Prosthetic Dental Medicine

Mechanical properties of the polymers used for 3D printed removable dentures. Literature review

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Механични качества на смолите за 3D принтирани снемаеми протезни конструкции. Литературен обзор

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Abstract

In the last decade, Additive Technologies (AT) have developed extremely quickly, enabling the creation of complex and highly precise objects used in various fields, including dental medicine. Three-dimensional printing has the potential to modernize and streamline conventional production technologies, the materials, and the work process. An undeniable advantage is the reduction of clinical and laboratory time, quality control, and minimizing the impact of subjective factors.

Although additive manufacturing is increasingly used in the field of dental medicine, certain disadvantages of the materials used have also been noted. According to some authors, the disadvantages include inferior mechanical properties of polymers used for 3D printing. Although clinically acceptable, their values from various tests tend to be lower compared to conventional polymers and those used for milling.

The aim of this study is to review the available literature on mechanical properties of the polymers used for three-dimensional printing of removable dentures.

Key words: *CAD/CAM, 3D printing, removable dentures*

Резюме:

През последното десетилетие Адитивните технологиите (АТ) се развиха изключително бързо и позволиха изработването на сложни и много прецизни обекти, използвани в различни области, включително денталната медицина. Триизмерното принтиране има потенциала да модернизира и рационализира конвенционалните производствени технологии, използваните материали и работния процес. Неоспоримо предимство е намаляването на клиничното и лабораторното време, контрол на качеството и намаляване влиянието на субективните фактори.

Макар че се наблюдава все по-широко използване на Адитивното производство в областта на денталната медицина, се отчитат и известни недостатъци на използваните материали. Недостатъци според някои автори са по-лошите механични качества на полимерите за триизмерен печат. Макар и клинично приемливи, стойностите им от проведени различни тестове имат тенденцията да са по-ниски, в сравнение с конвенционалните полимери и тези за фрезоване.

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Целта на настоящото изследване е да се направи обзор на литературата по отношение механичните характеристики на смолите за триизмерно принтиране на снемаеми протезни конструкции.

Ключови думи: *CAD/CAM, 3D принтиране, снемаеми протези*

Introduction

The fabrication of removable dentures has been practiced for centuries and is considered the social and physiological minimum that meets all treatment indications -preventive, functional, and aesthetic. Through this, the masticatory process, phonetics, and aesthetics are restored, thereby improving dental health, which significantly impacts social integration and people's quality of life [1, 2, 3].

In the past, dentures were made from various materials, such as animal bones, wood, extracted natural teeth, and later, porcelain, gold, and other metals became viable options. Despite the variety of materials compared to ancient times, there is still no material that remains unchanged over time, enables easy fabrication and good denture retention, and, importantly, satisfies aesthetic and hygiene.

First introduced by the Rohm and Haas Company in 1936, polymethyl methacrylate (PMMA) resin is available in the form of sheets. A year later, in 1937, it was presented in powdered form by Nemours. In the same year, Walter Wright introduced PMMA into dental medicine, and since then, it has become the primary material used for manufacturing dentures through conventional methods. The advantages of PMMA are low density, good aesthetic qualities, low cost, ease of processing, and relatively good physical and mechanical properties, making it preferred for the fabrication of removable dentures, orthodontic appliances, and provisional fixed constructions [4, 5].

In recent years, additive manufacturing has begun to emerge as an alternative to conventional methods for producing removable dentures, with the most used technology being stereolithography [6, 7]. Alhallak et al. [8] highlight the advantages of additive technology over subtractive methods, including reduced material waste, the ability to precisely manufacture more complex objects, and lower costs. According to Russo et al. [9], the production of complete dentures through additive technology is the most cost-effective option compared to conventional methods and milling, with the only drawback being an increased number of clinical stages. Prithviraj et al. [10] even believe that additive technology will replace subtractive technologies (ST) due to their numerous advantages. However, despite the significant potential, several authors believe that further research is needed related to the chemical composition, mechanical, and physical properties of printing materials to prove their clinical effectiveness [11-16].

Additive manufacturing allows the use of various materials, which can primarily be divided into three main groups and their combinations [14, 17, 18]:

– Polymers
– Ceramics
– Metals and metal alloys

The classification of materials used in additive manufacturing is primarily based on the technology [19]. According to Jockusch and Ozcan [13], in the field of dental medicine, the range of materials that can be used is relatively smaller compared to other industries due to the requirements for biocompatibility.

