**G10, G20**	
1075		**G10, G20**	
986–979	*trans*—(C–H) wagging	G0, G10, G20	
949	*trans*—(C=C) bending	**G0**	**IV**
842–807	Vinylidene (C=C) bending	**G10**	**V**
749	*cis*-(C–H) wagging	**G10, G20**	
721–720	-$(CH_2)_n$- methylene rocking (CP)	**G10, G20**	
673–642	δC=O carboxylic group	G0, G10, G20	

Bold values indicate the spectral differences among the groups

Table 4: One-way ANOVA concerning DBC

Source	*df*	*Sum of square*	*Mean square*	*F Statistic*	*p-value*
Groups (between groups)	2	2101.6381	1050.8191	1978.4627	0.000
Error (within groups)	27	14.3405	0.5311		
Total	29	2115.9786	72.9648		

Table 5: *Post hoc* Tukey test concerning DBC

Pair	*Difference*	*Q*	*Lower confidence interval (CI)*	*Upper CI*	*p-value*
G0-G10	6.649	28.8507	5.8409	7.4571	0.000
G0-G20	20.12	87.3028	19.3119	20.9281	0.000
G10-G20	13.471	58.4521	12.6629	14.2791	0.000

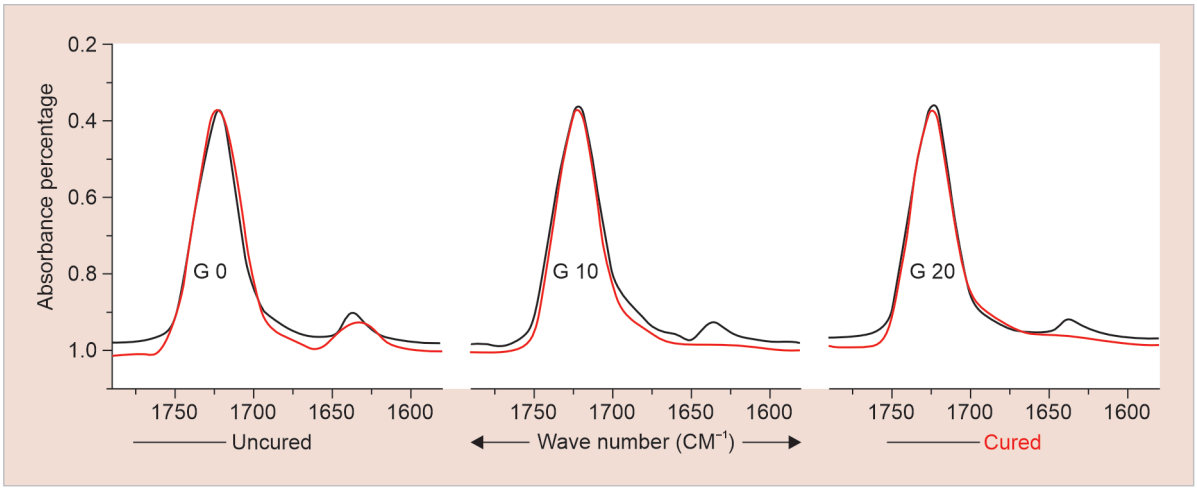


Fig. 2: Infrared (IR) spectra depicting the DBC

the presence of tertiary carbon ascertains polymerization at the vinyl terminals of BETU. In zone III, the presence of cyclic ether (–CH–O–CH_2–) linkage in both investigational groups confirms the spiroacetal moiety's inclusion. This can be corroborated by the results obtained by Chiriac et al.[24,27] In zone V, the presence of methylene rocking corresponding to the copolymeric backbone chain in the investigational groups ascertains the CP between MMA and BETU yielding a new copolymer P(MMA-*Co*-BETU).

In zone II, the absence of the peak at 1632/cm in both G10 and G20 is attributed to amplified DBC. The peak peculiar to the unsaturated C=C of the MMA monomer in the G0 group clearly indicates the presence of MR and inadequate DBC. Despite the formation of a three-dimensional polymeric network, the DBC in the resultant copolymer has a significant influence on the copolymer's mechanical strength. Also, in zone IV, the presence of *trans*-(C=C) bending in the G0 indicates the MR. The lower the DBC, the higher the MR quantity.[28] In the control group G0, the unreacted C=C bond's presence is due to the fact that the polymerization would never result in 100% DBC. Nevertheless, the ultimate DBC in the polymeric specimens relies on the liquid monomer's composition, polymerization temperature and duration, and manipulating room ambiance.[29] The range of DBC from C=C to C-C is usually between 55 and 65%.[30] However, it should not be interpreted as 35–45% of unpolymerized monomer content. Instead, it is the number of C=C bonds that remain uncured. There is a possibility that BETU containing two reactive vinyl terminals (C=C) might react with one of its terminals with the other unreacted.

