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Research Article

Color Stability and Roughness of Ocular Prosthesis Between Heat-Cured Acrylic and 3D Printed Acrylic After Artificial Weathering

Shahad Fadhil Bunyan,[1] **Shahad Mohammed Shakir**,[2] **and Faraedon Mohidden Mostafa Zardawi**[3]

[1]*Hawija Technical Institute, Northern Technical University, Kirkuk, Iraq*
[2]*Department of Prosthodontics Technology, Institute of Health and Medical Technology, Middle Technical University, Baghdad, Iraq*
[3]*Dean of the Faculty of Dentistry, Qaiwan International University, Sulaimania, Iraq*

Correspondence should be addressed to Shahad Fadhil Bunyan; shahad.alattaby67@ntu.edu.iq

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Eye loss can majorly impact a person's look, functionality, and psychological well-being. This study addresses a critical gap in understanding the durability of ocular prostheses by investigated the surface roughness and color stability of ocular prostheses fabricated using three-dimensional (3D) printing and heat-cured polymethyl methacrylate (PMMA) acrylic resin (QC-20 heat polymerize) after they were subjected to artificial weathering. Two techniques were used to create 100 samples (2 mm thickness and 20 mm diameter) that were fabricated and divided into 50 heat-cured PMMA samples, and 50 samples were made using Next Dent Denture 3D acrylic resin printed with 3D printing technology stereolithography (SLA) 3D printer. All samples were subjected to 300 h of artificial weathering using a weathering chamber. Color changes were tested using a spectrophotometer, while surface roughness micrometers (µm) were measured with a profilometer. Descriptive statistics were used, followed by one-way analysis of variance (ANOVA), independent sample *t*-tests were used, and the significance level was $\alpha = 0.05$. The results demonstrated a significant difference in color stability between the two materials and fabrication methods; the highest mean ΔE observed in heat-cured PMMA samples was 2.67 ($p = 0.003$) and the lowest in 3D-printed samples ΔE of 1.42, respectively. Regarding surface roughness, PMMA demonstrated the highest mean of 0.58 µm, while the lowest mean was with the 3D-printed samples at 0.33 µm ($p = 0.001$), 3D-printed prostheses exhibiting superior resistance to color changes after weathering. 3D-printed prostheses maintained a significantly smoother surface texture compared to heat-cured acrylic ones. These findings concluded that 3D-printed ocular prostheses offer potential advantages in color stability and surface smoothness, potentially enhancing esthetic outcomes, wearability, and patient satisfaction.

Keywords: 3D printing; artificial weathering; color stability; ocular prosthesis; surface roughness

1. Introduction

For those with anophthalmia, an ocular prosthesis, also known as prosthetic eyes, is vital for improving quality of life. Many elements may contribute to anophthalmia, including cancer, severe traumas, and congenital anomalies, thereby, posing major cosmetic and psychological problems [1]. Eye loss may affect social interaction and self-esteem, leading to shame and solitude [2]. By offering a realistic visual depiction of the missing eye, ocular prosthesis seeks to restore some normality, boosting self-confidence, and social integration [3]. Factors like an aging population, growing knowledge of prosthetic choices, and technological developments drive a consistent demand for ocular prostheses [4].

Usually, ocular prostheses are made using heat-cured acrylic polymers. The advantages of acrylic resins include biocompatibility, simplicity of use, and rather low cost [5, 6]. Besides these advantages, some drawbacks also accompany these materials, such as surface roughness and the tendency to change color under different conditions [7, 8]. For color change, practices have been put forward to improve the appreciation of acrylic dissections, showing that these remain in the modified color due to overexposure to light, heat, and humidity [9]. Usually, these changes can more thoroughly alter the outlook of the prosthesis, making this aspect of the prosthetic device less acceptable to the patient, who remains dissatisfied. Another disadvantage associated with the acrylic prosthesis is the problems related to surface roughness, which affects the user's physical appearance and comfort level. Therefore, surface irregularities of bone-implanted prostheses should be avoided as they are likely to irritate or cause discomfort or infection, thus, compromising the functionality of the prosthesis [10].