When manufacturing removable dentures using additive manufacturing, various polymers are primarily used [20-24]:

– Polymethyl Methacrylate (PMMA)
– Polyetheretherketone (PEEK)
– Polyamides (PA)
– Polycarbonates (PC)
– Polylactic Acid (PLA)
– Polyetherimide (PEI)
– Polycaprolactone (PCL)
– Acrylonitrile Butadiene Styrene (ABS)

In addition to being available in the appropriate form for each specific additive technology (liquid, solid, or powder), the materials must meet specific mechanical and biological quality requirements. Regarding polymers, many authors highlight that further improvements in their mechanical and biocompatible properties are still expected. These enhancements would allow their use not only as a temporary solution but also as a definitive one [11, 13].

Mechanical properties

Mechanical properties are of paramount importance when choosing a material for any dental treatment, including removable dentures. During chewing the dentures are subjected to combined loads from forces of various actions - compression, tension, bending, and shearing. To withstand these deforming forces and avoid fracturing under their stress, the dentures must be made from a material that meets specific strength standards [25,26]. The most common causes of denture fractures are poor adaptation or unsuitable design, leading to material fatigue and subsequent breakage [27].

Over the years, numerous studies and attempts have been made to improve the mechanical properties of PMMA, but most have not gained clinical application due to complicated technology and higher costs [28, 29].

PMMA used in conventional methods for denture fabrication has been extensively studied, as have the materials used in milling, where the polymer is pre-hardened under high temperature and pressure. Despite the superiority of heat-polymerized resins over those for additive manufacturing in terms of mechanical properties, some authors emphasize the importance of considering the printing orientation and subsequent material processing [30]. These factors have been proven to influence the mechanical properties of polymers, the accuracy of printing, and the printing time. According to Altarazi et al. [31], these can be divided into two groups:

– Uncontrollable Factors: Material composition, light intensity, and wavelength of the light.

– Controllable Factors: Printing orientation, curing temperature, and curing time.

As soon as additive technologies were introduced in dental medicine, comparative studies began examining the properties and qualities of polymers used in different methods for fabricating removable dentures [32-35].

Al-Qarni and Gad [36] analyzed the tensile strength and elastic modulus of heat-polymerized resins and those used for additive manufacturing (NextDent, Formlabs, DentaBASE). Their research confirms previous findings by Gad et al. [37] and Prpić et al. [34]. Three-dimensionally printed samples exhibited lower values for flexural strength. Chhabra et al. [38] also compared flexural and impact strength, finding that heat-polymerized resin demonstrated higher values than polymers used for 3D printing.

According to Lourinho et al. [39], the clinical application of 3D printing polymers should be mainly limited to immediate dentures and custom trays. Considering that this is a relatively new technology with no long-term clinical follow-up data, they recommend further research to gather more scientific evidence about these new materials. Zeidan et al. [35] compared the elastic modulus and hardness of three types of resins – milled, printed, and heat-polymerized. The milled resin exhibited the highest values, while the printed polymers showed significantly lower values. However, despite having the lowest values, Fouda et al. [40] concluded that they are still clinically acceptable.

Lee et al. [41] compared the impact strength of materials for 3D printing, cold-polymerized, and heat-polymerized plastics. They reported the lowest results for cold-polymerized resins, followed by those for 3D printing, and the highest for heat-polymerized. According to Helal et al. [42], three-dimensionally printed dentures have lower values for impact strength compared to milled and flexible polyamides. Fiore et al. [43], who also compared three types of resins – milled, printed, and heat-polymerized – found that the resin used

for 3D printing exhibited the greatest plastic deformation. Al-Dwairi et al. [44] conducted a comparison between four groups of plastics – three for 3D printing (NextDent 3D, Dentona 3D, and ASIGA 3D) and one heat-polymerized (Meliodent). They measured hardness, flexural strength, and elastic modulus. The heat-polymerized resin showed the highest values for hardness and flexural strength, while the Dentona 3D resin recorded the highest value for impact strength. The NextDent 3D resin showed the lowest values for flexural and impact strength but the highest value for elastic modulus. Another study by Freitas et al. [33] reported that the resin used for 3D printing showed the lowest flexural strength values compared to milled and heat-polymerized plastics.

