Journal of
Composites Science

MDPI

Review

Comparison between Conventional PMMA and 3D Printed Resins for Denture Bases: A Narrative Review

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Abstract: The aim of the current paper is to review the available literature reporting on comparative studies of heat-cured resins and three-dimensionally printed biomaterials for denture bases in terms of their composition, properties, fabrication techniques and clinical performance. The methodology included applying a search strategy, defining inclusion and exclusion criteria, selecting studies to summarize the results. Searches of PubMed, Scopus, and Embase databases were performed independently by three reviewers to gather literature published between 2018 and 2021. A total of 135 titles were obtained from the electronic databases, and the application of exclusion criteria resulted in the identification of 42 articles pertaining to conventional and 3D printed technology for removable dentures. The main disadvantages of the heat-cured resins for removable dentures are that they require lots of special equipment, skilled personnel and time. Emerging technologies, such as 3D printed dentures, have the potential to alleviate these problems allowing for faster patient rehabilitation. With the development of digital dentistry, it is becoming increasingly necessary to use 3D printed resin materials for the manufacturing of removable dentures. However, further research is required on the existing and developing materials to allow for advancement and increase its application in removable prosthodontics.

Keywords: 3D printed dentures; CAD/CAM dentures; digital dentures; acrylic resins; PMMA dentures

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Citation: 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. *J. Compos. Sci.* **2022**, *6*, 87. https://doi.org/10.3390/jcs6030087

Academic Editor: Francesco Tornabene

Received: 23 February 2022
Accepted: 7 March 2022
Published: 10 March 2022

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1. Introduction

Several different resins are used in prosthetic dental medicine, according to their composition and method of processing for the purposes of removable prosthetics. All types of dental resins have a satisfactory aesthetic and functional effect. They are easy to process and provide relatively good functional stability. Despite the number of advantages, they also have some characteristic disadvantages—they undergo significant volumetric and optical changes in the conditions of the oral cavity after a certain period of time, which are expressed in their shrinkage and coloring [1]. The absorption of water, the intake of coloring foods and beverages, adversely affect the removable prosthetic restoration. This is a cause of discomfort during masticatory function, deterioration of aesthetic qualities and over time—the patient's dissatisfaction [2].

When other methods of treatment are not possible due to various contraindications, these types of materials for removable prosthetic restorations will continue to be preferred by the majority of patients and dental professionals. Other main reasons are relatively low cost, high social significance and non-invasive treatment approach [3]. Complete edentulism is a serious problem for patients and prosthetic treatment with artificial substitutes, such as removable dentures is essential for the continuation of a healthy lifestyle.

Dental acrylic resins are macromolecular compounds of natural or synthetic origin that are composed of multiple repeating structural units (monomer units), forming macromolecules (polymers). Monomers, in turn, are single simple molecules with double and triple bonds or rings, by means of which they are linked in polymer chains [4]. Macromolecules are synthesized by a process called polymerization, which is divided into two types—condensation and addition.

Digital dentistry has revolutionized the practice of dentistry in many areas since its introduction in the 1980s [5,6]. The first attempt was to develop a computer-aided design/computer-aided manufacturing (CAD/CAM) system for making complete removable prostheses. In the last few years, CAD/CAM technology has been used to manufacture various types of prosthetic restorations, including implants and full dentures [7].

The purpose of this paper is to review the available literature on the juxtaposition of the heat-cured resins and the three-dimensionally printed biomaterials for denture bases, in terms of their composition, properties, fabrication techniques and clinical performance.

2. Methods

The methodology included applying a search strategy, defining inclusion and exclusion criteria, and retrieving studies; selecting studies; extracting relevant data to summarize the results. Searches of PubMed, Scopus, and Embase databases were performed to gather literature published between 2018 and 2021. The search terms used were "3D printed dentures" [Mesh] OR "CAD/CAM dentures" OR "Digital dentures" OR "Acrylic resins" AND "PMMA dentures" [Mesh].

