DIGITAL PMMA, WHEN AND WHICH

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ABSTRACT
Polymethyl methacrylate (PMMA) has become a cornerstone of dental prosthetics, valued for its adaptability, biocompatibility, and cost-effectiveness. In recent years, rapid advancements in material science and digital manufacturing technologies, particularly CAD/CAM milling and 3D printing, have driven PMMA to new levels of functionality and application. These innovations have enhanced the material's physical properties—such as strength, aesthetic quality, and wear resistance—making it suitable for both temporary and, in some cases, long-term dental restorations. This review examines the evolution of PMMA in dental applications, emphasizing recent modifications in material composition, digital processing techniques, and clinical outcomes. Topics covered include multi-layered and high-impact PMMA variants, milling advancements, 3D printing methods, and how these developments address clinical needs in modern dentistry.
Key words: PMMA; CAD/CAM milling; 3D printing; dental prosthetics

INTRODUCTION

The evolution of materials in dental prosthetics has significantly impacted oral health care by improving patient outcomes and enhancing overall quality of life. Traditionally, metals, ceramics, and polymers have been the mainstay for both fixed and removable prosthetic devices. Metals are often favored for their high durability and strength; however, they come with notable drawbacks, including less favorable aesthetics, issues with thermal conductivity, and potential biocompatibility challenges such as allergic reactions or tissue irritation [1-6].

To address these limitations, a shift towards non-metallic materials, particularly ceramics, polymers, and composite resins, has been evident in recent years [7-9]. These materials bring a variety of advantages to dental prosthetics, including superior aesthetics, enhanced biocompatibility, and insulating properties that prevent discomfort from temperature fluctuations. Additionally, they offer remarkable versatility and adaptability, which allows for a high degree of customization to meet the specific needs of each patient.

The customization of these non-metallic materials has been further advanced by digital technologies, such as computer-aided design (CAD), computer-aided manufacturing (CAM), and three-dimensional (3D) printing. These technologies enable precise fabrication and detailed tailoring of dental restorations, improving the fit, function, and appearance of prosthetic devices. As a result, modern restorations are not only more comfortable and durable but also more natural-looking, enhancing patient satisfaction and the likelihood of long-term success for dental prosthetics [10].

The aim of this study was to perform an up-to-date literature review of the application and implications of using digital polymethyl methacrylate (PMMA) in dental prosthetics.

DIGITAL TECHNOLOGY IN FABRICATION OF DENTAL PROSTHESIS

In dentistry, remarkable technological advancements has been transformed clinical practice in recent years. Two modern technologies are currently used in dental practice: milling and 3D printing, each with

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distinct advantages and limitation. Both construct a three-dimensional object like a dental restoration, from a digital model.

Dental milling is a subtractive manufacturing process, meaning it removes material from a block or disk to create the desired dental restoration, using high-precision machines. These restorations are very resistant, but generates significant material waste, making the process expensive [11].

Dental 3D printing is an additive manufacturing technology that uses 3D printing to fabricate fixed and mobile prosthesis, aligners, surgical guides, and models of teeth and jaws. This technology provide more accurate, efficient, and highly customizable solutions for both clinicians and patients. Compared with traditional subtractive manufacturing processes, 3D printing creates a complex shape or geometries that would be otherwise difficult to achieve through other technologies [12]. These restorations are fabricated layers by layers a digital model with minimal waste and, consequently are less expensive [13].

While both technologies digitalize traditional dental workflow, there are significant differences between them that play an important role in determining which is best for a certain situations. Key factors to consider when choosing between them include precision and accuracy, speed, esthetics, flexibility and cost [14].

Dental restorations based on digital workflow are generally highly-precise and accurate. Milling machines create highly precise and accurate dental restorations such as inlays, onlays, veneers, crowns, bridges, and dentures [15-17]. However, its fine detailing is limited by the size of the milling burs. Despite improvements in bur sizes, milling cannot match the intricate detail produced by high-resolution 3D printing [18].

Modern dental 3D printers excel at achieving high resolution, allowing for much finer details and smoother surface finishes than milling, which is crucial for the precise millimeter margins of dental restorations [19]. However, the accuracy of 3D printing can be affected by external factors like the resin's temperature and exposure to UV light.

In addition, milling technology provides consistent and repeatable results, with same accuracy over time, while 3D printing is capable of producing intricate details, but its consistency may be less predictable due to environmental factors.

On the other hand, milling is exceptionally accurate in the reproduction of original designs and can repeat the same results over time. 3D printing accuracy can be impacted by external factors such as environment, resin temperature, and UV light exposure [20].