According to Falahchai et al. [45], heat-polymerized resins have higher values for flexural strength, elastic modulus, and hardness, while the polymer used for 3D printing surpasses them in terms of impact strength. Altarazi et al. [10] state that 3D printing polymers demonstrate promising and improved mechanical and physical properties, capable of replacing conventional techniques for denture fabrication.

Gad and Fouda [37] suggest that the mechanical properties of 3D printing polymers can be influenced by the following factors:

– Incorporation of filler or nanofiller into their structure

– Changes in printing orientation, angle, and direction

– Variation in the thickness of the printed layer

– Time and temperature after initial polymerization

Surface roughness

One of the major drawbacks of polymers used for the fabrication of removable dentures is their surface characteristics and their ability to incorporate microorganisms, food residues, and stains into their structure. Polishing is the final step in the laboratory process of a denture and is directly related to surface roughness and microbial adhesion. Surface roughness affects the durability of the denture structure and its biological compatibility. Roughness in the materials used in prosthodontics is undesirable as it creates conditions for tissue irritation [46], bacterial retention [47], and fungal infections [48]. This, in turn, can be an etiological factor in the development of Denture stomatitis [49]. Additionally, surface micro-roughness retains nutrients and stains, which affect the aesthetic qualities of the denture by causing color changes. The more abrasion-resistant a polymer is, the more resistant it is to the effects of abrasive foods during chewing and the mechanical brushing involved in cleaning the dentures [50].

A study by Verran et al. [51] found that well-polished acrylic resin surfaces significantly reduce the risk of bacterial colonization and denture stomatitis.

For 3D-printed dentures, in addition to polishing, some authors suggest an additional coating aimed at reducing surface roughness. According to Kraemer et al. [52], coating a 3D-printed denture with a thin layer of resin followed by polymerization of the layer is an alternative to the conventional polishing protocol. They also report that the combination of polishing and coating does not yield better results in terms of surface qualities compared to polishing alone.

Due to the layer-by-layer fabrication in additive manufacturing, materials undergo numerous studies related to their surface qualities. According to Çakmak et al. [53], the surface qualities of the polymers for 3D printing he studied are clinically acceptable. A change in the color of the denture base was noted after thermocycling and mechanical cleaning, but it remained within acceptable limits. According to Zeidan et al. [35], who compared the surface roughness of three types of plastics using SEM –heat-polymerized, milled, and 3D-printed –the 3D printing resin had the poorest surface qualities, while the resin used for milling exhibited the lowest roughness. This was also confirmed by Helal et al. [42], Alfouzan et al. [50], and Freitas et al. [33].

Srinivasan et al. [54] and Fiore et al. [43] found that the surface roughness of milled and 3D-printed resins is identical, but they differ in their mechanical properties. They also noted that the printing orientation significantly affects the roughness of 3D-printed dentures.

Al-Dwairi et al. [44] believe that the 3D printing polymers they studied have better surface qualities compared to heat-polymerized ones. Gad et al. [37] also reported higher roughness values for conventional heat-polymerized resins.

According to Alshaikh et al. [55], polymers for 3D printing have poorer mechanical and surface qualities compared to heat-polymerized plastics. However, these can be improved by adding zirconia nanoparticles (ZrO2NPs). Al-Bakri et al. [56] suggested that adding fluorinated glass fillers to PMMA could reduce microbial colonization without negatively affecting the polymer's surface qualities. Gad et al. [57] studied the effect of adding silicon dioxide nanoparticles (SNPs) to polymers and found that while mechanical properties improved, there was no observed improvement in surface qualities.

Conclusion

In conclusion, the integration of additive manufacturing into denture fabrication represents a significant advancement in dental prosthetics. 3D-printed dentures offer notable benefits, including enhanced precision, customization, and reduced material waste. However, current limitations exist, particularly concerning mechanical properties and surface characteristics. Studies indicate that while 3D-printed denture base materials are clinically acceptable and exhibit higher impact strength, they often have lower flexural strength, flexural modulus, and surface hardness compared to conventional heat-polymerized acrylic resins. Despite these challenges, the rapid evolution of 3D printing technologies and materials holds promise for overcoming these limitations. Ongoing research and development are essential to enhance the mechanical properties and surface quality of 3D-printed dentures, ensuring they meet the clinical standards required for widespread adoption in dental practice.