At present, the most commonly used technology of additive manufacturing, in the part of ocular prosthetics, has been developing in the last few years [11]. This technique has differences in patients' treatment and costs from heat-cured ones by the following: greater flexibility, decreased turnaround time, more complex structures, and more features can be integrated [12]. In the case of prostheses, three-dimensional (3D) printing models of the face of the patient can be done accurately to enable a good-fitting and beautiful-looking prosthesis because the forms will be very comfortable for the patients. Moreover, due to the presence of various kinds of materials such as PLA, ABS, and resins, it becomes possible to meet particular and attractive characteristics of the final object, that is, surface smoothness and color stability [13, 14].

While there is a tendency for 3D printing to custom manufacture and use eye prostheses, the data is very scanty, focusing on the performance features of ocular prostheses and especially color stability and surface roughness over a prolonged period. The lack of appropriately standardized methods for the evaluation of the above measures has only made it possible to obtain the facts in a consistent and trustworthy manner, which concerns only the permanence of 3D-printed prosthetics [15].

Although 3D printing has been effectively used in many prosthetic applications, current research emphasizes that its capacity to preserve color stability and surface integrity over lengthy times is not well-documented [16]. Previous research has shown that polymethyl methacrylate (PMMA) prosthesis discoloration and surface deterioration may result from UV radiation, humidity, and temperature variations. This influences not just patient happiness but also the lifetime functionality of the prosthesis [17].

A review of past studies reveals the gap in the current literature regarding the durability of 3D-printed ocular prostheses under long environmental exposure. Previous research has either focused on short-term assessments or examined heat-cured PMMA prostheses without making direct comparisons to 3D-printed alternatives [18]. This study reports this gap by evaluating and comparing the performance of 3D-printed ocular prostheses and PMMA prostheses after 300 h of artificial weathering, simulating extended wear conditions.

The null hypothesis of this study was that there would be no significant difference in color stability and surface roughness between ocular prostheses fabricated with 3D printing technology and those made with heat-cured PMMA after artificial weathering. This work aims to investigate and compare the surface roughness and color stability of ocular prosthesis samples produced by using heat-cured acrylic PMMA and 3D printing techniques after 300 h of artificial weathering.

Figure 1: Metallic mold used for fabricating the heat-cured acrylic samples.

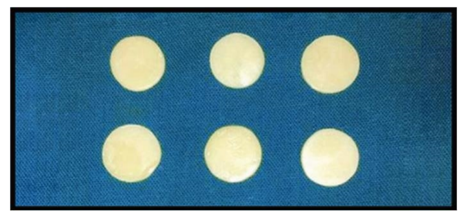

Figure 2: Resin samples after finishing.

2. Methodology

Two sets of ocular prosthesis samples were created, one using advanced 3D printing technology Next Dent Denture 3D resin (LOT: WY032N01, Next Dent, AV, Soesterberg, Netherlands) was selected as the material for the 3D-printed samples, while heat-cured PMMA acrylic resin (QC-20 heat-polymerized, LOT: D64015111, Degu Dent GmbH, Hanau, Germany) was used for heat-cured samples fabrication.

2.1. Heat-Cured Acrylic Prostheses. To generate circular-shaped specimens, a two-part metallic cylindrical mold with a 2 mm thickness and 20 mm diameter guarantees constant dimensions throughout all samples (Figure 1).

Preparation of resin samples using heat-polymerized acrylic with 2 mm thickness and 20 mm diameter. The packing process was conducted inside the metallic mold cavity. Subsequently, a trial closure was performed. The PMMA resin was processed following standard heat-polymerization procedures and cured in a water bath at 100°C for 1 h. After polymerization, the samples were separated, finishing and polishing procedures were performed. Finishing was done with careful grinding using gradually finer grit sandpaper, while polishing was done by means of a high-speed polishing lathe with a fine pumice slurry to accomplish a standardized surface texture (Figure 2). Following the finishing process, the samples were grouped and subjected to artificial weathering for 300 h.

2.2. 3D-Printed Samples. To maintain consistency with the heat-cured acrylic samples, a digital 3D model of the same standard sample (2 mm thickness and 20 mm diameter) was

Table 1: Descriptive statistics for color stability.

Studied groups	N	Minimum	Maximum	Mean	Standard deviation
Heat-cured acrylic	50	2.03	2.98	2.5297	0.23520
Three-dimensional (3D) printed samples	50	1.10	1.86	1.4090	0.19016
Total	100	—	—	—	—

Table 2: Independent sample *t*-test for color stability.