In term of speed milling is extremely fast for single restorations, often taking just a few minutes to a couple of hours depending on the complexity of the design [21]. This makes it ideal for same-day dentistry when creating a single crown or other restoration. However, milling machines are restricted to producing one restoration at a time, limiting their efficiency when multiple applications are needed simultaneously. While the layer-by-layer nature of 3D printing can take longer to complete a single restoration compared to milling, it has a significant advantage when producing multiple restorations at once. The speed of 3D printing depends on factors such as layer thickness, and the complexity of the object [22]. Despite its longer production time for individual items, still allows same-day dentistry.

When it comes to esthetics, both milling and 3D printing provide the ability to create highly customized dental restorations, allowing practitioners to closely match a patient's natural teeth [23,24]. However, there are important distinctions in their ability to

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achieve esthetic quality: milling materials, offer multi-layered translucency that closely mimics the natural appearance of teeth. This translucency, along with the ability to polish the material to a high gloss, results in more lifelike restorations.

Regarding flexibility, 3D printing clearly exceeds milling in terms of design possibilities and material adaptability. 3D printing excels at creating intricate and complex shapes that would be challenging or impossible to achieve through milling [25]. This flexibility is particularly valuable in producing removable dentures, orthodontic appliances, and maxilla-facial prosthetics [26,27]. 3D printing is superior for dental restorations where undercuts are critical, such as in denture fabrication. Undercuts, which help ensure a secure and comfortable fit, are difficult to achieve with milling. Additionally, 3D printing supports a wide range of flexible materials, making it the go-to choice for applications like splints, surgical guides, and in-bonding bracket trays [28]. These require the kind of material flexibility that milling cannot provide.

In term of cost, there are notable differences between milling and 3D printing, which impact the overall expenses associated with each technology. Milling machines are generally more expensive to purchase and set up compared to 3D printers. In addition to the initial cost, milling requires ongoing expenses such as tooling, maintenance, and material costs. Dental 3D printers are generally more affordable to purchase and set up compared to milling machines, and the operating costs are lower as it generates less material waste and does not require expensive tooling like milling [29].

POLYMETHYL METHACRYLATE FOR DIGITAL DENTISTRY

PMMA is a popular material in dentistry due to its advantageous properties like aesthetics, ease of handling, affordability, and customizable mechanical characteristics. All of these characteristics make it a perfect match in dentistry, from crown and bridges to dentures, but PMMA also has notable deficiencies such as weakness regarding hydrolytic degradation, poor fracture toughness, and a lack of antibacterial activity [30].

Researchers have developed strategies to improve PMMA’s physical and mechanical properties, as well as its antimicrobial characteristics, by incorporating additives and fillers. Mechanical reinforcement was done with fibers, nanofillers, and hybrid materials [31-33]. These nanoparticle enhanced the mechanical properties, making the resin suitable for artificial teeth, denture bases, orthodontic appliances, and provisional crowns [34-38].

In addition, multiple studies have focused on different fillers added to PMMA in order to obtain antimicrobial activity for denture base material [39-41], with special focus on *Candida albicans* [42-45], the main pathogen associated with denture stomatitis [46-48].

Due to popularity in dentistry researchers sought improvements through various means. Advances in manufacturing technologies and the development of innovative materials such as high-density polymers, especially cross-linked polymers, have significantly expanded the possibilities of PMMA. Cross-linking refers to the formation of bonds that link one polymer chain to another [49]. This results in a three-dimensional network structure rather than a linear polymer chain [50]. This structural change fundamentally improves the mechanical properties of PMMA. Compared to linear PMMA, cross-linked PMMA (Figure 2) is stronger, more resistant, and has higher durability. CAD/CAM resin blocks, which are made from highly cross-linked PMMA, are pre-processed under controlled industrial conditions and this ensures a consistent

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microstructure and higher mechanical properties compared to conventional polymerized PMMA [51].

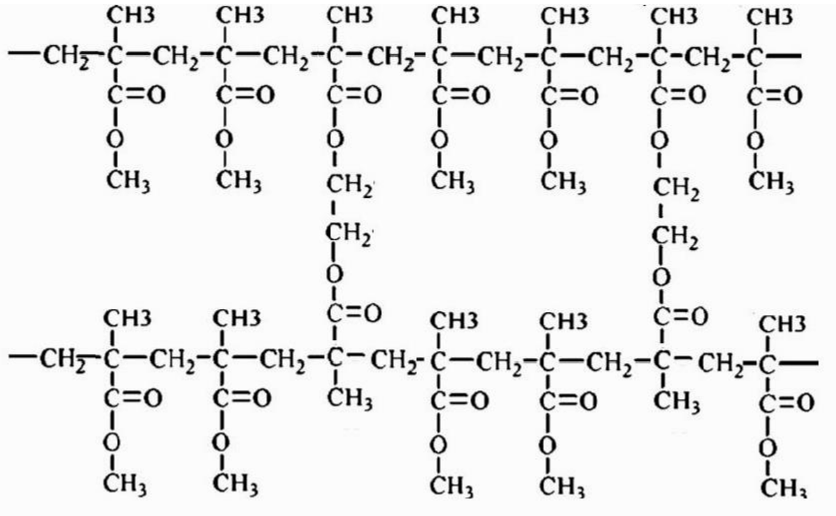

Figure 1. The chemical formula of cross-linked PMMA.

