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PMMA Bone Cement: Properties, Applications, and Innovations

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A B S T R A C T

Polymethylmethacrylate (PMMA) bone cement has been a fundamental material in orthopedic and dental surgeries for decades, primarily serving to stabilize implants and facilitate bone healing. This review explores the properties, clinical applications, challenges, and recent innovations related to PMMA. The chemical and mechanical properties of PMMA, including its compressive strength and biocompatibility, underscore its utility in procedures such as joint arthroplasties and vertebroplasty. However, limitations such as biomechanical mismatch, thermal damage during polymerization, and susceptibility to infection pose significant challenges. Recent advancements aim to address these issues through the development of antibiotic-loaded formulations, bioactive additives, and smart biomaterials that enhance osseointegration and reduce complications. As research continues to evolve, the future of PMMA bone cement looks promising, with innovations poised to improve patient outcomes and expand its applications in medicine.

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1. Introduction

Bone cement, primarily composed of PMMA, is a vital material in orthopedic surgery, known for its remarkable adhesive properties and mechanical strength [1]. PMMA is a synthetic polymer formed through the polymerization of methyl methacrylate (MMA) monomers. When mixed with a powdered component, it undergoes an exothermic reaction that results in a solid, durable material [2, 3]. This unique characteristic allows PMMA to bond effectively with bone tissue, making it an essential component in various surgical applications [4].

It is predominantly used in joint replacement procedures, such as hip replacements and knee replacements, that PMMA-based bone cement is used [2]. Bone cement stabilizes prosthetic implants by creating a secure interface between them and the surrounding bone. The stability of the joint replacement is crucial to its longevity and functionality [5].

Besides joint replacements, PMMA is used in minimally invasive procedures like vertebroplasty and kyphoplasty to restore structural integrity and alleviate pain in fractured vertebrae [6]. The versatility of PMMA extends to dental applications as well, where it is used for prosthetics and restorative treatments [7].

While PMMA has proven to be effective in numerous applications, it is not without challenges. Its lack of bioactivity can lead to issues such as bacterial contamination and loosening over time [7]. Therefore, ongoing research aims to improve PMMA's performance in clinical settings by adding antibiotics or bioactive materials.

2. Properties of PMMA

2.1. Chemical and Mechanical Properties

PMMA exhibits a range of chemical and mechanical properties that make it suitable for various medical applications, particularly in bone cement formulations[7]. Chemically, PMMA is derived from the polymerization of methyl methacrylate (MMA) monomers, resulting in a thermoplastic polymer that is known for its clarity and resistance to UV light [8].

Mechanically, PMMA bone cements demonstrate significant compressive strength, typically ranging from 70 to 100 MPa, which is essential for withstanding the forces exerted during daily activities [9]. The bending modulus of PMMA cements is also crucial, with a requirement of at least 1800 MPa for clinical applications [10]. This property indicates the material's ability to resist deformation under load. However, PMMA is relatively brittle compared to other materials, exhibiting lower tensile strength (approximately 25 MPa), which can lead to failure under tensile stress [11]. The exothermic nature of the polymerization process during cement application results in heat generation, which can influence the surrounding tissue if not managed properly [12].

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Table 1

PMMA Bone Cement Mechanical Properties [13].

Property	Value (MPa)
Compressive Strength	**70 - 100**
Tensile Strength	**25 - 40**
Bending Modulus	**1800 - 2000**

Furthermore, the mechanical properties of PMMA can be affected by additives such as antibiotics. For instance, Falagas et al. [14] reported that the addition of liquid antibiotics has been shown to reduce the compressive strength of PMMA due to interference with the polymerization process. PMMA bone cement's mechanical properties are summarized in the table 1. As well as being able to withstand the forces exerted by daily activities, a material's tensile strength indicates its ability to resist pulling forces. A material's bending modulus indicates its stiffness and resistance to deformation under bending loads. Also, the compressive strength is particularly important for withstanding daily forces, while the tensile strength indicates resistance to pulling forces. As a measure of the stiffness of a material and its ability to resist deformation under bending loads, the bending modulus is measured. [13].

2.2. Biocompatibility

Biocompatibility is a critical factor in the use of PMMA bone cement in clinical settings [1]. PMMA is generally considered biocompatible; however, its performance can vary based on its formulation and the specific application [15]. In vivo studies indicate that PMMA can absorb body fluids over time, leading to changes in its mechanical properties and elasticity [15]. This characteristic can be advantageous as it allows the cement to adapt somewhat to the surrounding biological environment [16, 17].