Studied groups	N	Mean	Standard deviation	*t*-test (*p* value)
Heat-cured acrylic	50	2.5297	0.23520	$p = 0.003$
Three-dimensional (3D) printed	50	1.4090	0.19016	HS

created. The design used specialized CAD software (3Shape Dental System, 3Shape, Copenhagen, Denmark) for its accuracy and ability to export files in formats compatible with 3D printers.

An industrial grade stereolithography (SLA) 3D printer (Formlabs Form 3B+, Formlabs, Somerville, MA, USA) was employed for fabrication. SLA is an additive manufacturing technology known for its ability to produce highly accurate and detailed parts with excellent surface quality, making it suitable for creating lifelike prostheses. The printing settings were configured for a 50-µm layer height to enhance surface precision. After printing, the samples were washed in isopropyl alcohol (IPA) using the Form Wash machine (Formlabs, Somerville, MA, USA) and postcured in a Form Cure unit (Form Cure, Formlabs, Somerville, MA, USA) under UV light for 30 min, as per manufacturer instructions. This ensured complete polymerization and mechanical stability. The final samples were also 2 mm thick and 20 mm in diameter. Postcuring guarantees resin complete polymerization, increasing its resistance to environmental damage and durability. After that, every sample underwent accelerated aging for 300 h in a Xenon arc weathering chamber (Q-Lab Corporation, Westlake, Ohio, USA).

2.3. Color Measurement. Color change, a critical factor in the esthetic quality and patient acceptance of ocular prostheses, was quantified using a spectrophotometer (CM-700d, Konica Minolta, Tokyo, Japan). To guarantee uniformity, five measurements on the front surface of every sample were made at equal distances. The readings were standardized against a neutral gray backdrop, therefore, lowering any ambient light influence. The color alterations were calculated using the CIE $L^* a^* b^*$ system, established by the "Commission Internationale del' Eclairage (CIE)." This system allows the value of ΔE (color variation) between two readings to be calculated using the formula:

$$\Delta E = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2],$$

where ΔL is the differences in the respective lightness, Δa is green–blue, and Δb is green–yellow values before and after aging, this formula was referenced from CIE standards, providing a reliable metric for color variation after weathering [19].

2.4. Surface Roughness Measurement. Changes in surface roughness were evaluated using a profilometer tester (TR220, Time High Technology Ltd., China). Five distinct locations were selected on the anterior surface of each prosthesis for roughness measurement and the mean roughness (Ra) was recorded. The instrument was calibrated with a standard roughness reference, and a stylus tip with a 5 µm radius was employed for accuracy. Measurements were performed with a 0.8 mm cutoff and 5.6 mm estimation length, following ISO 4287:1997 standards [20].

2.5. Statistical Analysis. SPSS (IBM SPSS Statistics, version 28, IBM Corp., Armonk, NY, USA), a powerful statistical software package, was used for statistical tests. A Kolmogorov–Smirnov test was used to ensure the normality of sample distribution, a one-way analysis of variance (ANOVA) was conducted to analyze the mean differences, and an independent samples *t*-test was used to compare the color change (ΔE) between the heat-cured acrylic and 3D printed acrylic and to compare the surface roughness between the studied groups after artificial weathering for 300 h. Statistical significance was set at a *p*-value of less than 0.05 for all analyses.

3. Results

The color stability samples, represented by the color change (ΔE^*) value, were evaluated after 300 h of artificial weathering using a spectrophotometer. Table 1 show the mean ΔE^* values after weathering for heat-cured acrylic and 3D printed samples. Table 2 show the independent sample *t*-test values after weathering for heat-cured acrylic and 3D printed samples. Table 3 show a descriptive statistic of the surface roughness values after 300 h of the artificial weathering for the studied groups. Table 4 shows the independent sample *t*-test of the surface roughness values after artificial weathering for heat-cured acrylic and 3D-printed samples.

4. Discussion

The purpose of the present study was to evaluate the color stability and the surface roughness of ocular prosthetics made

Table 3: Descriptive statistics for surface roughness.