PMMA has evolved significantly in its use within the field of dentistry, thanks to advancements in digital manufacturing technologies**.** PMMA is now employed both as milled disks and as a printable material, which has broadened its applications across various dental specialties, such as restorative dentistry, prosthodontics, implantology, and orthodontics [52].

CAD/CAM milling of PMMA allows the fabrication of a wide range of temporary or long-term dental restorations, such as crowns, bridges, dentures, and abutments. With the rise of 3D printing technologies, PMMA is used for creating complex dental structures in a more time-efficient manner. 3D printing PMMA is used for temporary crowns, bridges, and veneers, complete and partial dentures, temporary restorations and surgical guides in implantology, retainers, aligners, and orthodontic models in orthodontics. Advantages of 3D printing PMMA in dentistry are: customization, high-speed, reduced cost, precision and complexity [53]. Due to ability to create intricate designs and fine details, 3D printing PMMA is the ideal material for complex restaurations [14, 54].

Both CAD/CAM and 3D printing technologies have revolutionized the fabrication of dental prosthesis by allowing greater precision, improved fit, and quicker production times. 3D printing offers the advantages of high customization, easier design modifications, but typically lower strength compared to milled PMMA. While, CAD/CAM provides superior mechanical properties, reduced risk of defects, and the highest flexural strength [55]. The CAD/CAM denture fabrication reduces chair time and exhibit superior fracture resistance due to the high-density, cross-linked nature of the material [56]. In addition, the precision of CAD/CAM milling ensures a smoother surface finish compared to conventional methods, which reduces plaque accumulation and microbial adhesion [56].

Milled PMMA has proven to be an effective option for use as a short- and mid-term interim material in both restorative dentistry and implantology [57,58]. This is particularly valuable for testing patient

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response to treatment before final restorations are made. Also, milled PMMA promote a favorable fibroblast response, which translates into an appropriate soft-tissue seal, low bacteria adhesion, and long duration of the material in the oral cavity [58].

Two parameters have been intensely studied when refer to digital PMMA in comparison with conventional PMMA: flexural strength and antimicrobial activity.

When comparing digital PMMA (milled or printing) to conventional PMMA (typically processed through conventional heat or chemical polymerization), two key parameters have been the focus of intense study: flexural strength and antimicrobial activity.

In terms of flexural strength, CAD-CAM-milled PMMA showed the highest flexural strength in comparison with 3D-printed PMMA resins, 3D-printed composite resin, and conventional PMMA [60]. The flexural strength is dependent by the polymerization technique [60], and industrial polymerization of PMMA discs used for milling lead to better mechanical properties. In 3D printing the flexural strength is dependent on the printing orientation [61]. Below is Table 6, summarizing recent studies that compare the flexural strength of different types of PMMA materials.

Table 1. Comparison table summarizing the flexural strength of the three types of PMMA: conventional, 3D printing and milled.

Type of study	Conventional PMMA	3D printing PMMA	Milled PMMA	Reference
In vitro three-point bending test of PMMA rectangular specimens	66.1 ± 13.1 MPa		131.9 ± 19.8 MPa	[62]
	93.33 MPa	-	130.67 MPa	[63]
	87.9 (5.0) MPa	-	105.1 (2.2) MPa	[64]
	80.79±7.64 MPa	87.34±6.39 MPa Showed wider plastic deformation.	110.23±5.03 MPa The best flexural properties.	[65]
	-	55.3-59.9 MPa at 0˚ 80.6-86.1 MPa at 45˚ 88.4-88.9 MPa at 90˚	-	[61]
	92.44 ±7.91 MPa	74.89 ±8.44 MPa	-	[66]
In vitro three-point bending test of immediate implant-supported interim prostheses	91.35 ±18.92 MPa	-	143.94 ±36.79 MPa	[67]
In vitro three-point bending test of PMMA rectangular specimens	68.63 MPa	49.26 MPa	97.68 MPa	[68]

This table illustrates that milled PMMA offers the highest flexural strength, making it more durable and less prone to fractures. It is suitable for long-term use, though it is often more expensive due to the CAD/CAM milling process. 3D printed PMMA offers more customization at a lower flexural strength, allows fast production and customization at reasonable price. Conventional PMMA offers a balance between affordability and strength, but involved more manual work and more time for patient and dental care providers. The majority of the tested PMMA materials complied with ISO Standard 20795-1 for denture base polymers. This standard specifies that acrylic resins used for denture bases should achieve a minimum flexural

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strength of 65 MPa to ensure sufficient mechanical performance [69].