The inclusion criteria for selection were articles written in English published between 2018 and 2021 on conventional heat-cured resins and 3D printed materials for removable dentures, clinical studies and in vitro studies, articles that reported different fabrication techniques, clinical performance or quality assessment with conventional heat-cured and 3D printed dentures. Exclusion criteria included articles that failed to involve items described in the inclusion criteria or described repetitive data already included.

The search strategy for this review involved three stages: reviewing titles, abstracts, and final selection of articles for full text analysis. Articles selected from databases were sorted independently by three reviewers, and any differences in selection were discussed until a consensus was reached. Upon the reviewers' agreement, articles that did not meet the predetermined inclusion criteria were excluded. Abstracts of the articles selected at the second stage were independently evaluated by the same reviewers, and articles selected for the final analysis were obtained in full text. At the third and final stage, the full text of the obtained articles was analyzed.

3. Results

3.1. General Characteristics of Conventional Heat-Cured PMMA Resins for Denture Bases

Composition of Polymethyl Methacrylate Resins

Heat-cured acrylics are the most preferred materials for manufacturing denture bases [8]. Polymethyl methacrylate (PMMA) is a transparent resin with water-like transparency for light in the visible and ultraviolet range up to a wavelength of 250 nm. The plastic has a Knoop hardness of 18 to 20 KHN. The tensile strength is approximately 60 MPa, the density—1.19 g/cm^3, and the modulus of elasticity—approximately 2.4 GPa. This type of material is also extremely stable: it does not discolor in ultraviolet light and exhibits remarkable aging properties [9]. It is chemically stable when heated below 125 °C, it softens at 125 °C and can be molded as a thermoplastic material [10]. However, above 125 °C PMMA begins to depolymerize to form a methyl methacrylate monomer (MMA), and at about 450 °C 90% of the polymer undergoes the process of depolymerization. PMMA has a high molecular weight and degrades to a lower molecular weight polymer at the same time as it is converted to monomers. In general, PMMA is easy to work with, is strong, wear-resistant, can be pigmented to a realistic appearance, can be easily sterilized, and is biodegradable and very durable [11]. Like all acrylic resins, PMMA tends to absorb water through imbibition. Its non-crystalline structure has a high internal energy. Thus, molecular diffusion can occur in the resin, as less activation energy is required. In addition, the carboxyl group, although esterified, can form a hydrogen bridge with water to a limited extent. Because PMMA is a linear polymer, it is soluble in a few organic solvents that can be found in the dental laboratory, such as chloroform and acetone.

3.1.1. Properties

Dental acrylic resins intended for the fabrication of denture bases must possess a number of qualities, such as mechanical strength, chemical inertness, high bioavailability, as well as good aesthetic characteristics [12]. Many modifications have been made to improve the physical properties, durability, technological modes of operation and reduce the processing time of PMMA resin materials.

3.1.2. Aesthetics

PMMA resins have high aesthetic qualities due to their transparency and the ability to be easily colored to mimic the tissues that are replaced by them. The material must show sufficient transparency to match the appearance of the tissues it replaces. The plastic must be colorless and be able to be colored or pigmented, and there must be no change in the color or appearance of the material after its manufacturing [13].

3.1.3. Tensile and Compressive Strength

Distinctive of PMMA plastics for the production of partial and complete prostheses is that they have satisfactory tensile strength (48–62 MPa) and compressive strength [14,15] (75 MPa). Strength properties are determined in accordance with the following factors:

- Composition of the dental resin
- Degree of polymerization
- Technological protocol
- Water sorption
- Subsequent storage and use of the dentures

Ideally, the acrylic resins should have high impact strength to prevent the risk of breakage when the prosthesis is dropped [16]. Unmodified acrylic plastics are more brittle, with the addition of plasticizers aimed at improving their strength properties.