The surface characteristics of PMMA also play a role in its biocompatibility. Modifications such as surface roughening or coating with bioactive materials can enhance cellular responses and promote osseointegration—the process by which bone grows onto the surface of an implant [18]. Research into incorporating calcium phosphate (CaP) into PMMA formulations shows promise in improving bone on growth and enhancing overall biocompatibility [19].

Despite its advantages, concerns remain regarding potential inflammatory responses due to wear debris or bacterial colonization around PMMA implants [22]. In order to enhance biocompatibility while maintaining mechanical stability, ongoing research aims to improve drug elution profiles and reduce infection rates in modified PMMA formulations. [5].

3. Clinical Applications of PMMA Bone Cement

3.1. Orthopedic and Dental Uses

PMMA bone cement is extensively utilized in orthopedic surgery, particularly in joint arthroplasties such as hip and knee replacements [2]. Its primary function is to provide a stable fixation between the prosthesis and the surrounding bone, ensuring that the implant can withstand the mechanical loads experienced during movement [20]. The mechanical properties of PMMA, including its high compressive strength (approximately 114 MPa) and tensile strength (around 49 MPa), make it an ideal choice for these applications [21].

In addition to joint replacements, PMMA is also employed in minimally invasive procedures like vertebroplasty and kyphoplasty. These techniques involve injecting PMMA into fractured vertebrae to stabilize them and alleviate pain, particularly in patients with osteoporotic fractures. Studies have shown significant pain relief following PMMA injection, with visual analog scale (VAS) scores dropping from an average of 8 preoperatively to around 2 within a week post-surgery. The rapid setting time and injectability of PMMA contribute to its effectiveness in these procedures.

In dentistry, PMMA bone cement finds application in various restorative procedures, including denture fabrication and dental implants. Its excellent adhesive properties allow for effective bonding with both natural tooth structure and dental prostheses. PMMA is often used to create temporary crowns and bridges due to its aesthetic qualities and ease of manipulation. Furthermore, modifications of PMMA, such as the incorporation of bioactive materials, enhance its performance in dental applications by promoting osseointegration around implants [1].

3.2. Role in Surgical Procedures

The role of PMMA bone cement extends beyond mere fixation; it also plays a critical part in enhancing surgical outcomes. In orthopedic surgeries, the use of antibiotic-loaded PMMA has been explored to reduce the risk of postoperative infections. This modification allows for the gradual release of antibiotics at the surgical site, which can be particularly beneficial in patients at higher risk for infections [22].

Moreover, advancements in PMMA formulations aim to improve its biocompatibility and bioactivity [23]. Research into composite materials that combine PMMA with calcium phosphate or bioactive glass has shown promise in enhancing bone regeneration and integration at the cement-bone interface [1, 23]. These innovations not only improve the mechanical stability of the cement but also facilitate better healing outcomes for patients.

4. Challenges and Advances

4.1. Limitations and Complications

Despite the widespread use of PMMA bone cement in orthopedic and dental applications, several limitations and complications are associated with its use. One of the primary concerns is biomechanical mismatch; PMMA has different mechanical properties compared to natural bone, leading to potential issues such as fatigue fractures or loosening of the implant over time [24]. The stiffness of PMMA can hinder proper load transfer, which may result in osteolysis and aseptic loosening around the implant site [25].

Another significant challenge is the exothermic polymerization reaction that occurs when PMMA is mixed and applied [15]. This reaction generates heat, which can cause thermal damage to surrounding tissues, potentially leading to complications such as