Additionally, milled PMMA has been shown less water sorption and discoloration over time, as noted by Hada [64].

In term of antimicrobial activity, PMMA itself does not possess inherent antimicrobial properties. The antimicrobial activity of PMMA depends on the incorporation of various antimicrobial agents into its structure or the application of surface coatings with these agents. Both methods have proven effective in reducing microbial adhesion and growth on dental prostheses, but combining both methods have proven effective in reducing microbial adhesion and growth on dental prostheses [70].

A study conducted by Fiore compared the antimicrobial activity of three types of PMMA: conventional**,** 3D-printed, and milled PMMA, specifically against the adhesion of *Lactobacillus salivarius***,** *Streptococcus mutans***,** and *Candida albicans* to PMMA cylinder specimens [65]. The results showed that milled PMMA demonstrated the lowest surface roughness before polishing and the lowest bacterial adhesion after 90 minutes of incubation. However, after polishing, all tested PMMA types had similar surface roughness, and after 16 hours of incubation, the microbial adhesion was similar across the different types of PMMA.

In term of antimicrobial properties, 3D printed PMMA offers the advantage of incorporation of antimicrobial agents during the printing process. While conventional and milled PMMA lacks intrinsic antimicrobial properties. To obtain antimicrobial effects post fabrication treatments are needed.

It important to note that *Candida* colonization is facilitated by the porosity of PMMA, which promote microbial adhesion. However, new manufacturing techniques now allow for the production of PMMA with a smoother surface than conventional methods, reducing the risk of Candida growth. Mechanical polishing has been shown to result in lower surface roughness for CAD-CAM denture base resin, producing a superior smooth surface compared to conventional processed PMMA [65,71]. Additionally, pre-polymerized CAD-CAM acrylic resin exhibits a significantly better surface quality than traditional PMMA [72]. Although 3D printed PMMA exhibit acceptable surface roughness, less than standard threshold of 0.2 µm, studies indicate that the printing orientations and post-curing time have no significant effect on the final surface roughness [73].

While the studies for PMMA used for denture fabrication focus on flexural strength and antimicrobial activity, the studies for PMMA used for crowns and bridges focus on marginal fit accuracy. Recent in vitro research have shown similar accuracy between milled and 3D printed PMMA crowns [14].

In the context of PMMA used for dental crowns and bridges, the primary focus is to the marginal fit accuracy. This is because the precise fit of crowns and bridges is crucial for their long-term success, ensuring proper function, aesthetic integration, and prevention of complications such as secondary caries or crown loosening [74-77138-141].

Studies have shown that both milled and 3D printed PMMA crowns demonstrated better marginal fit in comparison with conventional crowns [14,78,79]. However, milled PMMA crowns have been found to provide a superior marginal and internal fit compare to 3D printed ones [80,81]. The material properties and accuracy of current 3D printing resins are still limited by lower precision and resolution compared to other additive manufacturing techniques [28].

For 3D printed PMMA crowns, the marginal and internal fit is influenced by factors such as layer thicknesses and

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inclination angle during the printing process. Research indicates that the best marginal fit is achieved with a layer thickness of 50 µm [81,82], and the optimal inclination angle for printing is 0˚ [83]. These parameters play a critical role in improving the precision of 3D printed crowns, although milled PMMA continues to outperform in terms of overall accuracy. As digital technology and materials improve, it is likely that 3D printed PMMA crowns will become more competitive in terms of fit and function.

The versatility and biocompatibility of PMMA, make is suitable for use in endodontics as post or endodontic implants. In these applications, PMMA's properties was enhanced by incorporating various additives to improve its mechanical performance [84].

The current used of PMMA in dentistry are summarized in Table 7.

Table 2. Dental use of PMMA.

Fixed Prosthodontics	Temporary crown, veneers and bridges, didactic models
Mobile Prosthodontics	Complete and partial denture, base and teeth, monolithic denture, repair of dentures
Dental Implantology	Surgical guides, abutments, short- and mid-term prosthesis
Maxillo-facial surgery	Retainers, aligners, orthodontics models
Orthodontics	Obturators, maxillo-facial prosthesis
Endodontics	Endodontic implants

CONCLUSIONS

PMMA remains a vital material in prosthodontics, benefiting from ongoing advancements in material science and digital technology. The association between innovative materials and digital fabrication techniques has significantly improved its clinical performance, expanding the use of PMMA in the dental and medical fields. These advancements have enhanced PMMA's durability, aesthetics, and functionality, making it an increasingly versatile solution for multiple restorative and therapeutic applications.

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