3.1.4. Hardness and Durability

Acrylic resins do not possess high hardness, they can be easily scratched or deformed. Polyvinyl materials have the highest wear resistance, compared to heat-curing and self-curing [17].

3.1.5. Biocompatibility

Biocompatibility indicates the compatibility of artificial materials in direct contact with the human body, and the stability of the materials in the biological environment. There are a series of regulated tests that a material must pass to be certified for use [18]. These include the Pharmacopoeia IV Biological Reactivity Test (USP Class IV) and the International Organization for Standardization (ISO 10993) Biological Assessment of Medical Devices. The main purpose of biocompatibility tests is to quantify the acute and chronic toxicity of a material and to identify any potential adverse effects during conditions of use.

3.1.6. Volumetric and Linear Changes

This type of material must also be resistant to volumetric changes under all conditions and not change its dimensions over time. The volumetric stability of acrylic plastics is good if a proper polymerization protocol is followed [19]. In the polymerization of the liquid methyl methacrylate monomer, the volume of the solid polymer of the same type will be 21% less than the original (21% shrinkage), which is practically unacceptable, as there will be a large discrepancy in the volume of the model and the actual size of the future prosthesis. For this reason, a mixture of polymer and monomer is used in practice, in which the polymerization shrinkage is significantly lower [20]. Acrylic resins undergo larger volume changes during the polymerization process than injection molded ones, and they were tested for 28 days. Volume shrinkage in intermolar width and occlusion height has been reported in both types of plastics, but for injectable plastics, this change is less significant than in conventional resins. The intermolar width represents the distance between the vestibular surfaces of the lower first molars, measured at the level of the occlusal plane, and within normal ranges between 54–55 mm [21]. Volumetric changes are expressed in polymerization shrinkage, which is compensated by the high sorption of water from this type of material. This can seriously affect its stability during chewing function. Deformation may occur during the polymerization process or at other times thereafter. The reason is the release of internal stresses during the technological process, which can be caused by the shrinkage of the material or by the sudden and rapid cooling during the packaging process [22]. These deformations can also be induced by polishing and raising the temperature locally, as well as by a sharp rise in the temperature environment of the denture. It has been found that to reduce the polymerization shrinkage, the monomer can be mixed with excipients. In this way, the number of reacting monomer molecules per unit volume decreases, respectively, the polymerization shrinkage. Another method suggests that the polymer-monomer mixture be pressed and polymerized under pressure, thereby reducing the amount of unpolymerized monomer. In a well-polymerized acrylic plastic denture, the unpolymerized monomer content is less than 1%, which is eliminated after 17 h in water [23]. According to ISO specification (ISO 1567: 1999; ISO 20795—1: 2013), the limit values for unpolymerized monomers are 4.5% for self-curing and 2.2%—for heat-curing plastics. The average values of polymerization shrinkage in heat-cured acrylics are:

- Volumetric shrinkage—8%
- Linear shrinkage—0.53%

3.1.7. Optical Properties

PMMA resins are characterized by good optical properties—they transmit ultraviolet and visible light with a wavelength of up to 250 μm. According to the three-dimensional characteristics of colors, published by Alfred Munsell in 1905, the color space resembles a sphere in which each color occupies a specific place [24]. Each color has three dimensions—hue, saturation and brightness. When color is determined using the Munsell system, brightness is determined first, followed by saturation. Finally, the color tone (hue) is determined. This system is used in the visual determination of color [25].

3.1.8. Adhesion

The adhesion of acrylics to metal and porcelain is not satisfactory. The bond between metal and porcelain can be improved by treating the surfaces of the “porcelain teeth” with silane “coupling” agents. Silane “coupling” agents do not affect adhesion between PMMA and metal, and mechanical retention is required. Adhesion between the acrylic denture base and plastic artificial teeth is good—it is carried out by means of a chemical reaction between the individual components [26].