Studied groups	*N*	Minimum	Maximum	Mean	Standard deviation
Heat-cured acrylic	50	0.48	0.59	0.5497	0.21529
Three-dimensional (3D) printed samples	50	0.32	0.35	0.3390	0.18013
Total	100	—	—	—	—

Table 4: Independent sample *t*-test for surface roughness between heat-cured acrylic and three-dimensional (3D)-printed acrylic.

Studied groups	*N*	Mean	Standard deviation	*t*-test (*p* value)
Heat-cured acrylic	50	0.5497	0.21529	$p = 0.001$ HS
3D printed	50	0.3390	0.18013	

with heat-cured PMMA material and modern 3D printing technology after subjecting the materials to 300 h of simulated weathering. Data showed a noticeable change in the color stability of the two materials compared to each other. With a mean color difference ($\Delta E = 1.42$), the 3D-printed samples showed a much smaller mean than the PMMA samples ($\Delta E = 2.67$). Clinical standards indicate that in dental and prosthetic applications, a ΔE value less than 3 units is regarded as acceptable so, both materials stayed within clinically reasonable bounds. However, the lower ΔE for 3D-printed samples suggests their increased resilience to color changes, most likely because of the UV-stabilizing chemicals included in the biocompatible resin used in 3D printing. Samples from 3D printing yielded better color stability than those from heat-cured printing. According to Ceballos et al. [12] and Kumar, Sharma, and Garg [14], 3D-printed ocular prostheses show high color stability.

The color change of polymer prostheses manufactured by 3D printing is attributed to several variables. The most essential consideration is the use of special biocompatible dental and medical-grade resins as well as UV-stabilizing agents that are commonly present in these resins and are responsible for preventing the action of UV rays, which causes discoloration [14, 21]. Also, 3D printing technology allows precise adjustment of certain printing parameters, including layer height and amount of infill, which improves overall structure uniformity as well. Rezaie et al. [22] observed that it minimizes the extent of changes in color absorption and reflection, making color reproduction better.

Measurements of surface roughness revealed that the 3D-printed samples maintained a smoother surface (Ra = 0.33 μm) than the PMMA samples (Ra = 0.58 μm). Surface roughness less than 0.5 μm is ideal clinically to reduce bacterial adherence and guarantee patient comfort. Although both groups showed more roughness with age, the 3D-printed prosthesis stayed below clinically acceptable limits, therefore, underlining its potential to provide superior wearability and lower irritation concerns than PMMA prosthesis [2].

Comparable investigations have shown the limits of PMMA in preserving color stability and surface integrity under environmental stress. Consistent with our results for conventional samples, Odell, D'Souza, and Varghese [7] noted significant discoloration in PMMA prosthesis following UV radiation and dampness. On the other hand, Scotti et al. [23] examined 3D-printed prosthesis and have been proven greater performance as updated resin technology. Jang et al. [24] approved printed layers' homogeneity have been guaranteed the exact control of surface texture made possible by 3D printing, hence, lowering the possibility of roughness-related problems that our findings support.

However, both materials showed an increase in surface roughness due to artificial weathering; the surfaces of the 3D prostheses were less rough than their standard equivalents made of acrylic material. Materials used for 3D printing are less prone to surface degradation due to exposure to relevant elements than heat-cured materials. The surface of the final product produced utilizes the layering technology that accompanies 3D printing with limited need for manual polishing compared to the heat-cured methods of fabricating prostheses [9]. A fine surface texture contributes to better esthetic appeal and more comfort to the patient by preventing irritation or friction against the soft tissues in the eye socket [25].

The implications of these findings are likely significant for the clinical management of ocular prostheses. The patients will gain from the wide range of color fastness and finer texture finishes by patient prostheses using 3D printing methods. Improvement of the surface smoothness may enhance comfort and biocompatibility, while improving esthetics may enhance the natural and realistic appearance enclosing the device. Furthermore, the disposable nature of 3D printing allows one to make exact changes to meet the needs of every patient, addressing the problems of the fit, esthetic outcome, and patient satisfaction [26].

Clinically speaking, the results of this investigation are really important. 3D-printed prosthesis' better color stability guarantees that patients gain from longer-lasting cosmetic results, therefore, lowering the need for regular replacements. Moreover, in sensitive ocular settings especially, better surface textures help to improve patient comfort and lower chances of irritation and infection. 3D-printed prosthesis capacity to meet or beyond clinical requirements for both color stability ($\Delta E < 2.7$) and surface roughness (Ra < 0.5 μm) highlights its possible preferred option in ocular prosthetic production [27].