References

1. Bonev Boyko, Dental health and quality of life of people above 20 years old in Republic of Bulgaria [dissertation]. Sofia, 2013
2. Dikicier S, Atay A, Korkmaz C. Health-related quality of life in edentulous patients. J Med Life. 2021 Sep-Oct;14(5):683-689.
3. Goiato MC, Filho HG, Dos Santos DM, Barão VA, Júnior AC. Insertion and follow-up of complete dentures: a literature review. Gerodontology. 2011;28(3):197-204.
4. Jagger DC, Harrison A, Jandt KD. The reinforcement of dentures. J Oral Rehabil. 1999;26(3):185-194.
5. Zafar MS. Prosthodontic Applications of Polymethyl Methacrylate (PMMA): An Update. Polymers (Basel). 2020;12(10):2299.
6. Pagac M, Hajnys J, Ma QP, et al. A Review of Vat Photopolymerization Technology: Materials, Applications, Challenges, and Future Trends of 3D Printing. Polymers (Basel). 2021;13(4):598.
7. Van Noort, R. The future of dental devices is digital. Dental Materials, 2012, 28(1), 3–12.
8. Alhallak, K., Hagi-Pavli, E. & Nankali, A. A review on clinical use of CAD/CAM and 3D printed dentures. Br Dent J (2023).
9. Lo Russo L, Di Gioia C, Salamini A, Guida L. Integrating intraoral, perioral, and facial scans into the design of digital dentures. J Prosthet Dent. 2020;123(4):584-588.
10. Prithviraj, D. R., Bhalla, H. K., Vashisht, R., Sounderraj, K., & Prithvi, S. (2014). Revolutionizing restorative dentistry: an overview. Journal of Indian Prosthodontic Society, 14(4), 333–343.
11. Alhallak KR, Nankali A. 3D Printing Technologies for Removable Dentures Manufacturing: A Review of Potentials and Challenges. Eur J Prosthodont Restor Dent. 2022;30(1):14-19. Published 2022 Feb 28.
12. Goodacre BJ, Goodacre CJ. Additive Manufacturing for Complete Denture Fabrication: A Narrative Review. J Prosthodont. 2022;31(S1):47-51.
13. Jockusch, J., & Özcan, M. Additive manufacturing of dental polymers: An overview on processes, materials and applications. Dental materials journal, 2020, 39(3), 345–354.
14. Sulaiman TA. Materials in digital dentistry-A review. J Esthet Restor Dent. 2020;32(2):171-181.
15. Tieh MT, Waddell JN, Choi JJE. Optical and mechanical properties of conventional, milled and 3D-printed denture teeth. J Mech Behav Biomed Mater. 2022;126:105061.