3.1.9. Water Sorption and Solubility

Acrylic resins tend to absorb water and expand slowly over time. This corresponding extension is expressed in three dimensions and is of great importance. The expansion of the acrylic resin is proportional to the time of immersion in the water until equilibrium is reached, according to ISO standard (ISO 20795-1: 2013) [27]. However, the mean equilibrium water content (saturated water content) must not exceed 32 $\mu g/mm^3$. The absorption of water can also release the inherent stresses that have arisen during the processing of acrylic plastic, mainly heat-curing, and a change in the shape of the prosthesis is possible. Constant wetting and drying of the removable plastic prosthesis should be avoided because it causes aging of the material and can cause deformation of the prosthetic structure. Water solubility is also an important property because it represents the mass of soluble materials from the polymers [28]. Both water sorption and solubility would lead to a variety of chemical and physical processes that may result in deleterious effects on the structure and function of dental polymers [29]. Denture base acrylic resins have low solubility, and the little that occurs is a result of the leaching out of traces of unreacted monomer and water-soluble additives into the oral fluids. However, these monomers sometimes produce a soft tissue reaction. It is important to determine the unpolymerized monomer content and solubility of the tested materials as these properties influence the allergy susceptibility of these materials [30].

3.1.10. Polymerization Protocol

The classical method involves mixing a polymer with a monomer on the bulk sample in a ceramic or glass vessel and coating the vessel with a glass plate to avoid evaporation of the highly volatile monomer [31,32]. The reaction is exothermic, takes place at room temperature and lasts for several minutes, during which the consistency passes through the following phases

- Sandy phase—the structure is granular, wet sand-like, does not stick, and clearly defined spheres are distinguished.
- Filamentous phase—fine threads are formed like a cobweb from the dissolved polymer, and it sticks to the spatula. Manipulation of the resin is still not recommended at this stage.
- Plastic phase—the polymer dissolved in the monomer turns into a plastic state.

This stage is suitable for handling plastic, so some authors define it as "a working phase". The mixture resembles dough and can be kneaded, allowing details to be formed in the cavity formed after packaging.

- Elastic phase—if not treated, the polymer-monomer mixture reaches an elastic state, no longer suitable for work. The consistency in this phase is non-flowing and difficult to press [33].

The ratio of polymer to monomer should be 3:1 by volume, or 2:1 by weight. After measuring, the monomer is poured into a clean porcelain container, the powder is added slowly in portions until each particle is well wetted by the monomer. It is then stirred and left covered while the polymerization takes place. If there are errors in dosing the monomer and a larger amount of it is used, the reaction will be accelerated, and the polymerization shrinkage will be more significant [34]. It is also possible that the porosity of the resin is increased. If a smaller amount of liquid is used, defects in the plastic would appear, the structure would be granular due to the lack of sufficient monomer to wet the polymer particles. The dough structure would be firmer, and it would be difficult to manipulate. If the mixture is dosed and mixed properly, the working time is about 5 min. It also depends on the temperature and humidity of the environment, and when they increase, it shortens. Acrylic heat-curing plastics are available in the form of powder and liquid, gel, or dough. The powder can be transparent or colored in pink, or tooth color, thus mimicking the color of the soft tissues in the oral cavity. The liquid is provided in tightly closed dark bottles to prevent the spontaneous polymerization of the monomer [35].

3.2. General Characteristics of 3D Printed Resins for Denture Bases and 3D Printing Devices

3.2.1. 3D Printing Denture Base Materials

Three-dimensional printing is a modern technology for making three-dimensional physical/analog construction, pre-created with a program for computer modeling digital prototypes. It is essentially a process of layer-by-layer addition of material, as a result of which is formed the printed object. Of great interest for 3D printing in dentistry are the technologies defined as Fused Filament Fabrication—production by threading (FFF) and Fused Deposition Modeling by layering (FDM) [36].