Based on these results, it seems that 3D printing has a great deal of potential to advance the area of ocular prostheses. It can provide better esthetic outcomes, enhanced patient satisfaction, and improved functioning. People who suffer from anophthalmia will likely find that technology plays an increasingly important role in improving their quality of life as it continues to improve.

Even though these findings are encouraging, the research does have a few limitations. Because this was in vitro research, the artificial weathering conditions, which were supposed to replicate real-world exposure, could not adequately capture the intricate interactions of environmental elements and biological fluids in cellular environments. First of all, the in vitro character of the research could not completely reproduce real-world environmental circumstances and interactions with biological fluids, therefore, affecting the generalizability of the results. Furthermore, even if the 50 samples per group provided strong comparison data larger sample numbers might confirm these results even more. Another restriction is the technique artificial weathering, which aims to replicate extended exposure, but may not cover all possible real-world stresses like changing temperatures and humidity levels over several seasons.

Future research should prioritize in vivo investigations to evaluate the long-term efficacy of 3D-printed ocular prostheses in clinical settings that represent the real world. More investigation into the various resins, printing conditions, and post-processing processes available for 3D printing would be very beneficial when it comes to improving this technology for ocular prostheses.

5. Conclusion

After 300 h of artificial weathering, the research finds that 3D-printed ocular prosthesis samples show better color stability and smoother surface textures than standard heat-cured PMMA resin samples. These results highlight the possibility of 3D printing to improve prosthetic results and underline the importance of ongoing research and development in this field to raise the quality of life for those needing ocular prostheses.

Data Availability Statement

The research data used to support the findings of current study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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References

[1] N. M. Al-Khateeb, H. Al-Akhras, and S. Al-Jadaan, "Anophthalmia: A Review," *Journal of the Saudi Board of Ophthalmology* 28, no. 1 (2014): 1–8.

[2] T. Kondo and Y. Suenaga, "Social Impacts of Ocular Prosthesis Wear in Japan," *Ophthalmic Plastic and Reconstructive Surgery* 34, no. 3 (2018): 197–202.

[3] S. Gupta and S. Singh, "Ocular Prosthesis: A Review," *Journal of the Indian Prosthodontic Society* 14, no. 2 (2014): 111–118.

[4] J. Sánchez-Sánchez, A. García-Pérez, J. López-García, and J. González-Martín, "Ocular Prostheses: A Review," *International Journal of Ophthalmology* 7, no. 2 (2014): 103–108.

[5] A. Gomes, F. Pereira, A. Costa, and P. Pereira, "Ocular Prosthesis: A Review of Materials and Techniques," *Journal of the Brazilian Society of Otorhinolaryngology* 82, no. 3 (2016): 143–150.

[6] M. M. Hatamleh, "Polymers in Maxillofacial Prosthodontics," in *Polymeric Materials for Biomedical Implants*, no. pp, (Woodhead Publishing, 2024): 295–318.

[7] I. Odell, R. D'Souza, and M. Varghese, "Color Stability of Acrylic Resin Ocular Prostheses: A Comparative Study," *Journal of the Indian Prosthodontic Society* 7, no. 3 (2007): 155–159.

[8] A. Schmitt, W. Koch, and J. Zöller, "Color Stability of Ocular Prostheses: A Clinical Study," *Clinical Oral Implants Research* 15, no. 2 (2004): 185–191.

[9] R. Batra, S. Singh, and M. Jain, "A Review on Ocular Prosthesis: Materials, Fabrication and Clinical Considerations," *Journal of the Indian Prosthodontic Society* 14, no. 3 (2014): 195–204.

[10] A. Das, P. Awasthi, V. Jain, and S. S. Banerjee, "3D Printing of Maxillofacial Prosthesis Materials: Challenges and Opportunities," *Bioprinting* 32 (2023): e00282.

[11] A. Dasgupta and P. Dutta, "Printability of Elastomer as a 3D Printing Material for Additive Manufacturing," *Journal of Rubber Research* 27, no. 1 (2024): 137–157.