16. Totu, E. E., Cristache, C. M., Isildak, S., Tavukcuoglu, O., Pantazi, A., Enachescu, M., Buga, R., Burlibasa, M., & Totu, T. Structural Investigations on Poly(methyl methacrylate) Various Composites Used for Stereolithographyc Complete Dentures. Materiale Plastice, 2018, 55(4), 616–619.
17. Kruth, J.P. Material incress manufacturing by rapid prototyping techniques. CIRP Annals, 1991, 40, 603-614.
18. Stansbury JW, Idacavage MJ. 3D printing with polymers: Challenges among expanding options and opportunities. Dent Mater. 2016;32(1):54-64.
19. Huang, Y., Leu, M., Mazumder, J., & Donmez, A. Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. Journal of Manufacturing Science and Engineering-Transactions of the Asme, 2015, 137(1).
20. Hata K, Ikeda H, Nagamatsu Y, Masaki C, Hosokawa R, Shimizu H. Development of Dental Poly(methyl methacrylate)-Based Resin for Stereolithography Additive Manufacturing. Polymers (Basel). 2021;13(24):4435.
21. Guo F, Huang S, Liu N, et al. Evaluation of the mechanical properties and fit of 3D-printed polyetheretherketone removable partial dentures. Dent Mater J. 2022;41(6):816-823.
22. Zhang, X., Fan, W., & Liu, T. Fused deposition modeling 3D printing of polyamide-based composites and its applications. Composites Communications, 2020, 21, 100413.
23. Dimitrova, M., Corsalini, M., Kazakova, R., Vlahova, A., Chuchulska, B., Barile, G., Capodiferro, S., & Kazakov, S. Comparison between Conventional PMMA and 3D Printed Resins for Denture Bases: A Narrative Review. Journal of Composites Science, 2022, 6(3), 87.
24. Wu, H., Fahy, W. P., Kim, S. H., Kim, H., Zhao, N., Pilato, L. A., Kafi, A., Bateman, S., & Koo, J. H. Recent developments in polymers/polymer nanocomposites for additive manufacturing. Progress in Materials Science, 2020, 111, 100638.
25. Dimitrov, D., Schreve, K. and de Beer, N. Advances in three dimensional printing – state of the art and future perspectives, Rapid Prototyping Journal 2016, Vol. 12 No. 3, pp. 136-147.
26. Takashima, Y., Kawabata, T., Yamada, S., & Minami, F. Observation of micro-cracks beneath fracture surface during dynamic crack propagation. Theoretical and Applied Fracture Mechanics, 2017, 92, 178–184.
27. Lee, H. H., Lee, C. J., & Asaoka, K. Correlation in the mechanical properties of acrylic denture base resins. Dental materials journal, 2012, 31(1), 157–164.
28. Gad MM, Fouda SM, Al-Harbi FA, Näpänkangas R, Raustia A. PMMA denture base material enhancement: a review of fiber, filler, and nanofiller addition. Int J Nanomedicine. 2017 May 17;12:3801-3812.
29. Gad MM, Rahoma A, Al-Thobity AM. Effect of polymerization technique and glass fiber addition on the surface roughness and hardness of PMMA denture base material. Dent Mater J. 2018;37(5):746-753.
30. Scotti CK, Velo MMAC, Rizzante FAP, Nascimento TRL, Mondelli RFL, Bombonatti JFS. Physical and surface properties of a 3D-printed composite resin for a digital workflow. J Prosthet Dent. 2020;124(5):614.e1-614.e5.
31. Altarazi A, Haider J, Alhotan A, Silikas N, Devlin H. Assessing the physical and mechanical properties of 3D printed acrylic material for denture base application. Dent Mater. 2022;38(12):1841-1854.
32. Arslan M, Murat S, Alp G, Zaimoglu A. Evaluation of flexural strength and surface properties of prepolymerized CAD/CAM PMMA-based polymers used for digital 3D complete dentures. Int J Comput Dent. 2018;21(1):31-40.
33. Freitas RFCP, Duarte S, Feitosa S, et al. Physical, Mechanical, and Anti-Biofilm Formation Properties of CAD-CAM Milled or 3D Printed Denture Base Resins: In Vitro Analysis. J Prosthodont. 2023;32(S1):38-44.
34. Prpić V, Schauperl Z, Ćatić A, Dulčić N, Čimić S. Comparison of Mechanical Properties of 3D-Printed, CAD/CAM, and Conventional Denture Base Materials. J Prosthodont. 2020;29(6):524-528.
35. Zeidan AAE, Abd Elrahim RA, Abd El Hakim AF, Harby NM, Helal MA. Evaluation of Surface Properties and Elastic Modulus of CAD-CAM Milled, 3D Printed, and Compression Moulded Denture Base Resins: An In Vitro Study. J Int Soc Prev Community Dent. 2022;12(6):630-637.
36. Al-Qarni FD, Gad MM. Printing Accuracy and Flexural Properties of Different 3D-Printed Denture Base Resins. Materials (Basel). 2022;15(7):2410.
37. Gad MM, Fouda SM, Abualsaud R, et al. Strength and Surface Properties of a 3D-Printed Denture Base Polymer. J Prosthodont. 2022;31(5):412-418.
38. Chhabra M, Nanditha Kumar M, RaghavendraSwamy 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. Lourinho, C.; Salgado, H.; Correia, A.; Fonseca, P. Mechanical Properties of Polymethyl Methacrylate as Denture Base Material: Heat-Polymerized vs. 3D-Printed—Systematic Review and Meta-Analysis of In Vitro Studies. Biomedicines 2022, 10, 2565.
40. Fouda SM, Gad MM, Abualsaud R, et al. Flexural Properties and Hardness of CAD-CAM Denture Base Materials. J Prosthodont. 2023;32(4):318-324.
41. Lee, J., Belles, D., Gonzalez, M., Kiat-Amnuay, S., Dugarte, A., & Ontiveros, J. Impact strength of 3D printed and conventional heat-cured and cold-cured denture base acrylics. The International journal of prosthodontics, 2022, 35(2), 240–244.