3.2.2. Composition and Properties

Three-dimensional (3D) printing materials available nowadays include resins, composites, metals, ceramics, biomaterials and food materials. Acrylonitrile butadiene styrene (ABS), polycarbonates (PC), polylactic acid (PLA) and polyetherimide (PEI) are the most popular resins for 3D printing. Polycaprolactone (PCL) is a semi-crystalline thermoplastic resin with a degree of crystallinity of about 45%.

The mechanical properties of PCLs are similar to those of medium density polyolefins [37,38]. Their elongation at break and elasticity modulus is of average value, and their softness and tensile strength are similar to that of nylon. The appearance of PCL is milky white in color, with a medium density, similar to polyethylene, and has a waxy texture. The PCL has a glass transition temperature of about 60 °C, a melting point of about 63 °C, and a dissolution temperature of about 250 °C. Because PCL has a low melting point and softens at about 40 °C, its application is limited [39]. According to the manufacturer (Formlabs Dental, Somerville, MA, USA), denture base resin experiences less shrinkage during polymerization than conventionally processed PMMA. Headquartered in Somerville, Massachusetts with offices in Germany, France, Japan, China, Singapore, Hungary, and North Carolina, Formlabs is the professional 3D printer of choice for engineers, designers, manufacturers, dental and medical professionals, and decision makers around the globe [40–42]; 3D printed resins for denture bases have inferior values for flexural strength, elastic modulus and fracture toughness. This can be explained by the combination of the reactivity of monomers of 3D-printing resin and the curing condition, which resulted in a lower degree of double-bond conversion when compared to conventional acrylic resins [40]. Another cause for the lower mechanical properties could be the weak interlayer bonding between successive printed layers. However, the 3D-printed denture base material fulfilled the ISO requirements for flexural strength (65 MPa) Therefore, 3D-printed materials can be considered as an option when fabricating denture bases [41].

NextDent® Denture 3D+ (NextDent B.V., Soesterberg, The Netherlands) is a biocompatible material class IIA, suitable for printing all types of denture bases. This material has excellent mechanical properties and is comparable to conventional acrylic plastics for removable dentures. It is available in several colors: dark pink, light pink, opaque pink, red-pink, translucent pink and a new shade of Classic Pink [40]. From 2020, it has a certificate for its application within the European Union territory [42]. The material hardens when exposed to light within the 315–400 and 400–550 nm range. The recommended post-processing time for an optimal cure is 10 min.

Dental resins for removable dentures from Formlabs, USA for prosthetic printing are available in two colors: pink—for prosthetic bases and white—for dentition [41]. Unpolymerized monomers may irritate the oral soft tissues, so it is desirable for the denture material to achieve a high level of polymerization (degree of conversion) to reduce the amount of unreacted monomer that may leach out. The greater the degree of conversion, the better the biocompatibility. Because 3D printed denture base is relatively new, little publicly available information on the cytotoxicity of the product is available. Limited information exists regarding MTT testing of as printed and post-cured specimens using Formlabs Clear resin and Dental SG resin for SLA printers.

3.2.3. 3D Printing Devices in Dentistry

The 3D printing process itself is performed using 3D printing devices. In Europe for dental purposes, one of the most widely used are the following devices:

The NextDent® 5100 3D printer (3D Systems, Valencia, SC, USA), combined with NextDent's extensive portfolio of dental materials, meets many indications, leading to unmatched speed, high accuracy, performance and overall high quality of the product.

NextDent® 5100 provides high-speed 3D printing for the production of dental appliances and prosthetic restorations. It is certified for free usage in the European Union [43].

The Formlabs® 3B 3D printer (Formlabs, Somerville, MA, USA) has advanced low force stereolithography (LFS) technology and a flexible resin tank [42]. A custom designed system of lenses and mirrors, i.e., light processing unit (LPU), obtains consistent and flawless results. The ability to print two to three times more products at once, compared to small platforms for building digital light processing (DLP) printers, is a great advantage. Other benefits are the options to design the model in a standard CAD program and import STL (stereolithography, standard triangle language, standard tessellation language) or OBJ (object) files in PreForm—the prepress program, thus can be sent directly to the Formlabs Form 3B 3D printer [44].