[12] A. Ceballos, A. Castillo, D. Rodríguez, G. Ruiz, E. Díaz, and M. García, "3D Printing in Ocular Prosthetics: A Review of the Current State and Future Directions," *International Journal of Ophthalmology* 12, no. 3 (2019): 403–410.

[13] D. Rokaya, J. Kritsana, P. Amornvit, et al., "Magnification of Iris Through the Clear Acrylic Resin in the Ocular Prosthesis," *Journal of Functional Biomaterials* 13, no. 1 (2022): 29.

[14] M. Kumar, M. Sharma, and P. Garg, "3D Printing in Ocular Prosthetics: A Review," *Journal of Advanced Research in Dental Sciences* 11, no. 1 (2020): 1–10.

[15] T. Khan, M. Ali, Z. Riaz, et al., "Recent Developments in Improving the Fracture Toughness of 3D-Printed Fiber-Reinforced Polymer Composites," *Composites Part B: Engineering* 283 (2024): 111622.

[16] B. Chuchulska, M. Dimitrova, A. Vlahova, I. Hristov, Z. Tomova, and R. Kazakova, "Comparative Analysis of the Mechanical Properties and Biocompatibility Between CAD/CAM and Heat-Cured Polymers Applied in Prosthetic Dentistry," *Polymers* 16, no. 7 (2024): 877.

[17] M. Whalen, M. Akula, S. M. McNamee, M. M. DeAngelis, and N. B. Haider, "Seeing the Future: A Review of Ocular Therapy," *Bioengineering* 11, no. 2 (2024): 179.

[18] E. Bunker, A. Kazlauciunas, T. Zoltie, et al., "Colour Stability During Production of Printed Ocular Prostheses," *Coloration Technology* 139, no. 5 (2023): 596–609.

[19] J. Kumari, A. Verma, D. Shankar, U. Chatterjee, and M. Ranjan, "Ocular Prosthesis- Fabrication and Microbial Assessment," *IOSR Journal of Dental and Medical Sciences (IOSR-JDMS)* 19, no. 7 (2020): 40–45.

[20] M. Z. I. Nizami, "Materials in Maxillofacial Prosthesis," in *Prosthetic Rehabilitation of Head and Neck Cancer Patients*, no. pp, (Elsevier, 2024): 268.e1–268.e28.

[21] N. P. Sanchez, *Staining and Aging Dependent Changes on Color and Translucency of 3D-Printed Resin-Modified Ceramics*, (Master's thesis, The University of Texas School of Dentistry at Houston, 2023).

[22] H. R. Rezaie, H. B. Rizi, M. M. R. Khamseh, and A. Öchsner, *A Review of Dental Materials* (Springer International Publishing, 2020).

[23] C. K. Scotti, M. M. D. A. C. Velo, F. A. P. Rizzante, T. R. de Lima Nascimento, R. F. L. Mondelli, and J. F. S. Bombonatti, "Physical and Surface Properties of a 3D-Printed Composite Resin for a Digital Workflow," *The Journal of Prosthetic Dentistry* 124, no. 5 (2020): 614.e1–614.e5.

[24] G. Jang, S.-K. Kim, S.-J. Heo, and J.-Y. Koak, "Fit Analysis of Stereolithography-Manufactured Three-Unit Resin Prosthesis With Different 3D-Printing Build Orientations and Layer Thicknesses," *The Journal of Prosthetic Dentistry* 131, no. 2 (2024): 301–312.

[25] A. A. Slijepcevic, A. Afshari, A. E. Vitale, S. M. Couch, L. M. Jeanpierre, and J. J. Chi, "A Contemporary Review of the Role of Facial Prostheses in Complex Facial Reconstruction Plastic and Reconstructive," *Plastic and Reconstructive Surgery* 151, no. 2 (2023): 288e–298e.

[26] K. K. Shah, V. Rajaraman, D. N. Veeraiyan, and S. Maiti, "A Systematic Review on Maxillofacial Prosthesis Concerning Their Color Stability," *Journal of Long-Term Effects of Medical Implants* 34, no. 3 (2024): 43–53.

[27] S. V. Apresyan, A. G. Stepanov, A. A. Vikhrov, M. S. Myasoedov, A. I. Prostyakova, and A. N. Generalova, "Polymers in 3D Printing of External Maxillofacial Prostheses and Their Retention Systems," *International Journal of Pharmaceutics* 657 (2024): 124181.