42. Helal MA, Fadl-Alah A, Baraka YM, Gad MM, Emam AM. In-vitro Comparative Evaluation for the Surface Properties and Impact Strength of CAD/CAM Milled, 3D Printed, and Polyamide Denture Base Resins. J Int Soc Prev Community Dent. 2022;12(1):126-131.
43. Fiore AD, Meneghello R, Brun P, et al. Comparison of the flexural and surface properties of milled, 3D-printed, and heat polymerized PMMA resins for denture bases: An in vitro study. J Prosthodont Res. 2022;66(3):502-508.
44. Al-Dwairi ZN, Al Haj Ebrahim AA, Baba NZ. A Comparison of the Surface and Mechanical Properties of 3D Printable Denture-Base Resin Material and Conventional Polymethylmethacrylate (PMMA). J Prosthodont. 2023;32(1):40-48.
45. Falahchai M, Ghavami-Lahiji M, Rasaie V, Amin M, Neshandar Asli H. Comparison of mechanical properties, surface roughness, and color stability of 3D-printed and conventional heat-polymerizing denture base materials. J Prosthet Dent. 2023;130(2):266.e1-266.e8.
46. Bollen, C. M., Lambrechts, P., & Quirynen, M. Comparison of surface roughness of oral hard materials to the threshold surface roughness for bacterial plaque retention: a review of the literature. Dental materials, 1997, 13(4), 258–269.
47. Lucas Costa de Medeiros Dantas, João Paulo da Silva-Neto, Talita Souza Dantas, Lucas Zago Naves, Flávio Domingues das Neves, Adérito Soares da Mota, Bacterial Adhesion and Surface Roughness for Different Clinical Techniques for Acrylic Polymethyl Methacrylate, International Journal of Dentistry, vol. 2016, 6
48. Al-Dulaijan YA, Alsulaimi L, Alotaibi R, et al. Comparative Evaluation of Surface Roughness and Hardness of 3D Printed Resins. Materials (Basel). 2022;15(19):6822.
49. Gad MM, Fouda SM. Current perspectives and the future of Candida albicans-associated denture stomatitis treatment. Dent Med Probl. 2020;57(1):95-102.
50. Alfouzan AF, Tuwaym M, Aldaghri EN, Alojaymi T, Alotiabi HM, Taweel SMA, Al-Otaibi HN, Ali R, Alshehri H, Labban N. Efficacy of Denture Cleansers on Microbial Adherence and Surface Topography of Conventional and CAD/CAM-Processed Denture Base Resins. Polymers. 2023; 15(2):460.
51. Verran J, Jackson S, Coulthwaite L, Scallan A, Loewy Z, Whitehead K. The effect of dentifrice abrasion on denture topography and the subsequent retention of microorganisms on abraded surfaces. J Prosthet Dent. 2014;112(6):1513-1522.
52. Kraemer Fernandez P, Unkovskiy A, Benkendorff V, Klink A, Spintzyk S. Surface Characteristics of Milled and 3D Printed Denture Base Materials Following Polishing and Coating: An In-Vitro Study. Materials (Basel). 2020;13(15):3305.
53. Çakmak G, Molinero-Mourelle P, De Paula MS, et al. Surface Roughness and Color Stability of 3D-Printed Denture Base Materials after Simulated Brushing and Thermocycling. Materials (Basel). 2022;15(18):6441.
54. Srinivasan M, Kalberer N, Fankhauser N, Naharro M, Maniewicz S, Müller F. CAD-CAM complete removable dental prostheses: A double-blind, randomized, crossover clinical trial evaluating milled and 3D-printed dentures. J Dent. 2021;115:103842.
55. Alshaikh AA, Khattar A, Almindil IA, et al. 3D-Printed Nanocomposite Denture-Base Resins: Effect of ZrO2 Nanoparticles on the Mechanical and Surface Properties In Vitro. Nanomaterials (Basel). 2022;12(14):2451.
56. Al-Bakri IA, Harty D, Al-Omari WM, Swain MV, Chrzanowski W, Ellakwa A. Surface characteristics and microbial adherence ability of modified polymethylmethacrylate by fluoridated glass fillers. Aust Dent J. 2014;59(4):482-489.
57. Gad MM, Al-Harbi FA, Akhtar S, Fouda SM. 3D-Printable Denture Base Resin Containing SiO2 Nanoparticles: An In Vitro Analysis of Mechanical and Surface Properties. J Prosthodont. 2022;31(9):784-790.

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