In general, 3D printers cannot print different types of light-curing acrylics with different colors and physical properties at the same time. Therefore, a special method has been developed for printing the artificial tooth and the base of the denture separately, subsequently assembling them afterward using photopolymer acrylics [45]. Methods for 3D modeling of printers include selective laser sintering (SLS) and selective laser melting (SLM) in powder bed fusion, fused deposition modeling (FDM) by extruding thermoplastics, stereolithography (SLA) and digital light processing (DLP) [46]. They are approximately classified into seven types according to the ISO standard (ISO 17296-2: 2015 AM Part 2: Overview of the categories of processes and raw materials). SLA is the preferred choice to produce prostheses by using a 3D printer [47,48].

3.2.4. Scanning Devices

Using intraoral scanners, it is possible to scan impressions within a patient's existing complete removable prosthesis. This scanning strategy delivers increased patient acceptance and satisfaction, reduces postoperative adjustments, and ultimately improves the patient experience as it requires fewer visits to the clinic.

The 3Shape TRIOS 4 scanner is a modern intraoral scanner and provides fast and accurate natural color scanning with a compact and ergonomic design. It allows real-time color scanning—high-precision prints with accurate reproduction of the texture and color of natural teeth. It can also be used for color determination by colorimetric analysis—it determines and preserves the color of the tooth (according to Vita) while scanning. It works with HD photos—suitable for marking more important details, as well as for accurately defining the boundaries of the preparation. It recognizes tooth color through the Shade measurement option, and also has the function to capture dynamic articulation. Tracking of changes in the oral cavity over time is achieved through the TRIOS Patient Monitoring option [49].

In order to achieve good accuracy with Denture 3D Plus, it is important to follow the part setup instructions below for orientation and support. All processing parameters ("support patterns", "layer thickness" and "layer angle of the prothesis") are specified: [50].

- For improved model-fit, angle the part 60° (60–70 mm height)—3–4 builds on a platform, with the posterior border of the maxilla and/or the lower trigone facing towards the build area, and with the mucosal side facing towards the build area.
- Generate supports by using Smart Supports. Rather than deleting auto-generated supports, consider moving them to another position. Removing critical supports because they interfere with a margin line may affect print quality.
- For best results use the Resin Mixer to gently stir between prints and after the resin has been sitting overnight.
- Verify proper cleaning method. Ensure cleaning solvents are not saturated and parts are allowed to dry for 10 min before post cure.

There is an approved protocol on the main stages of goal design prostheses with 3Shape Dental System, which includes the following steps:

(1) Creating an order for a set of the full dentures. There are two options—with factory artificial teeth and with printed artificial dentitions.
(2) Scanning of upper and lower model.
(3) Intermaxillary ratio scan—scanning the occlusion.
(4) Determination of the occlusal plane.
(5) Marking of anthropometric points on the upper and lower jaw.
(6) Outlining the boundaries of the upper and lower dentures.
(7) Check for undercut areas of the upper and lower jaws.
(8) Selection of factory artificial teeth from the "Library" and digital arrangement of the artificial teeth.
(9) Corrections on the denture base of the upper and lower prosthesis.
(10) Digital modeling of the finished removable dentures.

After the scanning process is completed, an STL file should be sent to the 3D printer software and the production process should be started; 3D printing materials are available in special cartridges and after opening, they are poured into a tray in the 3D printer. Once the printed prosthesis is ready, on the surface of the finished dentures remains an unpolymerized layer of the material to be cleaned by immersion in a bath of isopropyl alcohol. After cleaning, the removable denture should be subjected to additional polymerization in another apparatus [51].