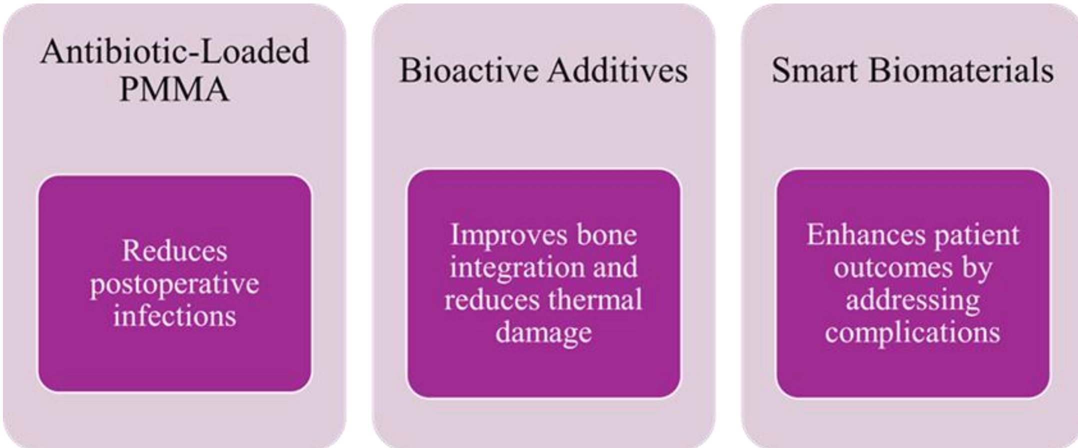

Fig. 1. Types of Recent Innovations in PMMA.

local tissue necrosis or even systemic effects like bone cement implantation syndrome (BCIS), characterized by hypoxia and hypotension [26]. Additionally, there is a risk of bacterial contamination; PMMA does not inherently possess antimicrobial properties, making it susceptible to infections at the cement-bone interface [2].

Other complications include allergic reactions to the components of PMMA, leakage of cement into surrounding tissues, and potential systemic toxicity from monomer release during polymerization [2]. These challenges necessitate careful consideration when selecting PMMA for clinical applications, particularly in vulnerable populations such as children, whose growing bones may be adversely affected by rigid materials [27]. As shown in table 2, PMMA bone cement is associated with a number of complications. Researchers and surgeons seeking to improve PMMA formulations and application techniques must understand these risks [4].

Table 2

Frequency of Complications Associated with PMMA Use [13].

Complication	Frequency
Thermal Damage	**1-5%**
Infection	**1-3%**
Aseptic Loosening	**5-10%**

4.2. Recent Innovations

In response to the limitations associated with traditional PMMA bone cements, recent innovations have focused on enhancing both the mechanical properties and biocompatibility of these materials [24]. One promising approach involves the development of antibiotic-loaded PMMA cements, which aim to reduce infection rates during surgical procedures. While the efficacy of these formulations is still debated, they represent a significant advancement in addressing one of the major complications associated with PMMA use[28].

Researchers are also exploring additives that can improve the performance of PMMA cements [29]. For instance, incorporating bioactive materials such as calcium phosphate or glassy carbon has shown potential in enhancing osseointegration and reducing polymerization temperature, thereby minimizing thermal damage during application [30]. These modifications not only aim to improve the mechanical strength of PMMA but also enhance its biological interactions with surrounding tissues [15].

Additionally, advancements in smart biomaterials are being investigated. These materials can respond dynamically to physiological conditions, potentially releasing therapeutic agents in response to infection or inflammation [31]. Such innovations could significantly improve patient outcomes by addressing complications associated with traditional PMMA cements [2]. PMMA bone cement innovations are shown in Fig. 1, along with descriptions of their benefits. The information is visually organized to demonstrate how each innovation addresses PMMA's limitations.

Conclusion

PMMA bone cement has established itself as a fundamental component in orthopedic and dental surgeries, offering essential benefits such as mechanical stability and ease of application. However, its use is accompanied by several challenges, including biomechanical mismatches, thermal complications during polymerization, and susceptibility to infections. Addressing these issues is crucial for enhancing the long-term success of surgical interventions involving PMMA. Despite its advantages, the limitations associated with PMMA such as its brittleness, potential for thermal damage, and lack of inherent antimicrobial properties highlight the need for continued innovation in this field. Looking ahead, future directions in PMMA research should focus on developing modified formulations that enhance both mechanical properties and biocompatibility. Innovations such as antibiotic-loaded cements, bioactive additives, and smart biomaterials represent promising avenues for improving patient outcomes and reducing complications. For understanding the implications of PMMA in young populations and those with compromised bone integrity, further studies on its long-term effects on bone health are needed. As the field evolves, interdisciplinary collaboration between materials scientists, orthopedic surgeons, and biomedical engineers will be essential to drive advancements that ensure PMMA remains a safe and effective choice for surgical applications. By addressing current limitations and embracing new technologies, the future of PMMA bone cement looks promising, with the potential to significantly enhance surgical success rates and patient quality of life.

Authors' contribution

Ali Shirbacheh: Conceptualization, Writing—Original Draft Preparation, Writing—Review and Editin, **Kamran Shirbache:** Investigation, Writing—Original Draft Preparation, Writing—Review and Editing

Declaration of competing interest

There are no known competing financial interests or personal relationships that could have influenced the authors' work.

Data availability

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