Albeit the DBC is always incomplete, the absence of peak at 1632/cm in the investigational groups may be taken for near-total conversion of monomers. This could be attributable to the presence of both methacrylate and vinyl moieties wherein the latter enhanced the DBC of the former which can be corroborated by the following studies. Gziut et al.[31] studied the effect of methacrylate and vinyl comonomers on the radical polymerization and properties of epoxy acrylates. It was found that vinyl comonomers increased the polymerization reaction rate resulting in high DBC%. Lee et al.[32] referred to the term hybrid polymerization where the methacrylates/acrylates and the vinyl esters were copolymerized. It was found that the CP of acrylates with vinyl esters significantly improved the DBC up to 80% which was much higher than acrylates' homopolymerization (≈50%). The vinyl group with low reactivity functioned as a plasticizer at the early stages of CP and allowed polymeric chain growth and mobility that ultimately led to a high polymerization rate, DBC, and crosslink density.[32] Hence, from the above context, practical CP was established between the MMA and BETU with higher DBC% for G20 followed by G10 than the control group in the current research.

Lee et al.[33] also studied the practical supremacy of hybrid polymerization wherein the vinyl moiety remained unreacted at the initial phases causing a significant reduction in polymerization shrinkage stress. The predominant disadvantage of methacrylates is oxygen inhibition. Nitrogen blankets and high initiator concentrations were employed to circumvent this problem.[34–36] An alternative to decrease oxygen inhibition consequences is by employing vinyl esters. Vinyl ester monomers significantly decreased oxygen inhibition.[37] Howbeit, vinyl ester monomers show a slow rate of polymerization when homopolymerized. At the same time, vinyl esters copolymerized with acrylate/methacrylate monomers resulted in both decreased oxygen inhibition and a prompt rate of polymerization.[32] Therefore, in the current research, BETU possessing two vinyl terminals has been selected and used as a cross-linker.

The current research utilized 10 and 20% BETU in MMA. Numerous studies concerning monomer modification have substituted MMA with 10 and 20% experimental comonomers with a mean range between 2.5 and 50%.[17] Since CP between MMA and BETU has been successfully demonstrated, it leads to futuristic research concerning the physicomechanical properties and biocompatibility of the new P(MMA-*Co*-BETU) copolymer. The current research is a triple-blinded study. The investigator, the operator, and the statistician were blinded by concealing the concentration of BETU in MMA to circumvent bias. Although several techniques are there to analyze CP and DBC%, FTIR remains the gold standard.[38] In the present research, BETU's concentration beyond 20% was not investigated. The dough-forming time was not taken into consideration. Further studies are mandatory with increased BETU concentration in MMA and its effect on the properties and biocompatibility has to be studied explicitly.

Conclusion

Considering the research constraints, it can be concluded that the CP between spiroacetal BETU cross-linker and MMA successfully yielded a new copolymer P(MMA-*Co*-BETU) at 10% and 20% BETU concentrations. The substitution of MMA with BETU increased the DBC% in the P(MMA-*Co*-BETU) when compared to the P(MMA).