3.2.5. Manufacturing Techniques for 3D Printed Removable Dentures

Removable denture processing was digitized first in the dental laboratory with scanning of the impressions or casts, using laboratory scanner, digital tooth set up, and printing of the trays and record bases or even the final removable dentures. Several advantages were demonstrated during different case reports, describing the CAD/CAM fabrication of digital dentures [52]. This process allowed for faster turnaround times and design storage in case of denture loss or fracture. For computer-engineered removable dentures, a worthwhile consideration is their economic implications as compared to traditional approaches. Efficiency is one of the driving factors towards workflow optimization through digital dentistry. There are mainly two protocols for the fabrication of digital dentures—the subtractive and the additive [53]. With the subtractive method, the denture base is milled from a pre-polymerized resin blank. Depending on the system, prefabricated or milled denture teeth are subsequently bonded on the base. They are attached by unpolymerized resin from the printer and subsequent polymerization. The second protocol includes a printed or milled denture base, and factory-made artificial teeth that are bonded the same way [54].

3.2.6. Comparative Studies between Heat-Cured and 3D Printed Resins for Denture Bases

Choi et al. [55] compared fracture toughness and flexural bond strength between three types of denture-base resins (DBRs), heat cure, CAD-milled, and 3D printed, and four different types of commercial denture teeth (Unfilled PMMA, double cross-linked PMMA, PMMA with nanofillers and 3D printed resin teeth). All specimens were surface treated, bonded, and processed according to the manufacturer's instructions. A 4-point bend test, using the chevron-notched beam method, was performed. The results revealed that teeth bonded to heat-cured denture-base resins produced the highest fracture toughness.

In an in vitro study, Gad et al. [56] analyzed the flexural strength, impact strength, hardness, and surface roughness of 3D-printed denture base resin subjected to heat-cured resins for a removable prosthesis; 120 specimens were fabricated and distributed into two groups: heat-polymerized; (Major.Base.20) as control and 3D-printed (NextDent) as the experimental group. Flexural strength (MPa), impact strength (KJ/m^2), hardness (VHN), and surface roughness (µm) were measured using a universal testing machine, Charpy's impact tester, Vickers hardness tester, and profilometer, respectively.

Alfouzan et al. [57] studied and compared the color stability of 3D-printed and conventional heat-polymerized acrylic resins following aging, mechanical brushing, and immersion in a staining medium. The disc specimens were prepared from two 3D-printed [DentaBASE (DB) and Denture 3D+ (D3D)] and one conventional polymethylmethacrylate (PMMA) denture material. They were thermo-cycled, subjected to mechanical brushing, and were immersed in either coffee, lemon juice, coke, or artificial saliva (AS) to simulate one and two years of oral use. Color measurements of the specimens were recorded by a spectrophotometer at baseline, and after one and two years of simulation. The color changes (ΔE) were determined and also quantified according to the National Bureau of Standards (NBS) units.

Regarding the material type, PMMA demonstrated the highest mean ΔE, followed by D3D, and DB. The difference in ΔE between the materials was statistically significant ($p < 0.001$). The color changes of 3D-printed denture resins were low compared to conventional heat polymerized PMMA [57].

4. Discussion

According to the current study of Alfouzan et al. [57], the color stability of two 3D-printed and one conventional heat-polymerized denture resins were evaluated and compared. The materials were subjected to aging by thermal cycling and mechanical brushing and exposed to a staining medium to simulate one and two years of oral use. The statistical analysis outcome recommends rejecting the null hypotheses as significant differences in color stability were observed among the resin materials.

The present findings are in disagreement with previous studies. Gruber et al. [58] evaluated the color stability of CAD/CAM subtractively and additively manufactured (3D-printed) and conventional heat-cured PMMA resin. The authors demonstrated maximum discoloration and inferior color stability with 3D-printed resin groups compared to CAD/CAM subtractively manufactured and conventional PMMA resins.

Similarly, Shin et al. [59] evaluated the color stability of CAD/CAM blocks and 3D-printing resins for their degree of discoloration based on material type, colorants types, and immersion duration in the colorants. The authors concluded that 3D-printing resins sdemonstrated color differences above the AT ($\Delta E > 2.25$) following immersion for 7 days or longer in all test groups. The authors also revealed that after thermal cycling, the water sorption of 3D-printed resin was high compared to prefabricated PMMA.

However, in the same study, the authors showed that each study material showed distinct properties, even when using the same 3D-printing method [60,61]. Thus, it was evident that other factors, such as material properties and other output parameters, could affect the water sorption rate of 3D-printing resin. While water sorption alone does not justify low color stability; it could be considered a contributing factor.

The current laboratory study's strength is the substantial methodological approach, including thermal cycling, mechanical brushing, specimen exposure to staining medium, and color measurements to reproduce the clinical environment. Despite the strength, this study had a few limitations. Firstly, the standard methodological approach may not be logical in in vivo environments. The brushing cycles adopted in this study are based on the fact that patients brush their dentures twice a day. Nevertheless, the exact brushing cycles vary for some patients who practice cleaning their dentures repeatedly [50]. Secondly, it is impractical to simulate the period that the beverage is in contact with artificial dentures inside the mouth before swallowing [61,62].

In the study of Gad et al. [56] were recorded significant differences in all tested properties between heat-polymerized and 3D-printed denture base materials ($p < 0.001$). The 3D-printed resin had inferior flexural strength, impact strength, and hardness values than heat-polymerized resin, but showed superior surface roughness.

Choi et al. [55] evaluated that the artificial teeth bonded to CAD/CAM and 3D printed DBRs showed significantly lower bond strength. The study suggested that despite the increasing popularity of CAD-milled and 3D printed materials, heat-cured denture base resins still produce the highest bond strength to various types of denture teeth.

Finally, there was no substantial comparison of the present findings with previous data due to the limited number of studies concerning the properties of 3D-printed resins, such as water sorption, surface roughness and hardness, before their inclusion in routine clinical practice.

5. Conclusions

Three dimensional printing has started entering esthetic dentistry and playing a major role, because the technique is used for manufacturing prosthetic restorations made from different materials, and the production time is significantly reduced compared to the conventional heat-cured polymerization process. Limitations of 3D printed materials include poor esthetics and retention, inability to balance occlusion and low printer resolution. Heat-cured PMMA showed better flexural, bond and impact strength, compared to 3D printed materials for removable dentures. It was evaluated, that 3D printed resins had superior surface roughness and lower hardness values than the conventional materials.

In comparison with the heat-cured acrylics for denture bases, the materials for 3D printing showed higher color stability over time.

The use of digital technologies facilitates new treatment concepts that reduce the number of appointments needed at the dental office. The factors that contribute to the listed advantages are promising short-term clinical performance, reasonable financial cost and positive patient-related results.

Author Contributions: Conceptualization, M.D. and M.C.; writing—original draft preparation, M.D. and M.C.; writing—review and editing, S.C., A.V., G.B., R.K. and B.C.; supervision, S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

OBJ	object
STL	stereolithography, standard triangle language, standard tessellation language
3D	three-dimensional
ABS	acrylonitrile butadiene styrene
CAD/CAM	computer-aided design/computer-aided manufacturing
DBRs	denture-base resins
DLP	digital light processing
FDM	fused deposition modeling
ISO	International Organization for Standardization
KHN	Knoop hardness
LFS	low force stereolithography
LPU	light processing unit
MMA	methacrylate monomer
NBS	National Bureau of Standards
PC	polycarbonates
PCL	polycaprolactone
PEI	polyetherimide
PLA	polylactic acid
PMMA	polymethyl methacrylate
SLM	selective laser melting
SLS	selective laser sintering

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