References

1. Brożek R, Koczorowski R, Rogalewicz R, et al. Effect of denture cleansers on chemical and mechanical behavior of selected soft lining materials. Dent Mater 2011;27(3):281–290. DOI: 10.1016/j.dental.2010.11.003
2. Saitoh S, Sasaki K, Nezu T, et al. Viscoelastic behavior of commercially available tissue conditioners under compression. Dent Mater J 2010;29(4):461–468. DOI: 10.4012/dmj.2009-130
3. Takahashi Y, Hamanaka I, Shimizu H. Flexural properties of denture base resins subjected to long-term water immersion. Acta Odontol Scand 2013;71(3-4):716–720. DOI: 10.3109/00016357.2012.715196
4. Andrzejewska E. Photopolymerization kinetics of multifunctional monomers. Prog Polym Sci 2001;26(4):605–665. DOI: 10.1016/S0079-6700(01)00004-1
5. Hamouda IM, Makke A. Heat-cured acrylic resin reinforcement with aluminum oxide: degree of conversion, monomer release and flexural strength. Dent Oral Maxillofac Res 2020;6:1–5. DOI: 10.15761/DOMR.1000359
6. Koroglu A, Ozdemir T, Pamir AD, et al. Residual acrylic monomer content of denture base resins with different fiber systems. J Appl Polym Sci 2012;125(1):471–476. DOI: 10.1002/app.35671
7. Bartoloni JA, Murchison DF, Wofford DT, et al. Degree of conversion in denture base materials for varied polymerization techniques. J Oral Rehabil 2000;27(6):488–493. DOI: 10.1046/j.1365-2842.2000.00536.x
8. Amin WM. Detection and estimation of monomeric eluates from poly(methyl methacrylate) resin of various polymerisation modes. Polym Polym Compos 2007;15(7):553–560. DOI: 10.1177/096739110701500705
9. Alawi MA, Amin WM. Effect of ageing on monomer elution from poly(methyl methacrylate) resin under simulated intra-oral conditions. Fresenius Environ Bull 2007;16(4):408–414.
10. Woelfel JB. Newer materials and techniques in prosthetic resin materials. Dent Clin North Am 1971;15(1):67–79. PMID: 4923235.
11. Vilaplana J, Romaguera C, Cornellana F. Contact dermatitis and adverse oral mucous membrane reactions related to the use of dental prostheses. Contact Dermatitis 1994;30(2):80–84. DOI: 10.1111/j.1600-0536.1994.tb00568.x
12. Lovell LG, Lu H, Elliott JE, et al. The effect of cure rate on the mechanical properties of dental resins. Dent Mater 2001;17(6):504–511. DOI: 10.1016/s0109-5641(01)00010-0
13. Sasaki H, Hamanaka I, Takahashi Y, et al. Effect of long-term water immersion or thermal shock on mechanical properties of high-impact acrylic denture base resins. Dent Mater J 2016;35(2):204–209. DOI: 10.4012/dmj.2015-291
14. Lovell LG, Berchtold KA, Elliot JE, et al. Understanding the kinetics and network formation of dimethacrylate dental resins. Polym Adv Technol 2001;12(6):335–345. DOI: 10.1002/pat.115
15. Jagger DC, Harrison A, Jandt KD. The reinforcement of dentures. J Oral Rehabil 1999;26(3):185–194. DOI: 10.1046/j.1365-2842.1999.00375.x
16. Rodford R. The development of high impact strength denture-base materials. J Dent 1986;14(5):214–217. DOI: 10.1016/0300-5712(86)90004-7
17. Ajay R, Suma K, Ali SA. Monomer modifications of denture base acrylic resin: a systematic review and meta-analysis. J Pharm Bioallied Sci 2019;11(Suppl 2):S112–S125. DOI: 10.4103/JPBS.JPBS_34_19
18. Alla RK, Sajjan S, Alluri VR, et al. Influence of fiber reinforcement on the properties of denture base resins. J Biomater Nanobiotechnol 2013;4(1):91–97. DOI: 10.4236/jbnb.2013.41012
19. Ajay R, Suma K, JayaKrishnaKumar S, et al. Chemical characterization of denture base resin with a novel cycloaliphatic monomer. J Contemp Dent Pract 2019;20(8):940–946. DOI: 10.5005/jp-journals-10024-2634
20. Bural C, Aktaş E, Deniz G, et al. Effect of leaching residual methyl methacrylate concentrations on in vitro cytotoxicity of heat polymerized denture base acrylic resin processed with different polymerization cycles. J Appl Oral Sci 2011;19(4):306–312. DOI: 10.1590/s1678-77572011005000002
21. Borelli B, Zarone F, Rivieccio V, et al. Polyacrylic resins regulate transcriptional control of interleukin-6, gp80, and gp130 genes in human gingival fibroblasts. J Oral Sci 2017;59(1):87–91. DOI: 10.2334/josnusd.16-0388
22. Kurata S, Morishita K, Shimoyama K, et al. Basic study on the application of novel functional monomers to a denture base resin. Dent Mater J 2008;27(2):273–277. DOI: 10.4012/dmj.27.273
23. Salamone JC. Polymeric Materials Encyclopedia, 1st edition. Florida, United States: CRC Press; 1996. p. 7858.
24. Chiriac AP, Nita LE, Nistor MT. Copolymerization of 2-hydroxyethyl methacrylate with a comonomer with spiroacetal moiety. J Polym Sci Part A: Polym Chem 2011;49(7):1543–1551. DOI: 10.1002/pola.24575
25. Kundie F, Azhari CH, Ahmed ZA. Effect of nano- and micro-alumina fillers on some properties of poly(methyl methacrylate) denture base composites. J Serb Chem Soc 2017;82:1–17. DOI: 10.2298/JSC170118056K
26. Rodriguez LS, Paleari AG, Giro G, et al. Chemical characterization and flexural strength of a denture base acrylic resin with monomer 2-tert-butylaminoethyl methacrylate. J Prosthodont 2013;22(4):292–297. DOI: 10.1111/j.1532-849X.2012.00942.x
27. Chiriac AP, Nistor MT, Nita LE, et al. Poly(n,n-dimethyl acrylamide-co-3,9-divinyl-2,4,8,10-tetraoxaspiro (5.5) undecane) synthesis as matrix ensuring intramolecular strategies for further coupling applications. Rev Roum Chim 2013;58:129–136.
28. Durner J, Obermaier J, Draenert M, et al. Correlation of the degree of conversion with the amount of elutable substances in nano-hybrid

dental composites. Dent Mater 2012;28(11):1146–1153. DOI: 10.1016/j.dental.2012.08.006
29. Mahfooz AM, Alammari MR. The use of Fournier Transform Infrared (FTIR) spectroscopic analysis and cell viability assay to assess pre-polymerizes CAD/CAM acrylic resin denture base materials. Int J Pharm Res Allied Sci 2018;7(2):111–118. Available from: https://ijpras.com/article/the-use-of-fourier-transform-infra-red-ftir-spectroscopic-analysis-and-cell-viability-assay-to-assess-pre-polymerized-cadcam-acrylic-resin-denture-base-materials
30. Miletic VJ, Santini A. Remaining unreacted methacrylate groups in resin-based composite with respect to sample preparation and storing conditions using micro-Raman spectroscopy. J Biomed Mater Res B Appl Biomater 2008;87(2):468–474. DOI: 10.1002/jbm.b.31128
31. Gziut K, Kowalczyk A, Schmidt B, et al. Influence of methacrylate and vinyl monomers on radical bulk photopolymerization process and properties of epoxy-acrylate structural adhesives. Polymers (Basel) 2023;15(4):926. DOI: 10.3390/polym15040926
32. Lee T, Cramer N, Hoyle C, et al. (Meth)acrylate vinyl ester hybrid polymerizations. J Polym Sci A Polym Chem 2009;47(10):2509–2517. DOI: 10.1002/pola.23327
33. Lee TY, Carioscia J, Smith Z, et al. Thiol-allyl ether-methacrylate ternary systems. Evolution mechanism of polymerization-induced shrinkage stress and mechanical properties. Macromolecules 2007;40(5):1473–1479. DOI: 10.1021/ma0624954
34. Hoyle CE, Kim KJ. The effect of aromatic amines on the photopolymerization of 1,6-hexanediol diacrylate. J Appl Polym Sci 1987;33(8):2985–9996. DOI: 10.1002/app.1987.070330831
35. Hoyle CE, Keel M, Kim KJ. Photopolymerization of 1,6-hexanediol diacrylate: The effect of functionalized amines. Polymer 1988;29(1):18–23. DOI: 10.1016/0032-3861(88)90194-2
36. Gou L, Opheim B, Coretsopoulos CN, et al. Consumption of the molecular oxygen in polymerization systems using photosensitized oxidation of dimethylanthracene. Chem Eng Commun 2006;193(5):620–627. DOI: 10.1080/00986440500193921
37. Lee TY, Kaung W, Jönsson ES, et al. Synthesis and photopolymerization of novel multifunctional vinyl esters. J Polym Sci Part A Polym Chem 2004;42(17):4424–4436. DOI: 10.1002/pola.20181
38. International Organization for Standardization, ISO 10993-18. Biological evaluation of medical devices—part 18: chemical characterization of materials. British Standards: ISO; 2009.